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Overview on Technologies for Biomass Combustion and Emission Levels of Particulate Matter

prepared for

Swiss Federal Office for the Environment (FOEN)

as a contribution to the

Expert Group on Techno-Economic Issues (EGTEI) under the
Convention on Long-Range Transboundary Air Pollution (CLRTAP)

Zürich, June 2010

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Abstract

Particulate matter (PM) in the ambient air is related to adverse health effects. In addition, PM exhibits various direct and indirect effects on the global temperature. Since small combustion installations are an important source of PM, the Working Group on Strategies and Review (WGSR) in the UNECE Convention on Long-range Transboundary Air Pollution (CLTRAP) invited the Expert Group on Techno-economic Issues (EGTEI) to explore the possibility of establishing emission limit values for PM for combustion installations with a thermal input smaller than 50 MW. The present report was prepared as a technical background for the definition of emission limit values by the EGTEI with focus on biomass combustion. The fundamentals of wood combustion chemistry are described to introduce the mechanisms of particle formation. From this, three different particle types are distinguished, i.e., soot, salts, and condensable organic compounds. Depending on furnace type and combustion regime, one or more of these particle types are emitted in high concentrations and thus need to be reduced by different measures according to the formation mechanisms. For residential wood combustion, primary measures to improve the burnout quality are crucial, while for automatic wood combustion plants, inorganic particles need to be reduced by secondary measures. The technologies for residential and industrial scale biomass combustion are described including primary measures to improve the combustion quality by a two-stage combustion, which enables a high combustion temperature and a good mixing between combustible gases and air to reduce products of incomplete combustion. In addition, secondary measures for PM abatement such as electrostatic precipitators and fabric filters are described and their effects on cost are discussed. Finally, PM emission factors and achievable PM emission levels are compared and the influence of the measurement method for PM is discussed.

Keywords: Biomass combustion, particulate matter, emission factors.

1 Introduction

1.1 Motivation

The Working Group on Strategies and Review (WGSR) under the UNECE Convention on Long-range Transboundary Air Pollution (CLTRAP) invited the Expert Group on Techno-economic Issues (EGTEI) to explore the possibility of establishing emission limit values for PM for combustion installations with a thermal input smaller than 50 MW. The present report was prepared as a technical background for the definition of emission limit values by the EGTEI with focus on biomass combustion. Biomass is widely applied as a renewable energy source for heat and power production and will become more important in the next decades due to declining fossil fuels. While sustainable use of biomass can be regarded as partly CO₂ free, biomass combustion is an important source of air emissions, especially:

- Volatile organic compounds (VOC).
- Inhalable particulate matter smaller than 10 microns (PM₁₀), containing:
 - soot (found as black carbon (BC) in the atmosphere),
 - condensable organic compounds (COC), which, together with additional secondary organic aerosols (SOA), result in brown carbon in the atmosphere
 - SOA formed from non-methane VOC (NMVOC),
 - inorganic particles (salts).
- Polycyclic aromatic hydrocarbons (PAH) (partly found on the surface of PM).
- Nitric oxide emissions (NO_x).
- Polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F) (in case of contaminated fuels).

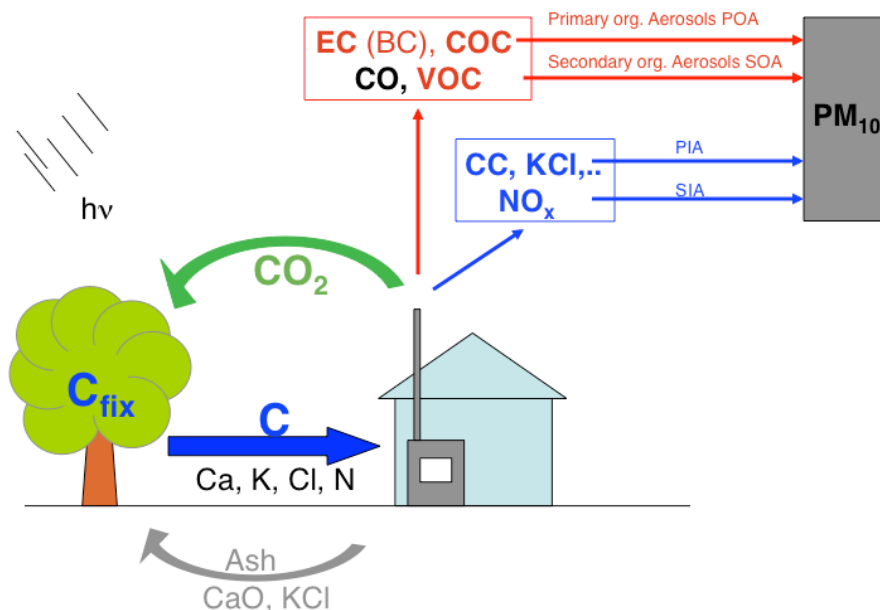


Figure 1.1 Air emissions from biomass combustion and their contribution to PM₁₀.

Figure 1.1 shows the main pathways of air emissions from biomass combustion to the atmosphere. Since PM is regarded as one of the most relevant parameters in air pollution [Dockery et al. 1993, Donaldson et al. 2002], the PM emissions from biomass combustion can hinder the further propagation of bioenergy. Besides, particulate matter from biomass combustion exhibits a severe toxic and carcinogenic potential [Nussbaumer 2005 a]. To overcome this disadvantage, new technologies with reduced emissions of PM and products of incomplete combustion (PIC) are of interest:

