

SURVEY ON MEASUREMENTS AND EMISSION FACTORS ON PARTICULATE MATTER FROM BIOMASS COMBUSTION IN IEA COUNTRIES

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ABSTRACT

Since biomass combustion is related to high emissions of particulate matter (PM), the International Energy Agency (IEA) Bioenergy Task 32 is promoting the implementation of technical measures for PM reduction. As a basis to set priorities and as a guideline for future regulations, emission factors from different types of combustion are of interest. The target of the present study is to collect and critically discuss emission factors from residential wood combustion in the IEA member countries. The reported results on emission factors from manual wood combustion devices exhibit huge ranges from less than 20 mg/MJ under ideal conditions up to more than 5 000 mg/MJ under poor conditions. Hence ideal operation is regarded as a major target for the future. Furthermore, the implementation of heat storage tanks is identified as an important need for log wood boilers. Since different PM measurements are applied, the influence of the sampling method, i.e., hot filter probe, quenching, and dilution tunnel, is discussed. Measurements reveal that the mass on solid particles and condensables need to be distinguished. Under poor combustion conditions, the mass of condensables can exceed the mass of solid particles and should be considered to evaluate the impact of wood combustion on the ambient air quality.

Keywords: PM₁₀, emission factor, particle emissions, condensables, wood combustion.

1 INTRODUCTION

1.1 Motivation

The International Energy Agency (IEA) Bioenergy Task 32 on Biomass Combustion and Co-firing is promoting an increased use of biomass for energy production to replace fossil fuels. However, biomass combustion is an important source of inhalable particulate matter smaller 10 microns (PM₁₀) in the ambient air. Since PM is regarded as one of the most relevant parameters in air pollution [1,2], the PM emissions from biomass combustion can hinder the propagation of bioenergy. To overcome this disadvantage, detailed information on particles from different combustion applications is needed. Based on this, the most significant particle sources among biomass combustion can be identified and measures for PM reduction can be deduced. Consequently activities on the characterisation of particle emissions from biomass combustion have been performed in many IEA countries in the past years or are currently ongoing.

1.2 Objectives

The objectives of the present study is to review emission factors of particulate emissions from biomass combustion and measurement techniques applied to characterise particle emissions [3]. Priority is given to wood fuels used in residential wood combustion and in district heating plants. To enable a comparison of different data, the sampling and measurement techniques shall be documented and differences due to different sampling or analysis shall be discussed. Furthermore, the influence of combustion type, fuel parameters and different operation conditions on PM emissions shall be identified.

1.3 Work programme

The main work method was to collect emission data from research institutes and universities and to review official national emission factors. Furthermore, information on measurement methods was collected. For this purpose, a detailed questionnaire on particles was compiled and sent to IEA appointed experts. Beside this, data

available from literature was also considered. Relating to emission factors the questionnaire comprehends residential wood burning as well as industrial wood combustion. The residential category consists of fireplaces, manual stoves, manual boilers and pellet combustion, each case with subcategories oriented on technology and wood fuel (log wood, pellets). For the emission inventory data a range of values were requested for best results at ideal operation, typical results at practical operation and worst results at very bad handling. Values were also differentiated between measurements with and without start phase emissions and measurements for solid particles (indicated as SP), solid particles plus condensables found in impinger bottles (SPC), and total particles collected in a dilution tunnel (DT).

1.4 Participating countries

A total of 17 institutions from seven countries, i.e., Austria, Denmark, Germany, Norway, The Netherlands, Sweden, and Switzerland, participated in the survey and contributed with data to the questionnaire. In addition, data for national emission factors were reported or gathered from literature. Table 1 gives an overview on the participating countries, table 2 shows the names and abbreviations of the institutions. The introduced country codes and the abbreviations of the institutions are used in the following graphs.

1.5 Sources of presented data

Most of the data presented in the following figures have been indicated by the participating experts from the institutions described in Table 2. In these cases, there is no literature quotation, as these data have been collected by the questionnaire sent out in the present study.

In several cases, additional data have been used from reports or literature. In these cases, the source is cited in the figures with numbers in squared brackets as e.g. [7] which refer to the reference list given in addition to the literature list, which quotes literature cited in the text with numbers in forward slashes as e.g. /7/.

Table 1 Participating countries and country codes.

Country	Country code
Austria	AUS
Denmark	DEN
Germany	GER
The Netherlands	NET
Norway	NOR
Sweden	SWE
Switzerland	SWI

Table 2 List of participating institutions.

Country	Institution (full name)	Abbreviation
AUS	Biomass Logistics Technology, Wieselburg	BLT
	Bios and Graz University of Technology, Graz	Bios
	Joanneum Research, Graz	Joanneum
	Austrian Tiles Stove Association, Vienna	KOV
DEN	FORCE Technology, Brøndby	Force
GER	Institute for Energy and Environment, Leipzig	IE
	Technologie- und Förderzentrum, Straubing	TFZ
	University of Stuttgart, Inst. of Process Eng. and Power Plant Technology	Uni Stuttgart
	ZAE Bayern, Garching	ZAE
NET	TNO Science and Industry, Apeldoorn	TNO
NOR	SINTEF NBL, Norwegian Fire Research Laboratory, Trondheim	SINTEF
SWE	SP Technical Research Institute of Sweden, Borås	SP Tech.
	Umeå University, Energy Techn. and Thermal Process Chemistry, Umeå	Umeå Uni
	Växjö University, Dep. of Bioenergy Technology, Växjö	VXU
SWI	Centre of Appropriate Technology and Social Ecology, Langenbruck	CATSE
	Verenum Research, Zürich	Verenum
	Vock Engineering, Maschwanden	Vock

2 METHODOLOGY

2.1 Definition of emission factor

Emission factors are representative values which attempt to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. Emission factors for energy production are expressed as mass of pollutant divided by a unit energy, volume, or weight of the activity emitting the pollutant (e. g., grams of particulate emitted per kilogram of wood burned). They are used to make source- or appliance-specific emission estimates.

Emission factors represent an average range of emission rates. Manual operated combustion appliances exhibit a wide range of emission factors. Essential are the operating mode, the fuel type, and the technique of the equipment. Measures regarding manual operated combustion devices show that the emissions during practical operation have a factor leastwise twice as high as during ideal operation whereas by improper handling the emissions can be even ten times or in some cases even more than hundred times as high (e.g. /4/). The accuracy of emission factors has a central impact on the quality of emission inventories.

To obtain a clearer picture of the emission range, one target of the survey is to record values containing data from best results at ideal operation over typical results at practical operation to worst results at very poor operation. The collected emission factors are results of measurements and data from literature of various countries. To enable a comparison of the different reported data, all values are converted to mg particles emitted per MJ end energy contained in the fuel based on lower heating value indicated as [mg/MJ]. If not determined in the evaluated literature, emission factors are assumed to be measured without start. Further, results from PM measurements on hot filters and results from dilution tunnels are distinguished, since they cannot be directly compared.

2.2 Influence of particle sampling methodology

Combustion particles are a mixture of solid particles and condensables, both containing organic and inorganic fractions. Especially the organic emission is strongly influenced by the combustion conditions. High organic emissions are correlated with low combustion efficiency and high potential for toxic organic substances, e.g. benzo(a)pyrene (BaP) or fluorene and can be avoided by high combustion temperature, sufficient oxygen availability in the flame enhanced by good mixing and sufficiently long residence time in the combustion zone.

The emission of inorganic particles can be slightly influenced by the combustion conditions, however it depends on other formation mechanisms than organic particles. High temperature enhances the conversion of ash constituents to the gas phase and consequently the emission of inorganic particles. Under typical conditions, organic particles are most relevant in poorly operated manual wood combustion devices, while inorganic particles are dominant in automatic wood combustion plants operated at high temperatures. Depending on the aim of the measurement, different sampling strategies are commonly used e.g. for product testing and health studies. In the present survey, four types of particle sampling are distinguished as illustrated in Figure 1:

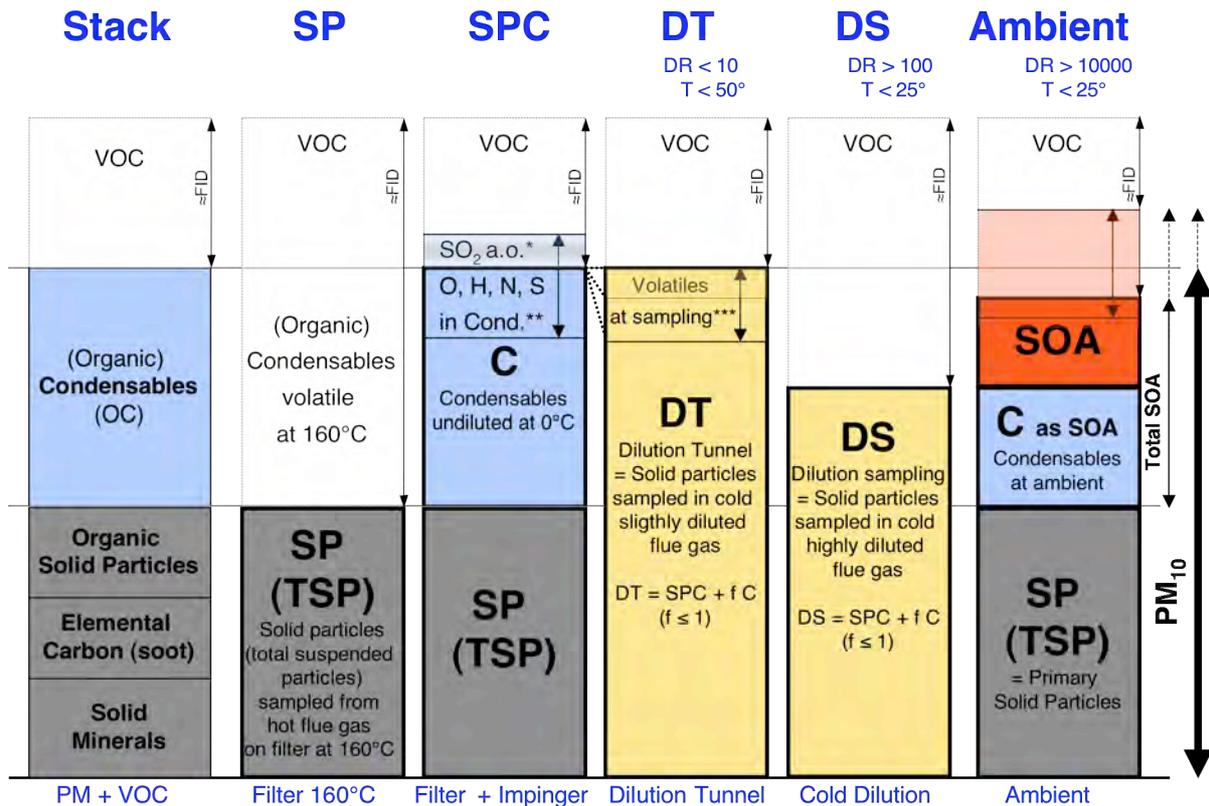


Figure 1: Comparison of PM sampling with PM in the ambient.

*SO₂ and other soluble gaseous compounds in the flue gas may be dissolved in the impingers.

**In case of determination of TOC in impingers, the mass of O, H, N, S and other elements contained in the organic condensables needs to be accounted for separately.

***Organic compounds which are liquid or solid at partial pressure in the flue gas and ambient temperature but volatile at sampling due to reduced partial pressure by dilution and temperature above ambient.

SP: Filter (Method a) resulting in solid particles SP (total suspended particles TSP).

SPC: Filter + Impinger (Method b) resulting in solid particles and condensables SPC.

DT: Dilution Tunnel (Method c) with typical dilution ratio (DR) in the order of 10 resulting in a PM measurement including SPC and most or all C. Hence DT is identical or slightly smaller than SPC + C due to potentially incomplete condensation depending on dilution ratio and sampling temperature (since dilution reduces not only the temperature but also the partial pressure of contaminants).

DS: Dilution Sampling with high dilution ratio (DR > 100).

PM₁₀: Total Particulate Matter < 10 microns in the ambient including SP and SOA

SOA: Secondary organic aerosols, consisting of condensables C at ambient and SOA formed by secondary reactions such as photochemical oxidation.

Method a)

Sampling of particles on a heated filter, through a probe, from undiluted flue gas in the chimney at gas temperatures of e.g. 160°C (German norms, VDI) or 120°C (US EPA). These particles are defined as solid particles (SP) in the study and consist of filterable particles and droplets at the indicated temperature. If not indicated otherwise, data on PM in the present report are given as SP.

Solid or filterable particles consist of inorganic particles and organic particles. The inorganic particles are constituted to a large part of K₂SO₄ and KCl (depending on the fuel composition) at favourable combustion conditions, while soot (elemental carbon, EC) and organic particles are also emitted as solid particles if the combustion conditions are poor.

Method b)

Sampling of particles as described in a) and subsequent sampling of condensable organic matter (C) in impinger traps at temperatures close to 0°C. Typically condensable particulate emissions are sampled in a series of impinger flasks, e.g. containing water to collect inorganic compounds and containing methylene chloride to capture organic compounds. The sum of solid particles and condensables are defined as (SPC) in the present report.

Inorganic matter, excluding water, found in the impingers can originate from gaseous products such as e.g. SO₂. Hence in case of relevant amount of such compounds, the allocation of the respective mass to either gaseous or particulate emissions is uncertain and needs further information. Under typical wood combustion conditions (with low sulphur concentrations), the inorganic PM is sampled in the filter, while condensable inorganic matter in the impinger bottles is assumed to be negligible.

Method c)

Sampling of filterable particles in a dilution tunnel with a filter holder gas temperature at e.g. $< 35^{\circ}\text{C}$ (e.g. Norwegian standard NS 3058-2). Due to the cooling, condensable organic material in the hot flue gas condenses on the filter. Condensable inorganic PM is assumed to be negligible for residential combustion of wood. Hence the particle concentration found by method c) is assumed to be similar or equal to the mass detected by method b). The particles detected by method c) are defined as particles in dilution tunnel (DT) in the present study and correspond to particles detected at small dilution ratios (DR), i.e., typically DR in the order of magnitude of 10. For a comparison and interpretation of results from dilution tunnel measurements needs to be considered, that the dilution ratio can vary during one single measurement and from one measurement to another. This can lead to differences of the detected particle mass in regimes where effects of condensation and re-evaporation are sensitive to the dilution ratio, as the initial dilution with cold air may lead to an increase of particle mass due to condensation, while further dilution may lead to a subsequent loss in particle mass due to re-evaporation of semivolatile compounds.