- Improved wood boilers include a two-stage combustion principle and an injection of secondary air prior to a hot combustion chamber. Furthermore, electronic combustion control should be applied to ensure optimum operation in practice, and forced ventilation should be applied to enable good mixing and less dependence on the ambient climate conditions such as air temperature and wind. In addition, wood boilers used for house heating should be equipped with a heat accumulation tank to avoid part-load operation with increased emissions. This type of boiler is available as state-of-the-art technology in Europe and can be widely implemented.
- Similar to boilers, wood stoves might be developed, which exhibit an improved combustion principle with a hot combustion chamber and good mixing of combustion air with combustible gases. However, stove design for visible flames and operation without a ventilator exhibits limited possibilities of improved combustion principles. For stoves, design principles should be developed that avoid improper operation of the stove. Therefore, overfilling of the combustion chamber and the possibility to reduce the air inlet, resulting in smoldering conditions, should be avoided. Since wood stoves do not safely achieve these requirements, further development is needed, secondary measures might be considered, or in case of relevant heat demand, alternatives such as log wood boilers and pellet stoves might be enforced.
- In addition to the implementation of improved technologies for new heating appliances, it is essential to ensure ideal operation of existing wood stoves and boilers. This can be achieved to some extent by providing recommendations to the consumers.
- Beside technical improvements for residential wood heating appliances, it is also essential to prohibit burning of wood and other biomass in open fires, as well as private waste incineration. These types of combustion are related to excessively high air pollution without energy use.
- As an alternative for log wood, wood pellets can be used for residential heating. Thanks to constant fuel properties and small size, automatic feeding can be applied, which allows improved combustion conditions. However, for pellet combustion, optimum operation needs to be ensured by combustion control, which avoids smoldering conditions especially during start-up and shut-down.
- As an additional measure, technologies for flue gas cleaning for small scale applications is being developed and offers a certain potential for pollutant reduction for existing and new wood heating appliances.
- Finally, wood fuel can be used in automatic biomass combustion plants, which can be equipped with flue gas cleaning such as electrostatic precipitators (ESP) or fabric filters. If well designed and operated, automatic combustion plants for wood fuels achieve almost complete combustion, which safely avoids uncombusted particles. Inorganic particles can be precipitated by filters thus allowing low PM emissions.

Improvements in different sectors should be aimed at achieving a significant reduction of PM emissions from biomass combustion. Due to the steep increase in PM emissions and the high health risk of particles and condensables released during incomplete combustion, the main goal is to safely avoid the use of wood stoves and boilers operated at such conditions. Visible smoke and noticeable odors are clear indicators of high and toxic emissions, which need to be safely avoided, or be limited to short periods during start-up (i.e., certainly less than 15 minutes). Beside development of improved technologies, regulations are important, which allow a useful evaluation of PM emissions.

In addition to the implementation of technical measures to reduce PM from wood combustion, there is a need to improve information on the contribution of biomass combustion to the total PM in the ambient air and its relevance for the environment and the health. Investigations in Switzerland reveal a significant contribution of wood combustion to PM in the ambient air. For example more than 80% of the soot in the alpine valleys in Switzerland close to transit highways during winter originates from wood combustion [Prévot et al. 2006]. There is a specific need for information on emissions from residential wood combustion as well as from open biomass burning and its relevance to PM in the ambient air. Consequently, the conversion of emissions released from the stack to the ambient is an important issue, too, since secondary organic aerosols (SOA), induced by photochemical oxidation of volatile and semivolatile organic compounds, can significantly contribute to the total PM concentration in the ambient air (e.g. [Shrivastava et al. 2006, Lipsky & Robinson 2006, Robinson 2007, Robinson et al. 2007]).

1.2 Environmental impact of biomass combustion

1.2.1 Life cycle assessment

Biomass combustion exhibits relatively high emissions of NO_x and particulates in comparison to the combustion of natural gas or light fuel oil. Hence, biomass combustion contributes significantly to particulate matter (PM), ozone, and NO₂ in the ambient air. For wood combustion, a life cycle assessment (LCA) indicates that 38.6% of the environmental impact of a modern automatic wood furnace is attributed to NO_x, 36.5% to PM 10, only 2% to CO₂ and 22.9% to all other pollutants (Table 1.1). The LCA for wood, light fuel oil, and natural gas also show that the environmental impact of wood is higher than that for natural gas for a standard valuation of the greenhouse effect. Hence, improvements in the wood chain are necessary. However, it is also evident that the conclusions of the LCA strongly depend on the valuation of the greenhouse effect, since the ranking changes significantly as a result of the different CO₂ impacts of the three fuels.

On the other hand, in case of poor combustion conditions in manually operated wood stoves or boilers, PM emissions can be higher than assumed in the cited LCA by a factor of 10 thus leading to a far higher environmental impact than described here [Klippel and Nussbaumer 2007 (a) and (b)].

In addition, at excessively high emissions of unburnt hydrocarbons including methane, even the greenhouse gas effect can be higher than from light fuel oil or natural gas due to the higher impact of methane [Johansson et al. 2004]. Hence wood combustion can only be assessed as being environmentally friendly in case of low airborne emissions.

In addition, black carbon (BC) is a strong driver for global warming, as its global warming potential (GWP) is 500 to 700 times the GWP CO₂ for 100 years or 2000 times the GWP CO₂ for 20 years

[Bond 2007]. According to [ICCT 2009], BC is responsible for a radiative forcing of approx. 0.34 Wm^{-2} of total 1.6 Wm^{-2} . Hence BC is number two or number three component for global warming after CO_2 or after CO_2 and methane. Figure 1.3 illustrates that biomass combustion is the main source of black carbon in the atmosphere. Hence BC needs to be considered for LCA.

Table 1.1 Environmental Impact Points (EIP) according to the Ecological Scarcity Method for heating with wood chips (base case for greenhouse effect), data from [Kessler et al. 2000].

	[EIP/GJ]	[%]
NO_x	13 030	38.6%
PM 10	12 600	36.5%
CO_2	670	2.0%
SO_x , NH_3 , CH_4 , NMVOC, primary energy, residues, and others	8 200	22.9%
Total	34 500	100%

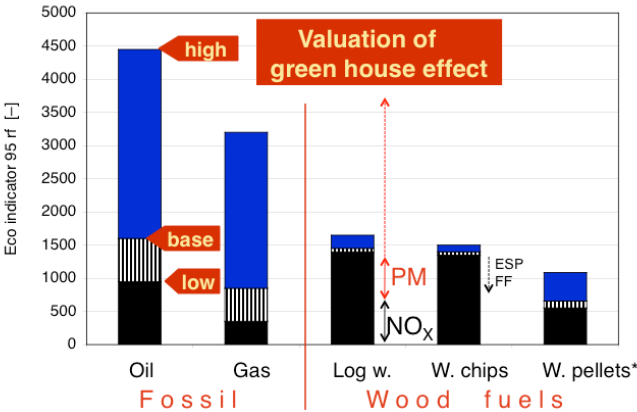


Figure 1.2 Environmental impact points (EIP) for different valuations of the greenhouse effect. Data from [Kessler et al. 2000], except wood pellets, own calculations [2003].