Method d)

Dilution can also be performed at high dilution ratios, i.e., in the order of 100 or more, which is defined as dilution sampling (DS) in the present study. To mimic conditions in the ambient, sampling can be performed in cold, highly diluted flue gas. Dilution with cold air at high dilution ratios is applied e.g. by analysing the plume by following a vehicle under real-world conditions in a certain distance on the road. As in dilution tunnels, the dilution ratio can vary during sampling.

For on-line analysis of the particle size and number concentration, a hot dilution stage followed by a cold dilution is usually applied resulting in a total dilution ratio in the order of 100. The hot dilution avoids condensation and hence enables to identify the particles similar as found in the stack (i.e., SP) but gathering information on the particle size and number instead of the total particle mass.

Applications of methods a) to d)

For residential combustion devices analysed in the laboratory, all methods can be applied, while for large combustion devices and for normal measurements in practice, sampling in a dilution tunnel is usually not applicable due to practical reasons.

Sampling on hot filters by method a) is useful for testing of combustion devices, but can significantly underestimate the total organic PM in ambient air resulting from biomass combustion for applications with high concentrations of organic substances. Since condensable organic matter has been identified as highly toxic, method a) may not only underestimate the mass concentration of PM, but in addition also the health impact.

Measurements in dilution tunnel by method c) may over-estimate the particle mass in the ambient under certain circumstances, since evaporation by subsequent dilution in the ambient may lead to a reduction in particle mass which, however, is then resulting in volatile organic matter instead of particulate matter as illustrated in Figure 4.2.

Figure 1 shows the qualitative difference between the described sampling methods, i.e. hot filter (SP), hot filter and impingers (SP+C), dilution tunnel (DT), and dilution sampling (DS). However, the partitioning between SP and C strongly depends on the combustion type. At good combustion conditions C is negligible and hence all sampling methods lead to similar results. On the other hand, C can significantly exceed SP during incomplete combustion conditions. Hence the sampling type can strongly influence the result for residential wood combustion, while for large automatic combustion plants, the differences can be small.

3 RESULTS ON METHODOLOGY

To evaluate the influence of the sampling methodology as described above, the contribution of condensables to the total PM emissions is crucial. Hence measurements on wood stoves were performed which allow an estimation of the influence of condensable organic matter available in the flue gas.

Figure 2 shows that the PM emission factor found in the dilution tunnel is significantly higher than the solid particle emissions detected in the chimney. The same is true for the data found including condensables in impingers.

Figure 3 illustrates the ratio of DT/SP in case of dilution tunnel and of SPC/SP in case of condensables found in impingers. In one single case (Verenum stove 3) which corresponds to a high combustion quality resulting in low total PM emissions, the ratio SPC/SP is only slightly greater than 1 (i.e., ≤ 1.1), while in all other cases with poor combustion conditions (throttled air supply), the reported ratios DT/SP are between 2.5 and close to 10 (data from Sweden) and the ratios of SPC/SP are between 3 to 6 (data from Switzerland).

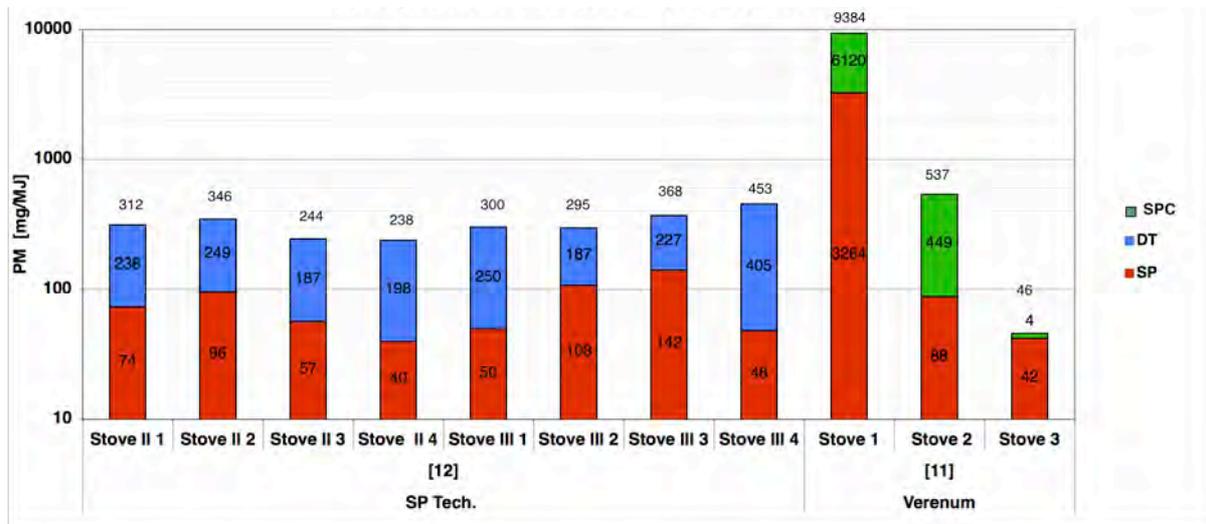


Figure 2: Comparison of PM emission factors on solid particles (SP), particles in dilution tunnel (DT), and solid particles plus condensables from impinger (SPC) for wood stoves.

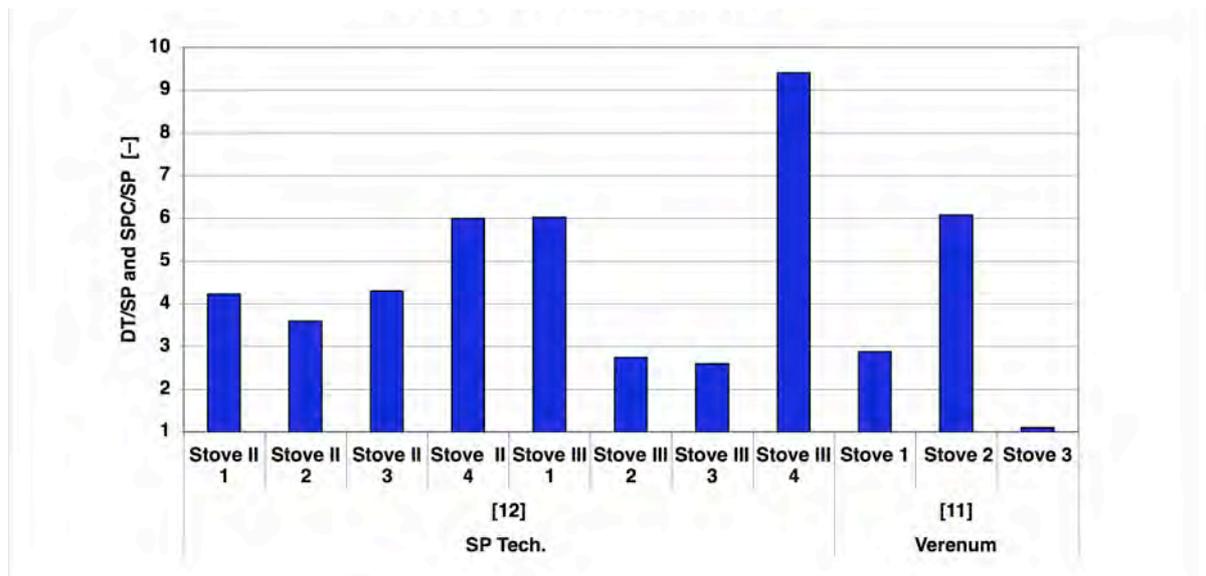


Figure 3: Ratio DT/SP and SPC/SP for wood stoves acc. to Figure 2.

4 RESULTS ON EMISSION FACTORS

4.1 Open fireplaces

Figure 4 shows the PM emission factors for open fireplaces. The range for typical measured emission factors on solid particles (SP) varies between 23 and

265 mg/MJ. National emission factors range from 160 (GER) to 447 mg/MJ (UKM). The emission factors for Finland and Norway are 860 mg/MJ and 910 mg/MJ respectively indicated for measurements with dilution tunnel (DT).

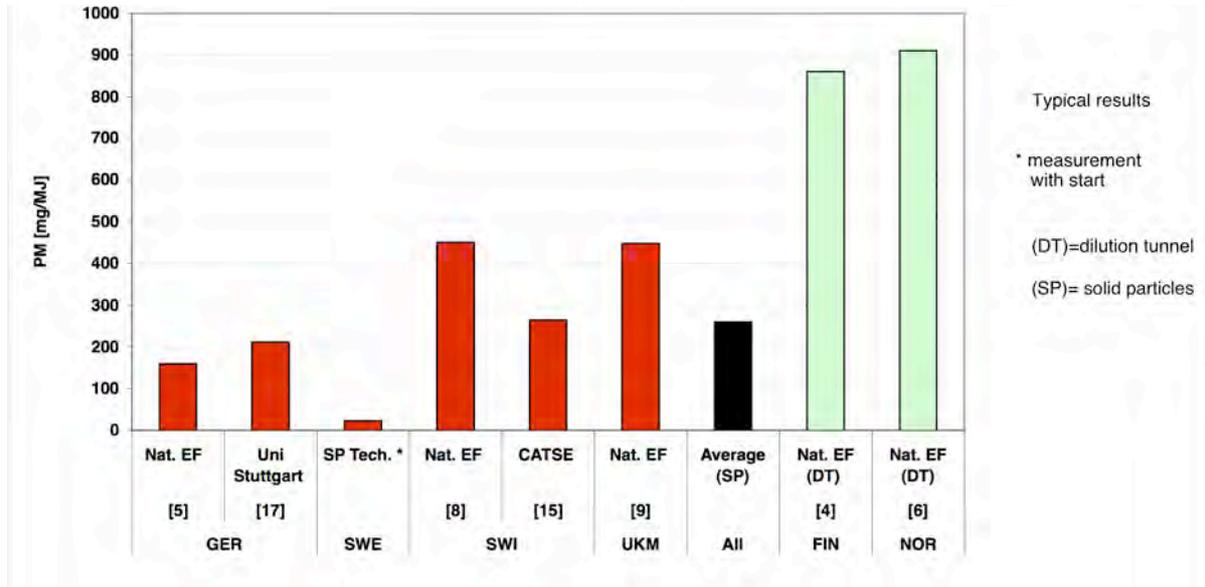


Figure 4: Emission factors for open fireplaces for solid particles (red) and for particles measured in dilution tunnel (green).

4.2 Closed inset appliances (closed fireplaces)

For closed inset appliances (closed fireplaces according to EN 13229:2001), only few data were available

(Figure 5). Worst results for emission factors range from 180 – 204 mg/MJ, typical results from 47 – 83 mg/MJ and best results from 14 – 26 mg/MJ.

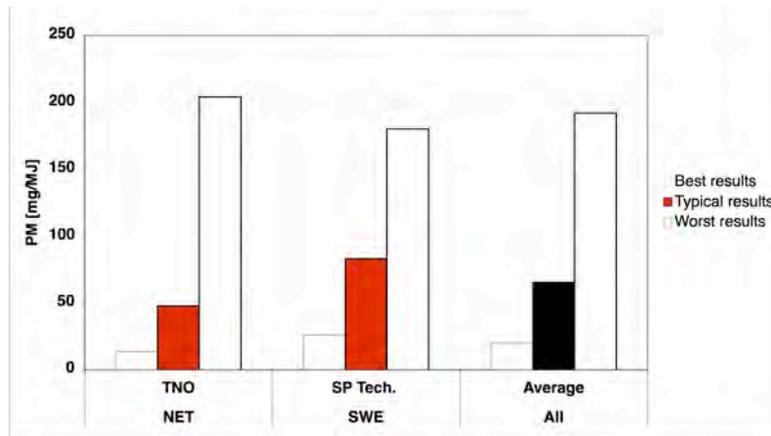


Figure 5: Emission factors for closed inset appliances.

4.3 Wood stoves

In this paragraph, PM emission factors for conventional wood stoves with natural draft are discussed. Within the survey most data was delivered for the category of wood stoves so that this rubric represents a broad overview. For typical measured solid particles with start phase, the scope ranges from 64 to 87 mg/MJ. Measurements with condensables and in dilution tunnel show persistently higher results in the range from 340 to 544 mg/MJ.

Figure 6 shows the emission factors for wood stoves with indication of ranges from best, typical to worst type of operation or combustion type. Figure 7 summarizes the same data with indication of the typical data only. Figure 8 shows national emission factors used for calculations of emission inventory reports. One of the most important applications is the reporting of national greenhouse gas

inventories under the United Nations Framework Convention on Climate Change. The comparison of default PM emission factors for wood stoves reveals a wide range for solid particles from 94 mg/MJ (Germany) to 650 mg/MJ (Sweden). In countries with compulsory measurements with dilution tunnel the factors are higher compared to solid particles and vary from 750 mg/MJ (Finland) to 1932 mg/MJ (Norway). The Finnish value is a new revised number which will apply soon, while currently the old value of 400 mg/MJ is still in force. The Norwegian emission estimate is based on an aggregated emission factor for traditional/conventional stoves, new stoves and open fireplaces /5/. An explanation to the high Norwegian emission data is that the Norwegian standard for wood stoves includes measurements at low heat output with throttled air supply. Thus the data should represent real use of wood stoves in Norway.

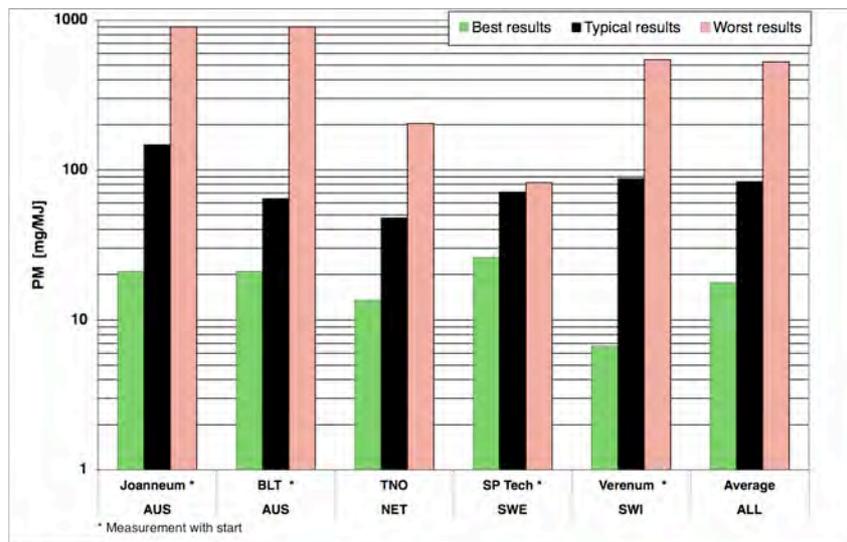


Figure 7: Range of emission factors for PM measured as Solid Particles (SP) from worst to best (where available) for wood stoves depending of type of operation and/or equipment.