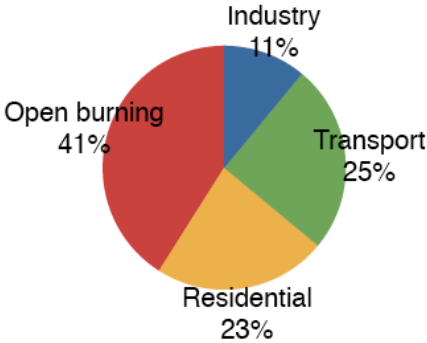


Figure 1.3 Contribution to global black carbon in the year 2000 [Bond 2009].

1.2.2 Health relevance of particulate matter from biomass

Investigations on particle emissions showed that well-designed and properly-operated advanced-technology automatic wood combustion plants (mostly used in the size range > 200 kW) achieve a high combustion quality, which results in low emissions of uncombusted hydrocarbons and soot [Nussbaumer 2005]. However, automatic wood boilers exhibit fairly high mass concentrations of particle emissions in raw gas (typically a magnitude of 100 mg/m^3 at 13 Vol.-% O_2 for natural wood chips and up to several 100 mg/m^3 for other fuels such as bark or non-woody biomass). Particles from advanced-technology and well-operated automatic wood combustion consist mainly of inorganic matter such as salts, while particles from wood stoves operated under poor conditions consist mainly of soot and organic substances.

Typical inorganic particles in the flue gas of advanced-technology automatic combustion devices are shown in Figure 1.5. From a poorly operated wood stove, soot particles, as well as tar droplets, can be identified as shown in Figure 1.6. In conditions with lack of oxygen in the combustion chamber, the particle mass concentration increases dramatically as shown in Figure 1.4. This is due to uncombusted soot and organic primary aerosols. As a result of agglomeration, the particle size distribution is shifted to larger particles. In addition, high concentrations of condensable organic matter and volatile organic compounds (VOC) are released with the flue gas, which are potential pre-cursors of secondary organic aerosols (SOA).

Soot from diesel engines has been identified as being carcinogenic in many investigations. However, particulate matter from incomplete combustion of wood consists of solid soot particles and condensable organic substances. Significantly higher concentrations of polycyclic aromatic hydrocarbons (PAH) (Table 1.2) as well as far higher cell toxicity and carcinogenic potential indicated by chromosome aberration were found in particles and condensables from incomplete combustion of wood than in diesel soot [Klippel & Nussbaumer 2007 a]. Condensable organic substances such as tar components are a product of wood pyrolysis, which may occur under smoldering conditions such as a wood stove operated with reduced air inlet at low burning rate and low temperature. Highly toxic PAH may also be formed as secondary tar in subsequent gas phase reactions in the combustion chamber under conditions with lack of oxygen [Morf et al. 2002].

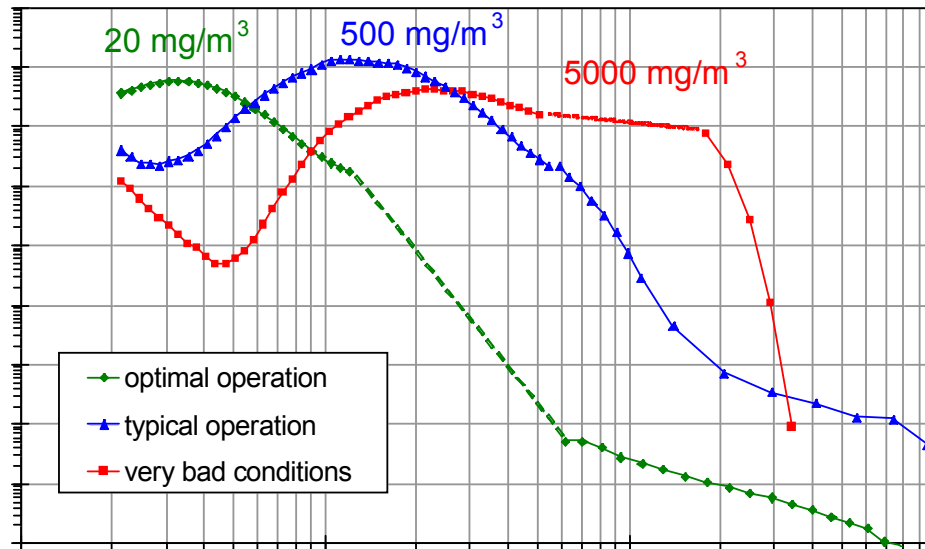


Figure 1.4 Number size distribution of particles from wood stoves under different operation conditions monitored in the size range from 20 nm to 10 µm by Scanning Mobility Particle Sizer (SMPS) and Optical Particle Counter (OPC). Mass concentrations measured with gravimetric method according to VDI and indicating only solid particles without condensables at 13 Vol.-% O₂ [Klippel & Nussbaumer 2007 b].

Table 1.2 PAH concentrations in particles from badly operated wood stove and in Diesel soot [Klippel & Nussbaumer 2007 a].

mg/kg	Wood stove	Diesel
Naphthalene	13	42
Acenaphthylene	129	7.1
Acenaphthene	17	< 3
Fluorene	173	< 3
Phenanthrene	231	3.7
Anthracene	65	< 3
Fluoranthene	154	< 3
Pyrene	170	< 3
Chrysene	54	< 3
Benzo(a)anthracene	44	< 3
Benzo(b)fluoranthene	30	< 3
Benzo(k)fluoranthene	11	< 3
Benzo(a)pyrene	25	< 3
Indeno(1,2,3-cd)pyrene	9	< 3
Dibenzo(a,h)anthracene	< 8	< 3
Benzo(g,h,i)perylene	< 8	< 3
Total PAH	1 120	53