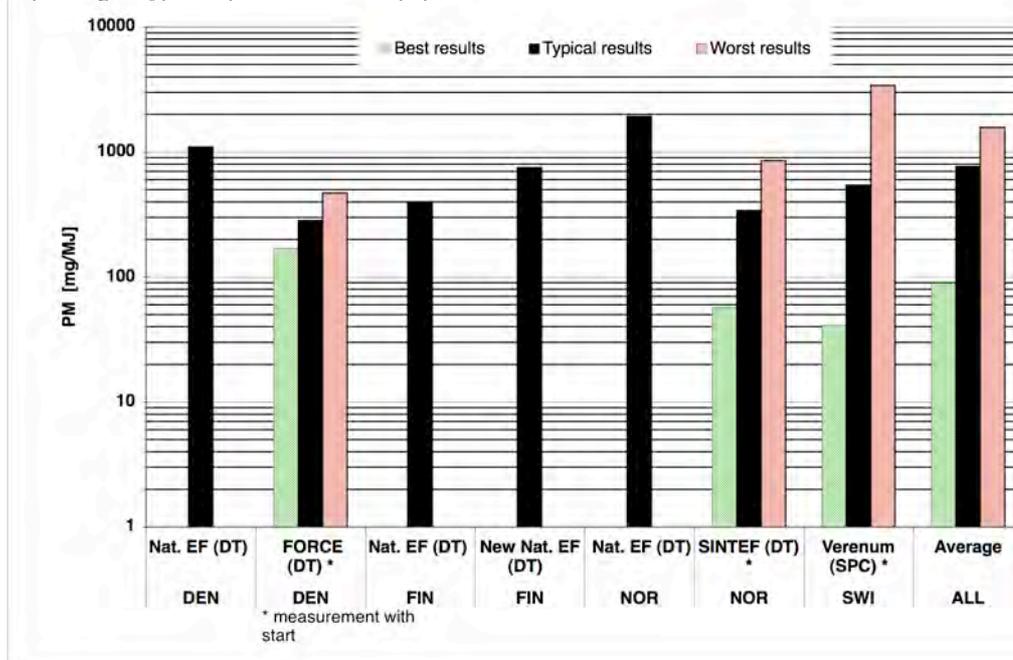


Figure 7: Range of emission factors for PM measured in Dilution Tunnel (DT) except for data from Verenum measured as Solid Particles and Condensables in impingers (SPC) from worst to best (where available) for wood stoves depending of type of operation and/or equipment.

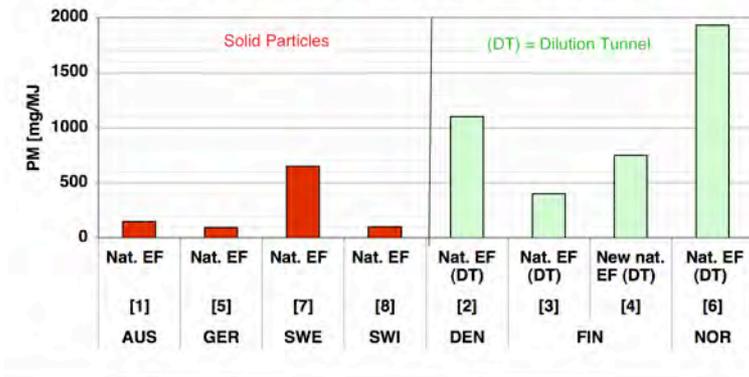


Figure 8: National emission factors for wood stoves currently used for emission inventories.

4.4 Log wood boilers

For log wood boilers, the technology of two stage combustion has been implemented for more than 20 years. Most modern log wood boilers used e.g. in Switzerland, Austria, and Germany are based on a two stage combustion with primary air for the solid fuel conversion, a subsequent mixing zone with injection of secondary air followed by the post combustion chamber and finally the heat exchanger in the boiler section /6/. Such boilers are usually designed by the downdraft principle and most commonly operated with forced draft, either by application of ventilators for the air inlet and/or for the flue gas exhaust. In the present survey, data from downdraft boilers with forced draft and data from updraft boilers were collected.

Figure 9 shows the range of emission factors for updraft boilers, although available from a limited number of institutions only. If compared to data from the same countries, updraft boilers exhibit comparable ranges of emissions as wood stoves.

Figure 10 shows emission factors from log wood boilers with forced draft. Under typical operation conditions, boilers with downdraft principle enable significantly lower emissions than updraft boilers.

Beside the combustion principle, the hydraulic implementation of the boiler in the heating system and in particular the application and management of a heat storage tank can significantly influence the emissions in practical operation. Figure 11 shows a comparison of emission factors of log wood boilers with and without heat storage tank. The combination of a log wood boiler with a heat storage tank enables an operation at full load or at steady-state part-load with low emissions. On the other hand, boilers operated for house heating without heat storage tank may be used with throttled air inlet thus leading to excessively high emissions of uncombusted carbon and particles.

Figure 12 shows an overview of data from log wood boilers, where no information about the combustion principle was available.

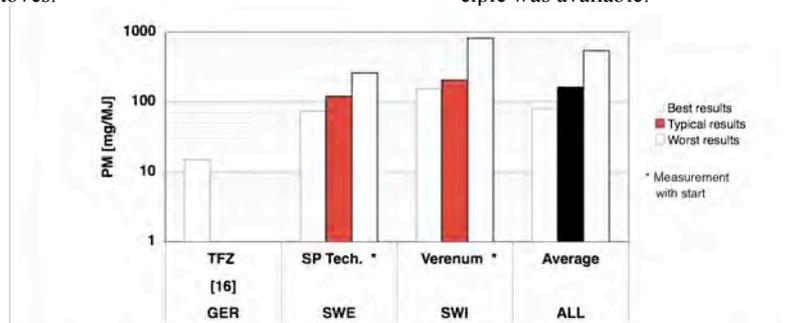


Figure 9: Range of emission factors from worst to best (where available) for log wood boilers with updraft combustion without ventilator.

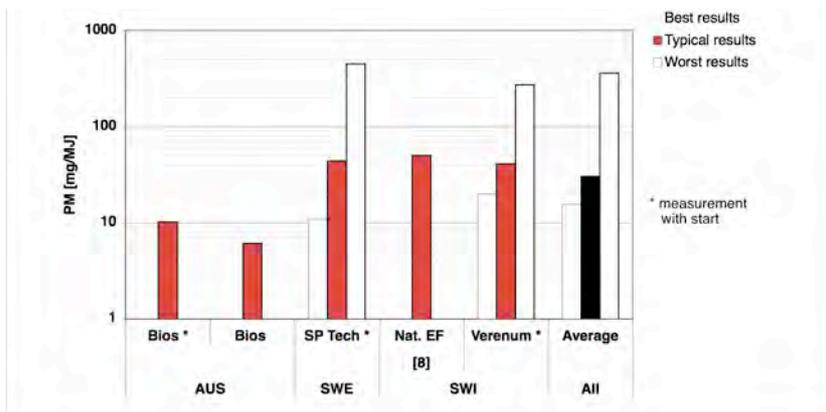


Figure 10: Range of emission factors from worst to best (where available) for log wood boilers with forced downdraft.

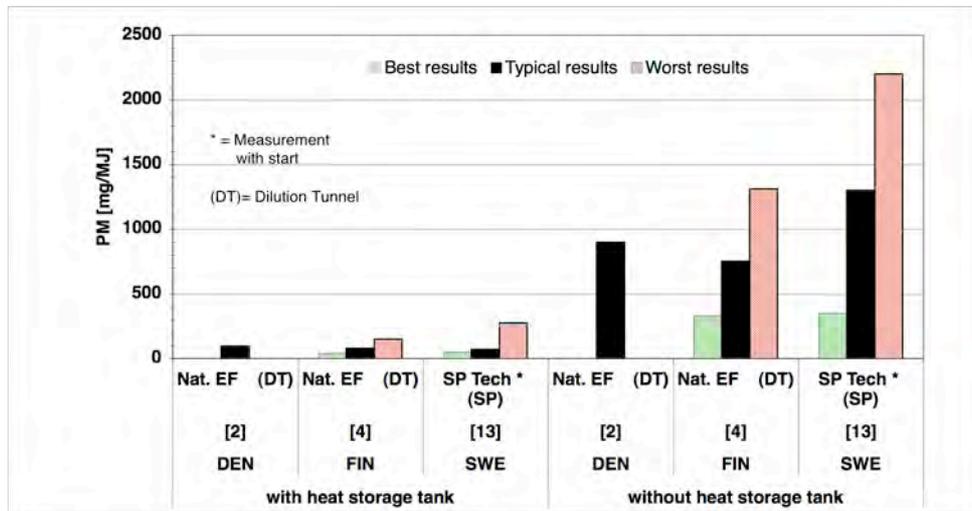


Figure 11: Emission factors for log wood boilers with and without heat storage tank.

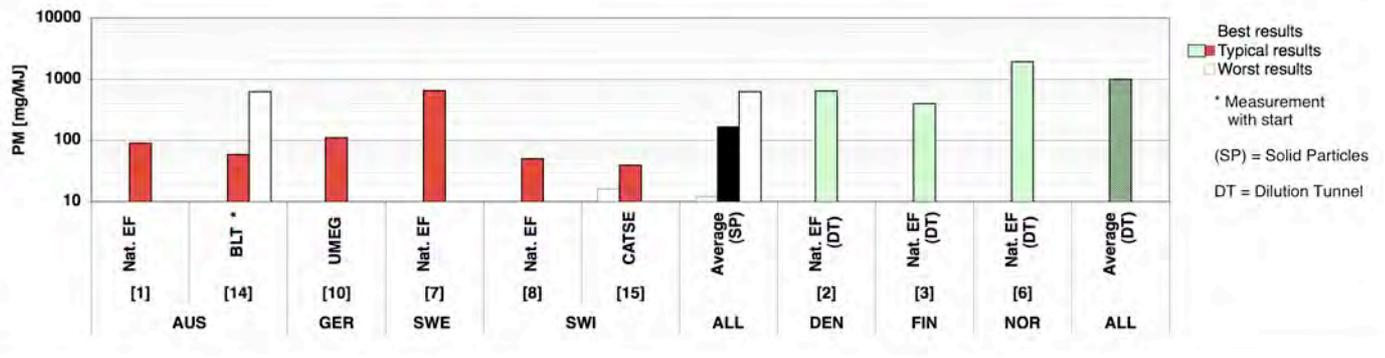


Figure 12: Emission factors for log wood boilers, where combustion type is not specified.

4.5 Pellet stoves and boilers

Figure 13 and Figure 14 show the emission factors of pellet stoves, while Figure 15 shows the results for pellet boilers. For all applications, only results from the operation with pellets made from wood with low bark content are considered. The emission factors for pellet combustion are in most cases between 10 – 50 mg/MJ for typical operation and hence comparable to the best results achieved by log wood combustion. If worst results under poor operation conditions are compared, a relatively moderate increase in emissions is expected for pellet combustion.

In comparison to log wood combustion, emission factors at non-ideal operation are at least an order of magnitude lower, which is regarded as the main advantage of pellet combustion. However, many investigations have shown, that the utilization of other biomass than wood with low amounts of bark for pellet combustion in residential heating appliances results in significantly increased emissions of particulate matter (i.e. typically by a more than a factor of 3) as well as in emission of NO_x. Hence the reported data are valid for wood pellets with low ash content only.

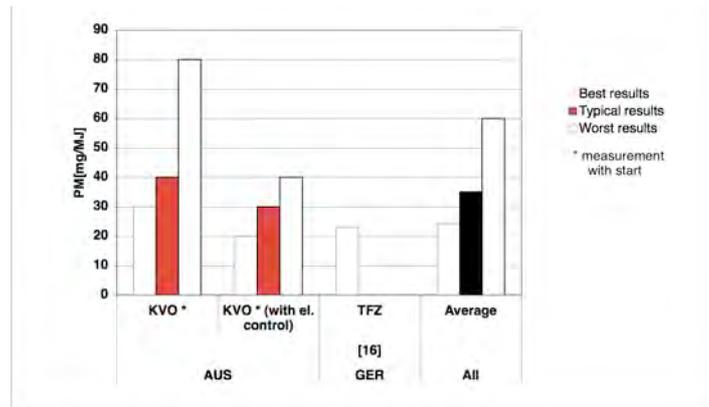


Figure 13: Range of emission factors from worst to best (where available) for pellet stoves with natural draft.

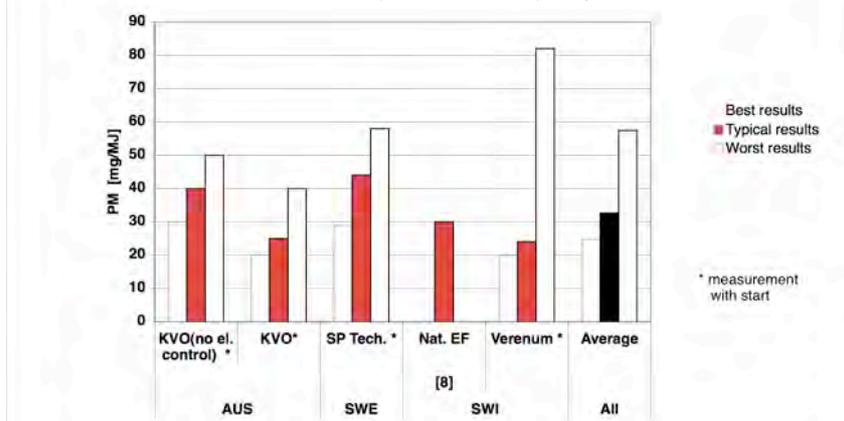


Figure 14: Range of emission factors from worst to best (where available) for pellet stoves with forced draft and electronic combustion control.