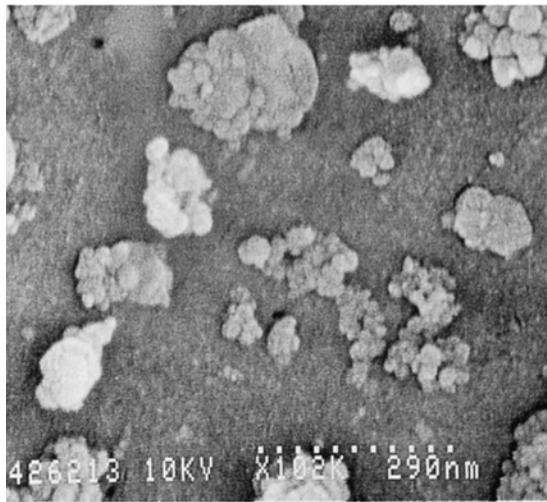


Figure 1.5 SEM-pictures of particles in the flue gas of an automatic wood combustion system. Left is the combustion of wood resulting in submicron particles. Right is the combustion of herbage grass resulting in larger particles at higher mass concentrations [Kaufmann et al. 2000].

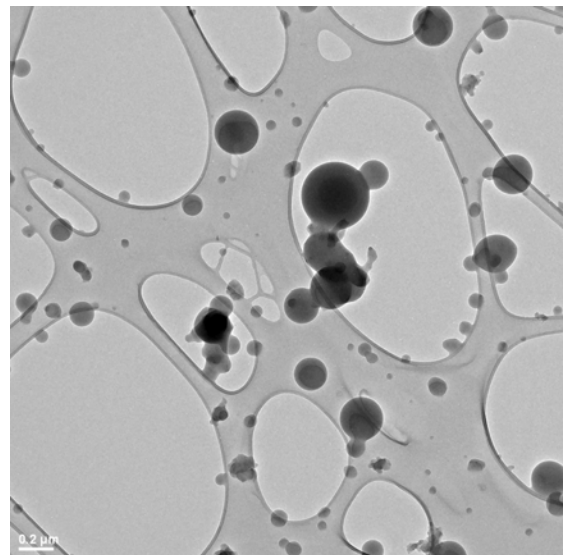
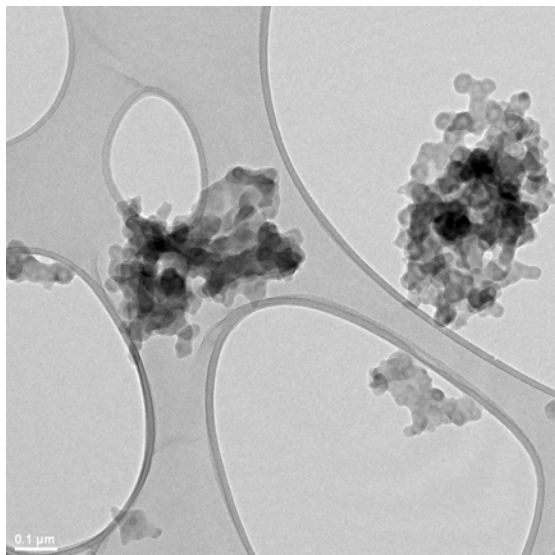


Figure 1.6 TEM-pictures of soot agglomerates (left) and tar droplets (right) from the flue gas of a poorly operated wood stove. Scale of white line in the left picture: 100 nm, right: 500 nm. Pictures from Heuberger, EMPA Dübendorf, published in [Klippel & Nussbaumer 2007 b].

1.2.3 Contribution to global warming

Beside CO₂ and other tracer gases, aerosols have a significant impact on the energy balance of the earth by direct effects on the radiative forcing and through different indirect effects. Figure 1.7 shows the global warming potential (GWP) and Figure 1.8 the global temperature change potential (GTP), the latter being more important but also more uncertain. Figure 1.9 and Figure 1.10 illustrate the total effect as reported by [IPCC 2007]. For aerosols from biomass combustion, the following effects need to be considered:

- Black carbon (BC) in the atmosphere, which results from soot from fossil fuel combustion and from biomass combustion, strongly absorbs sunlight and has a strong direct warming effect. In addition, BC deposited on ice and snow enhances the melting and changes the albedo of the earth surface with an additional indirect warming effect called snow albedo effect. [IPCC 2007] accounts the GWP of soot to be 460-times the one of CO₂ for 100 years or 1006 times for 20 years. [Bond 2007] estimates BC to have a GWP of 500 to 700 times the one of CO₂ for 100 years, and 2000 times for 20 years, and that indirect effects significantly increase the relevance of BC.
- Sulfates change the albedo by reflecting sunlight and directly cool the earth surface.
- Organic carbon exhibits a direct effect of net cooling according to [IPCC 2007], which is approx. 50% of the net warming effect of BC. [Bond 2007] assesses organic carbon having a slight cooling or slight warming effect, hence the net effect seems uncertain.
- The major effect of aerosols is contributed to global dimming. Global dimming results from a direct reduction of the solar radiation to the earth and an increased reflection by clouds. Due to aerosols acting as cloud condensation nuclei (CCN), more clouds are formed existing of smaller droplets and with increased lifetime in the atmosphere resulting in the cloud albedo effect and the cloud lifetime effect.

Due to the different direct and indirect effects of the different particle types, and due to the variation of the particle types depending on the combustion regime, the net effect of biomass burning on the climate change is uncertain. However, the reduction of BC is essential to reduce health effects and direct global warming, while COC are strongly health relevant with a minor effect on climate and consequently need to be reduced with high priority too.

	GWP20	GWP100	GWP500
Black carbon	1600	460	140
Methane	72	25	7.6
Nitrous oxide	289	298	153
Sulfur oxides	-140	-40	-12
Organic carbon	-240	-69	-21
Carbon dioxide	1	1	1

Note: The methodology used for black carbon was also used for organic carbon and sulfur oxides. Values for black carbon, organic carbon and sulfur oxides were not published by the IPCC and are not official estimates.

Figure 1.7 Global Warming Potential (GWP) [IPCC 2007].

	GTP20	GTP100
Black carbon	470	64
Methane	57	4
Nitrous oxide	303	265
Organic carbon	-71	-10
Sulfur oxides	-41	-5.7
Carbon dioxide	1	1

Source: Fuglestad, J., K. Shine, T. Berntsen, et al. (2009) Transport impacts on Atmosphere and Climate: Metrics. *Atmos Environ* In press.

Figure 1.8 Global Temperature Change Potentials (GTP) [ICCT 2009].

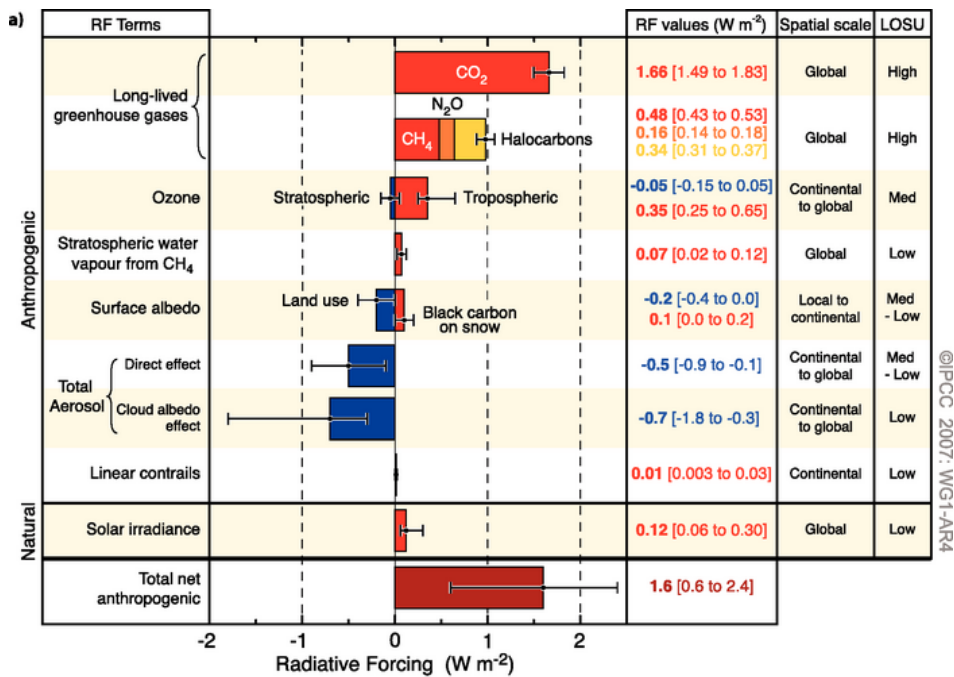


Figure 1.9 Warming and cooling of different components [IPCC 2007 (4. Report)].

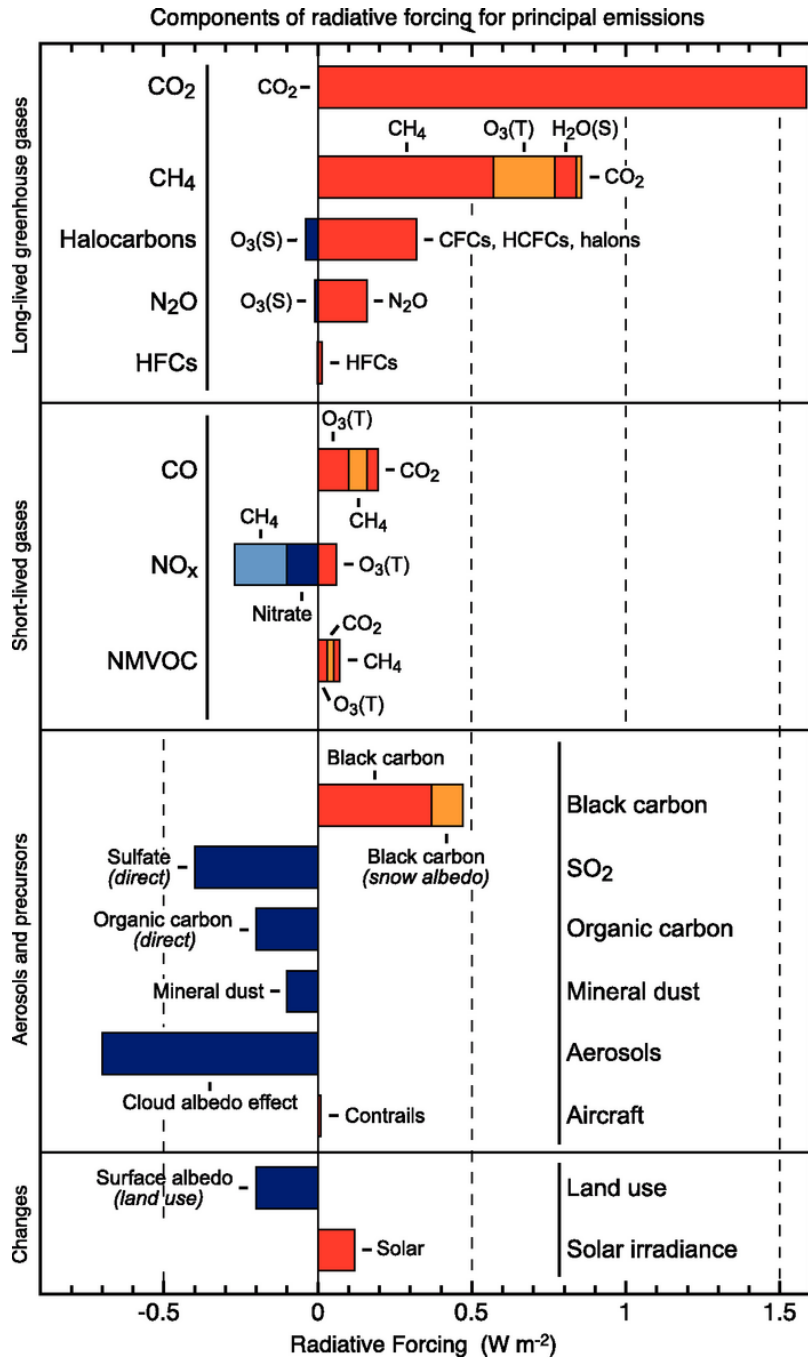


Figure 1.10 Warming and cooling of different components [IPCC 2007 (4. Report)].