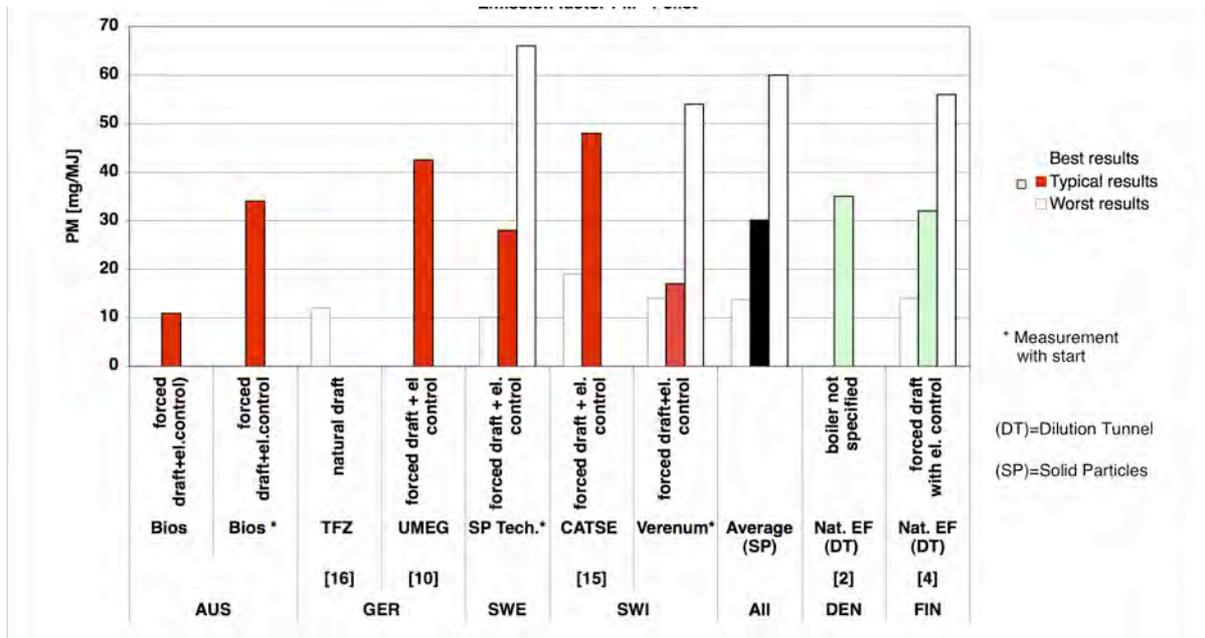


Figure 15: Range of emission factors from worst to best (where available) for pellet boilers.

4.6 Summary on residential wood combustion

Figure 16 gives a summary of the average emission factors for pellet combustion, log wood boilers, and wood stoves and shows the following results:

Pellet combustion and log wood boilers with forced draft achieve relatively low particle emissions not only under ideal operation conditions, but also under operation conditions which are assumed to be typical and should reflect the emissions under practical conditions of most installed heating devices of the respective categories. The reported data lead to an estimated average emission factor of approximately 30 mg/MJ indicated as filterable or solid particles (SP) for these categories under typical operation conditions. However, these emission factors are valid for natural, uncontaminated dry wood, while significantly higher emissions are found for other fuels such as bark, straw pellets, wet log wood and other inappropriate fuels for residential applications.

Under poor operation conditions, an increase of roughly a factor of 2 is found for pellet combustion, although this value is uncertain due to limited investigations and hence might be underestimated. For downdraft boilers, an increase by a factor of 10 is expected under poor operation conditions. Hence the main advantage of pellet combustion is that very poor operation is assumed to be very rare thanks to the homogeneous fuel and thanks to the continuous fuel feeding. Especially for log wood combustion, the effect of the start-up can significantly increase the average emissions. However, information on this issue is scarce and also uncertain for pellet combustion.

Wood stoves may achieve similar emissions as pellet combustion or downdraft boilers, if operated ideally. However, ideal operation for wood stoves is expected to be rarely found in practice, as it demands for small

batches of small and dry logs, which hence leads to a constant and low heat output by semi-continuous manual feeding of the stove in short periods and assuming an optimised start-up phase, which is often not the case. Since these conditions are often not fulfilled in practice, an increase of almost a factor of 10 is expected for wood stoves under typical operation conditions, thus leading to an estimated value of roughly 150 mg/MJ of solid particles.

Similar values as for stoves are expected for old-type wood boilers with natural updraft combustion. Hence two stage combustion with forced draft is regarded as a significant improvement. However, the type of operation of log wood boilers in practice strongly depends on the hydraulic integration in the heating system. For conventional house heating, a combination with heat storage tank is needed to avoid an operation with sharply throttled air inlet and excessively high emissions.

For wood stoves, measurements including condensables found in impinger bottles and measurements of particles in diluted flue gases in a dilution tunnel are available as well. A comparison of these data with measurements of solid particles only reveals significantly higher average emission factors. Since the data are derived from different investigations and different combustion devices, they do not enable a direct comparison between the different measurement methods. However, the significantly higher (i.e. by a factor of roughly 4) average emission factor reported from measurements in dilution tunnels or data including condensables is in line with the potential of additional particle mass from condensation of organic compounds found during poor combustion conditions.

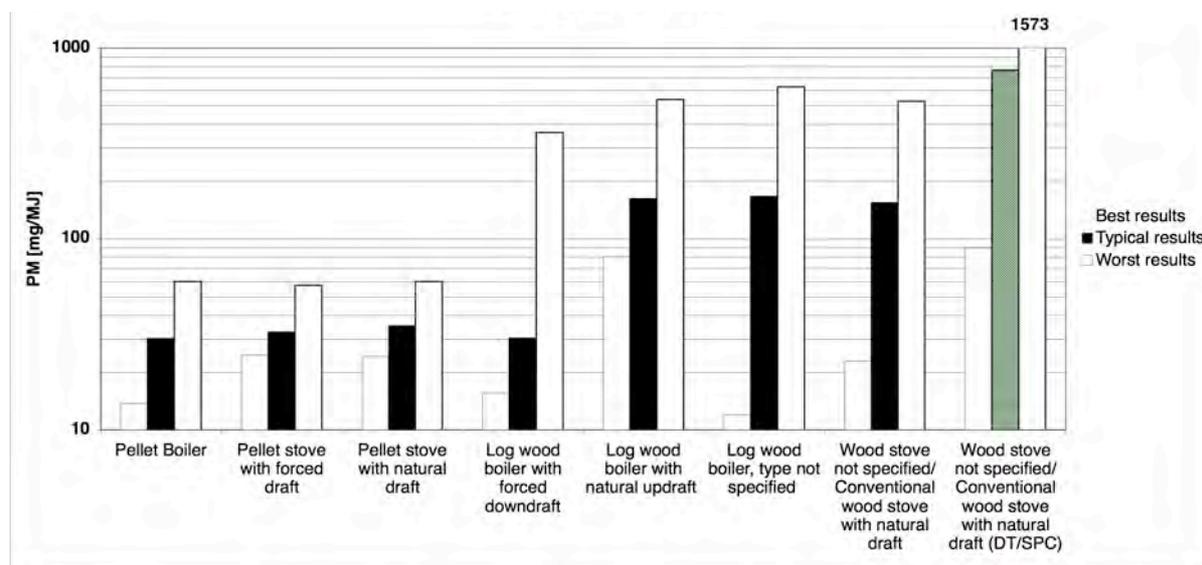


Figure 16: Average emission factors (best, typical, worst) for pellet boilers, pellet stoves, log wood boilers, and wood stoves. All data indicated as solid particles SP except for wood stoves, where data including condensables or measured in dilution tunnel (DT/SPC) are given additionally in the last column.

4.7 Automatic biomass combustion plants

The survey revealed emission factors for automatic combustion plants from 70 kW to 500 kW in a typical range from 50 – 100 mg/MJ, which is in line with the emission limit values as they have been valid during the

years when the emission factors were collected (e.g. 150 mg/m³ at 13 Vol.-% O₂ in Switzerland).