2 Wood combustion technology

2.1 Overview

There are three basic technologies for an initial thermochemical conversion of biomass: pyrolysis, gasification, and combustion. Among these, combustion is the most proven technology for heat and power production. Pyrolysis is of interest as an initial process for liquid biofuel production. However, pyrolysis is in an early stage of development. Gasification is of interest for future applications due to two advantages: higher electric efficiencies and low airborne emissions. PM emissions can be significantly reduced in comparison to conventional combustion, since highly efficient particle removal in the raw gas needs to be applied to protect the gas turbine and/or the turbo charger. Furthermore, an almost complete combustion of the producer gas in the gas turbine combustion chamber is reached, thus resulting in negligible organic emissions such as VOC and organic condensables. Hence, clean gas emissions from gasification plants can be very low. Although such applications should be considered in the future as a promising alternative, today the majority of the wood fuel is used in combustion applications, which are available as proven technology. Biomass combustion systems are available from a few kW up to more than 100 MW with typical applications as follows:

1. Manual wood stoves are most commonly used from 5 kW to 15 kW. However, due to the batch-operation, the instantaneous combustion heat performance can also exceed 50 kW for a short period of time in applications as e.g. tile stoves which exhibit a heat accumulation in the mass of the stove.
2. Manual log wood boilers are most commonly used from 20 kW to 70 kW. For typical house heating, heat accumulation tanks with a few 1000 liter of water are used to increase comfort and avoid part-load operation of the boilers at low efficiency and high emissions.
3. Pellet stoves and boilers for residential heating are common from 15 kW up to 70 kW (in case of boilers). Furthermore, pellet boilers are also applied from 70 kW to 1 MW and in some cases also for applications greater than 1 MW. Due to the higher energy density, pellet storage is less space consuming compared to wood chips, which in some cases is an important advantage.
4. Automatic wood boilers are most often used from 200 kW to 10 MW heat output, although in some cases wood chips are also used from 20 kW and up to more than 100 MW. For applications greater than 1 MW, grate boilers are most common, while for smaller plants, under stoker boilers are in use in case of relatively high quality wood chips. Applications with heat output of more than 10 MW to 20 MW are often combined with steam production for combined heat and power production. Fluidised bed combustion is applied in this size as an alternative enabling high combustion quality, but often additional need of fuel pretreatment due to limited particle sizes.

The efficiency for heat production is considerably high, and heat from biomass is economically feasible in many applications. Commercial power production is based on steam cycles. The specific cost and the efficiency of steam plants are only adequate at large-scale applications. Both, electric efficiencies and specific cost exhibit significant economy-of-scale effects. Hence, co-combustion of biomass with coal in thermal power stations is promising, as it combines high efficiency with reasonable transport distances for the biomass. However, biomass combustion is often related to significant

pollutant formation and needs to be improved. To develop measures for emission reduction, the specific fuel properties need to be considered. Pollutant formation occurs due to three reasons:

1. Incomplete combustion can lead to high emissions of uncombusted pollutants such as CO, volatile organic compounds (VOC), soot, condensable organic compounds (COC, also referred to as "tar"), and polycyclic aromatic hydrocarbons (PAH).
2. Pollutants such as NO_x and inorganic particles are formed as a result of natural fuel constituents such as N, K, Cl, Ca, Na, Mg, P, and S.
3. Biofuels can be carriers of additional contaminants such as heavy metals or chlorine, which can lead to high emissions of heavy metals, HCl, and potentially highly toxic polychlorinated dibenzo-*p*-dioxins and furans (PCDD/F).

Biomass combustion exhibits relatively high emissions of NO_x and submicron particles. Air staging and fuel staging can be applied as primary measures for NO_x reduction that offer a potential of 50% to 80% reduction. For further reduction, secondary measures such as selective catalytic and selective non-catalytic reduction (SCR, SNCR) can be applied. However, SNCR can lead to undesired side-products that need to be carefully avoided.

For particle reduction, the main goal is to achieve an almost complete combustion that safely avoids soot, organic particles and droplets, and volatile organic compounds in the flue gas. Primary measures to reduce inorganic PM by staged combustion with an initial gasification stage offer a certain reduction potential. Furthermore, optimized plant operation is needed to guarantee low emissions and high efficiency under real-world conditions. Nevertheless, secondary measures for PM removal are needed for medium and large-scale applications. In addition, there is also an interest in secondary measures for future applications in residential wood combustion.

Combustion can be applied to biomass feedstock with water contents up to 60%. Fuel constituents beside C, H, and O are undesired, since they are related to pollutant and deposit formation, corrosion, and ash. The most relevant constituents in native biomass are nitrogen as a source of NO_x, and ash components (e.g. K and Cl as a source of KCl) that lead to particulate emissions. Native wood is usually the most favorable bio fuel for combustion due to its low content of ash and nitrogen. Herbaceous biomass such as straw, miscanthus, and switch grass have higher contents of N, S, K, Cl, which lead to higher emissions of NO_x and particulates, increased ash, corrosion, and deposits. While wood is well-suited for household heating as well as for larger plants, herbaceous biomass is reserved for larger plants. The same is true for urban waste wood and demolition wood. The combustion of such contaminated biomass should be strictly limited to combustion plants with efficient flue gas cleaning for the abatement of toxic pollutants such as heavy metals and chlorine compounds.

The driving force for biomass combustion for energy purposes is either the CO₂ neutrality of sustainable cultivated biomass or the use of biomass residues and waste. Large potentials of both native biomass and biomass wastes are still available and allow a relevant increase of sustainable bio energy use in the future. Combustion is the most important technology available today for biomass use. Improvements in efficiency, emissions, and cost are needed for further exploitation. In addition, alternatives such as gasification and combinations of different processes such as gasification as fuel pre-treatment for co-combustion need to be considered.