However, an investigation of field measurements in Switzerland for a large number of installations revealed a relatively broad range of emissions from 30 mg/MJ to

350 mg/MJ which demonstrates, that the type of operation is also important for automatic wood combustion plants and that periodic monitoring of such plants is crucial. The same is true for plants from 500 kW to 10 MW. However, emission factors of installations in this category strongly depend on the type of flue gas cleaning and thus on the imposed emission limit values. In the category of combustion plants greater than 500 kW, significant changes are expected in Switzerland, since new emission limit values in this category (i.e., 20 mg/m³) will make the application of fine particle removal necessary in future and thus lead to a significant reduction of PM emissions.

4.8 Assessment of emission factors

For the comparison of different particle sources it needs to be recognized that the presented emission factors are indicated as particle mass concentrations and hence do not respect the health relevance of different particle types. Particles and condensables found from wood burnt under very poor combustion conditions, i.e., in a wood stove with throttled air inlet, contain high concentrations of polycyclic aromatic hydrocarbons and exhibit high cell toxicity and high carcinogenic potential, while particles found from automatic wood combustion staged design at good operation conditions consist mainly of salts and consequently exhibit far lower toxicity and carcinogenicity [4]. Hence the data presented here do not reflect the potential health effects of different combustion applications, but only the expected PM emissions indicated as mass concentrations. It is likely, that the relevance of manual wood combustion is underestimated by comparing the particle mass only.

5 CONCLUSIONS

Data on emission factors of residential wood combustion have been collected from 16 institutions in seven IEA countries. Huge ranges of emission factors are reported for residential wood combustion, while emission factors of medium and large scale applications strongly depend on particle removal equipment, related to national or local emission limit values. Consequently, conclusions from the present study mainly focus on residential applications

The reported emission factors from manual wood combustion devices exhibit huge ranges from less than 20 mg/MJ under ideal conditions up to more than 5 000 mg/MJ under poor conditions (data refer to end energy indicated as lower heating value). Even national emission factors vary from less than 100 mg/MJ (measured as solid particles in the chimney) up to almost 2 000 mg/MJ (measured in a dilution tunnel).

For wood stoves, huge ranges are found due to different operation conditions. Consequently, high priority should be given to avoid inappropriate operation of manual wood combustion appliances. Excessive PM emissions are found during smoldering conditions at reduced load and throttled air supply. This type of operation needs to be strictly avoided, but nevertheless seems to be relevant in practical operation in many countries.

For wood boilers, excessive PM emissions are reported for boilers operated without heat storage tank. This is in line with the observation found in stoves, since boiler operation for house heating without heat storage tank often leads to part load combustion. Hence in Switzer-

land, heat storage tanks are mandatory for log wood boilers, except if the boiler does achieve the emission limit values at part-load operation, i.e., at constant heat demand of maximum 30% of the nominal load, which is possible for pellet boilers but not realistic for log wood boilers.

For residential wood boilers, the type of combustion is also significantly influencing the PM emission. Modern boilers with forced downdraft combustion and electronic combustion control devices enable low particle emissions under appropriate combustion conditions, while old-type boilers with updraft combustion exhibit higher emissions under similar conditions. However, the influence of operation mode cannot be evaluated in detail based on the reported data.

For pellet boilers and stoves, typical particle emissions of around 30 mg/MJ are reported with a relatively narrow variation from < 20 to < 60 mg/MJ. Hence, the total PM emissions under typical operation conditions are expected to be far lower than for manual wood stoves. The problem of variations between ideal operation and inappropriate operation are certainly less emphasized than in manual boilers, although data on poorly operated pellet combustion are scarce and hence the upper range from pellet combustion is uncertain. It should be noted that the market for pellets is growing and the production of second grade quality pellets with higher ash content will increase. The use of these pellets in small-scale equipment without particle removal will result in significantly higher emissions (i.e. an expected increase of a factor of 3 to 5 in PM and NO_x for agricultural pellets instead of wood pellets). Hence domestic scale applications should be restricted for good quality wood pellets, while other pellets should be reserved for applications in larger plants which are equipped with flue gas cleaning.

For automatic wood combustion plants, the emission factors for plants without electrostatic precipitator (ESP) or fabric filter (FF) are relatively high, i.e. typically between 50 to 100 mg/MJ, which, under good combustion conditions, is attributed to high emissions of inorganic particles. Hence clean gas emissions strongly depend on the type of flue gas cleaning applied, which depends on national or local emission standards. In many European countries, emission limit values for such applications have recently been sharpened and hence the situation of typical PM emissions will change in many countries in the near future, since particle removal enable clean gas emissions of typically smaller than 30 mg/MJ (simple ESP) or smaller than 10 mg/MJ (improved ESP or FF).

For the comparison of different data, the sampling and measurement procedure needs to be considered. In the present study, three types of data are distinguished:

- 1) Filterable, solid particles (SP) collected on heated filters (at 160° acc. to VDI or at 120°C acc. to EPA),
- 2) solid particles plus condensables (SPC) found by liquid quenching at < 20° or < 5°C, and
- 3) particulate matter sampled in cold, diluted flue gas in a dilution tunnel (DT).

A comparison between SP and SPC shows that the mass of condensables may significantly exceed the mass of solid particles during poor combustion conditions in wood stoves. A comparison between results from a dilution tunnel with sampling in the chimney reveals significantly higher concentrations in the diluted flue gas and thus shows, that the condensable matter is found partially

or quantitatively as filterable material after a moderate dilution at a dilution ratio in the order of 10 of the flue gas with cold air, which results in a fast temperature reduction at moderate decrease of the partial pressure of volatile organic compounds. Consequently, PM emission inventories based on emission factors of solid particles may significantly underestimate the contribution of biomass to PM in the ambient air. This is in line with results from PM measurements in the ambient air, where a higher contribution from wood combustion is found than expected from emission factors used currently in Switzerland [7]. On the other hand, evaporation may occur during further dilution in the ambient to a dilution ratio in the order of 10 000 due to a significant reduction of the partial pressure of volatile organic compounds. Hence the primary aerosols expected in the ambient air might be over estimated by measurements in the dilution tunnel. However, for the final PM concentration in the ambient air, the formation of secondary aerosols needs to be considered, thus leading to an additional increase of total PM resulting from wood combustion, which is induced condensation and by photochemical oxidation to secondary organic aerosols (SOA).

Due to different sampling of PM in different countries and norms, a comparison of data reported from countries with regulations on solid particles as e.g. in Germany, Austria, and Switzerland cannot be directly compared with data reported from countries using dilution tunnels as e.g. in Norway. Consequently, the type of measurement is indicated in all results presented in this survey and it is recommended to clearly indicate the type of measurement for future emission inventories. For measurements according to US EPA, sampling in the stack or in the dilution tunnel can be applied, which may also result in different emission factors and which also needs to be considered for comparison with European emission factors.

Condensables from wood combustion have been identified as highly toxic substances which can significantly contribute to total PM in the ambient air. Hence for improving emission inventories to deduce ambient air quality levels, it is essential to respect solid particles and condensables found in the stack. Furthermore, the potential formation of secondary organic aerosols resulting from volatile organic compounds, which are not trapped in the condensables, need to be respected too. Since organic condensables are highly toxic, while solid particle can exhibit low toxicity (in case of salts) or high toxicity (if resulting from incomplete combustion or from contaminants such as heavy metals), a separate measurement of both parameters, i.e., solid particles and condensables, is advantageous. However, measurement of solid particles only is less equipment and time consuming and still gives a performance value for PM emissions for comparison of different combustion appliances. In case of nearly complete combustion, as e.g. found in modern automatic wood boilers under good operation conditions, the concentration of condensables is usually negligible and hence the measurement of solid particles only might be sufficient.

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