2.2 Combustion process and particle types

Biomass combustion is a complex process that consists of consecutive heterogeneous and homogeneous reactions. The main process steps are *drying*, *devolatilization*, *gasification*, *char combustion*, and *gas phase oxidation*. The time used for each reaction depends on the fuel size, properties, temperature and combustion conditions. Batch combustion of a small particle shows a distinct separation between a volatile and a char combustion phase with time (Figure 2.1). For the design of combustion appliances, the high content of volatiles (80% to 85%) needs to be respected. For large particles, the phases overlap to a certain extent. Nevertheless, even for log wood furnaces, a certain separation of distinct combustion regimes with time can be found.

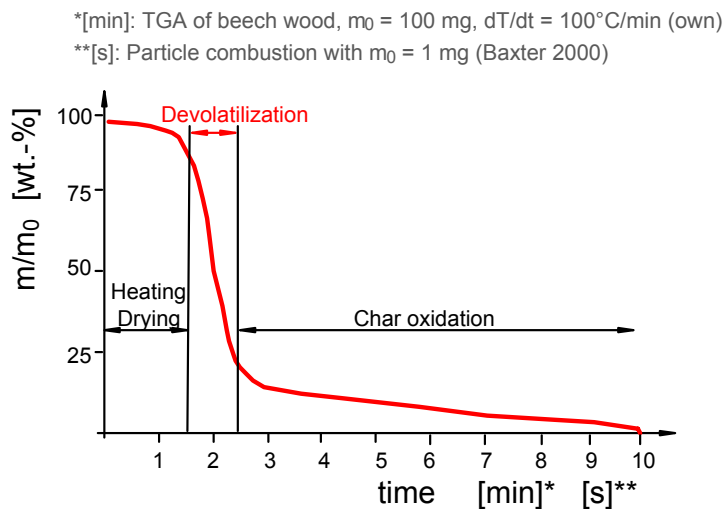
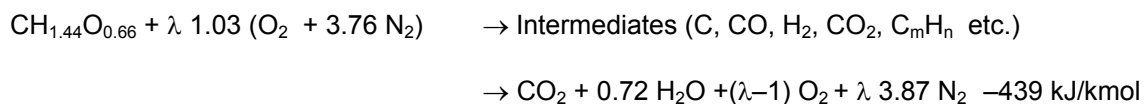


Figure 2.1 Mass loss as function of time during combustion of wood.

Since automatic combustion systems are operated continuously, the consecutive reactions occur simultaneously at different places in the furnace (e.g., in different sections on and above a grate). Therefore, the zones for different steps during combustion can be optimized by furnace design. A distinct separation of different steps can be advantageous with respect to pollutant formation.

The main combustion parameter is the *excess air ratio* (λ ; λ) that describes the ratio between the locally available and the stoichiometric amount of combustion air. For typical biomass, the combustion reaction can then be described by the following equation, if fuel constituents such as N, K, Cl etc. are neglected:



where $\text{CH}_{1.44}\text{O}_{0.66}$ describes the average composition of typical biomass used for combustion, i.e., wood, straw, or similar. As a result of the combustion process, different types of pollutants can be distinguished:

1. Uncombusted pollutants such as CO, VOC, PAH, COC, soot, carbon, H₂, HCN, NH₃, and N₂O
2. Pollutants from complete combustion such as NO_x (NO and NO₂), CO₂, and H₂O, and
3. Ash and contaminants such as ash particles (KCl, etc.), SO₂, HCl, PCDD/F, Cu, Pb, Zn, Cd etc.

Biomass combustion is related to three basic types of particles, which are summarized as 'salts', 'soot', and Condensable Organic Compounds 'COC', and exhibit completely different chemical and physical properties:

- Inorganic particles, basically salts, are formed from minerals (i.e., ash constituents) in the fuel. These particles are dominant at near-complete combustion
- COC are formed in different processes:
 - At low temperature volatile or condensed organic compounds are formed from wood pyrolysis with characteristic compounds depending on residence time, heating rate, temperature and other operation parameters.
 - At moderate temperatures and local lack of oxygen, organic compounds can be converted to secondary tars, which appear as condensables.
- Soot is formed from organic precursors in zones of high temperatures and lack of oxygen, where volatiles and primary tars react to secondary tars and form polyaromatic hydrocarbons, which consequently can form soot particles by further agglomeration and release of hydrogen.

Figure 2.2 describes the main pathways leading to particulate matter in the flue gas or in case of secondary organic aerosols by subsequent photochemical reactions in the atmosphere. In automatic wood combustion, nearly complete combustion can be achieved and hence salts are dominant as particles. However, during start-up, and in phases of inappropriate operation, condensables or soot can also be emitted from automatic plants. Incomplete combustion is often found in manual wood combustion, whereby soot or condensables can be the dominant part of the total particulate matter released to the atmosphere. Due to the different temperature regimes and the different influence of the residence time for soot and COC formation, usually either one of the two particle type dominates the particle ensemble.

Figure 2.3 summarizes the main properties of salt, soot, and COC found in biomass flue gases. In addition, the combustion regimes leading to the different particle types are indicated in the diagram CO as function of lambda.

Figure 2.4 gives a qualitative indication about the combustion regimes referring to the different particle types and emission levels.

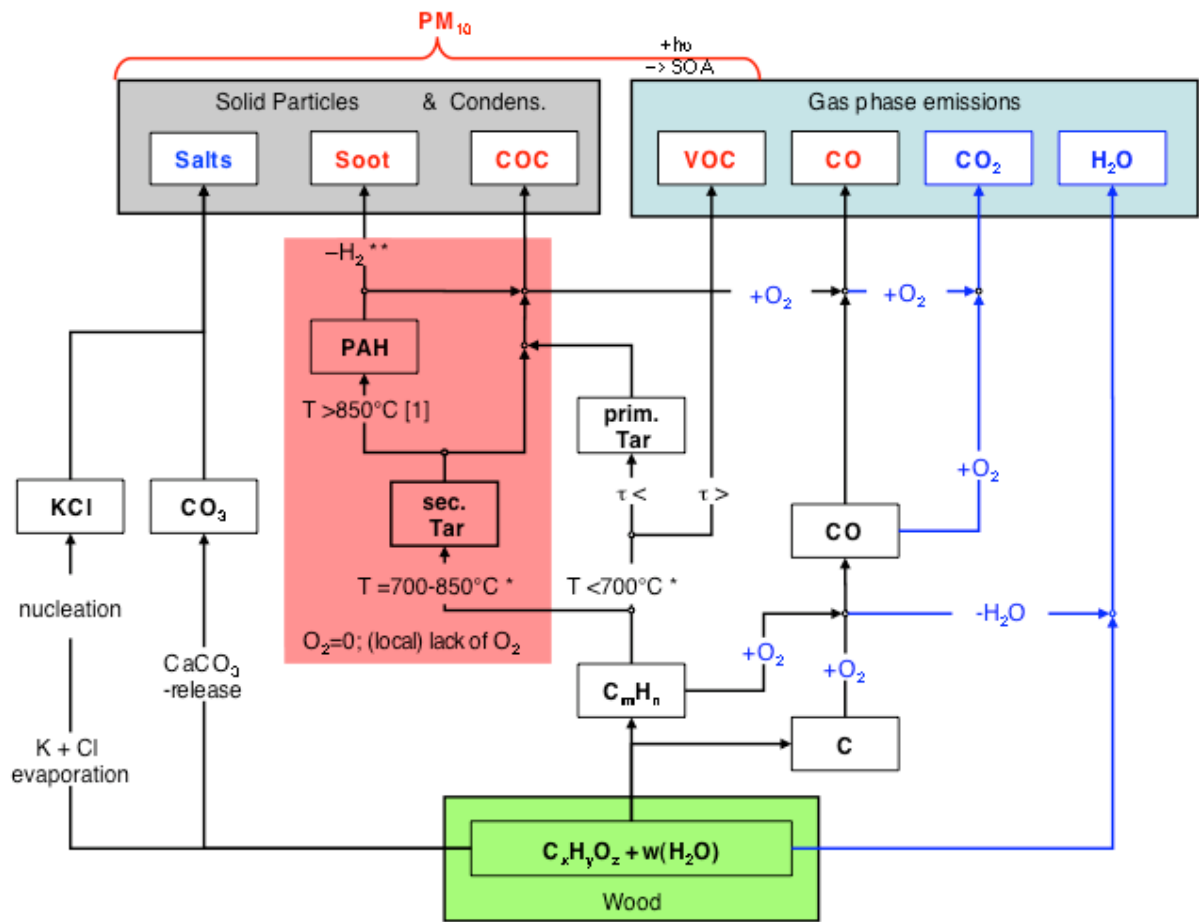





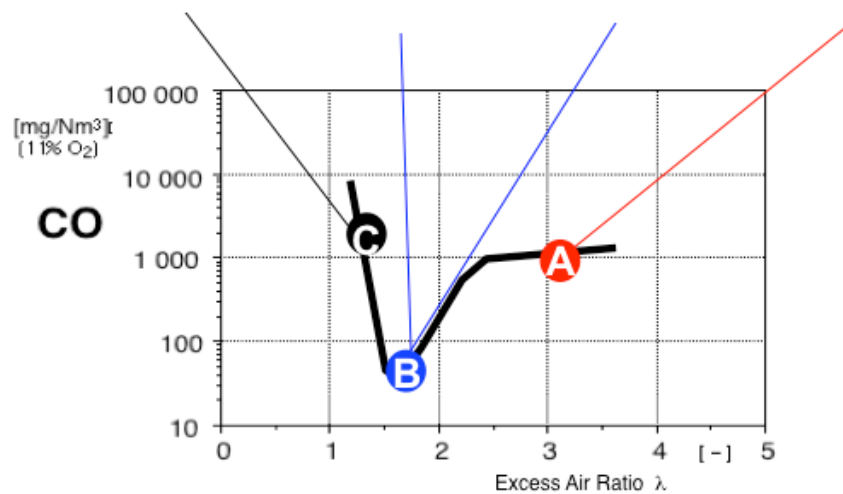


Figure 2.2 Mechanisms of aerosol formation in biomass combustion [Nussbaumer & Lauber 2010].
 *[Evans & Milne 1987], **[Jess 1996].

Aerosols from	Flaming Combustion			Pyrolysis
	high temperature and lack of O ₂ in the flame	– Mix –	T and O ₂ good	low temperature due to pyrolysis conditions or very high excess air
Biomass Combustion				
View				 
PM	Soot	Salts + Soot	Salts	COC
Composition	EC / BC chemical / optical C/H > 6...8	↔	CC + Minerals carbonate C + inorg. M	OC = TC-EC-CC C/H < 2
Colour	black	grey	white	brown none
Health effect	toxicity carcinogeny inflammatory	↔	low toxicity low carcinogeny inflammatory	high toxicity high carcinogeny inflammatory
Climate: Direct	↑ absorbs light and heats atmosphere	↔	↓ scatters light and cools earth surface	→ weakly absorbs and scatters
Climate: Indirect	↑ snow albedo ↓	↓	↓	↓
All particles act as CCN and lead to indirect cooling due to cloud albedo and cloud lifetime effect				



[T. Bond, Testimony, US House of Repr. 10.18.07]: BC = 2000 x CO₂ for 20 y
 [ICCT, June 2009]: BC responsible of 0.34 Wm⁻² of total 1.6 Wm⁻²

Figure 2.3 Physical and chemical properties of the main types of aerosols from biomass combustion (above) and combustion regimes of a modified pellet boiler enabling the production of the particles displayed as examples (below) [Nussbaumer & Lauber 2010].

Point C: At $\lambda = 1.2$, the flame temperature is high, thus enabling synthesis reactions in the flame in zones with local lack of oxygen resulting in high soot concentrations.

Point B: For $\lambda = 1.55$, almost complete combustion is achieved thanks to high flame temperature and sufficient oxygen availability thus resulting in inorganic particles at low soot and COC.

Point A: By increasing the excess air ratio to 3.5, high concentrations of CO and HC is achieved. Due to low temperature, high concentrations of COC are found although oxygen is available in excess. However, high COC concentrations can also be found under pyrolysis conditions at excess air ratios significantly smaller than 1 and locally close to 0. Due to low conversion temperature, soot formation is avoided thus resulting in pyrolysis products such as COC in the flue gas.

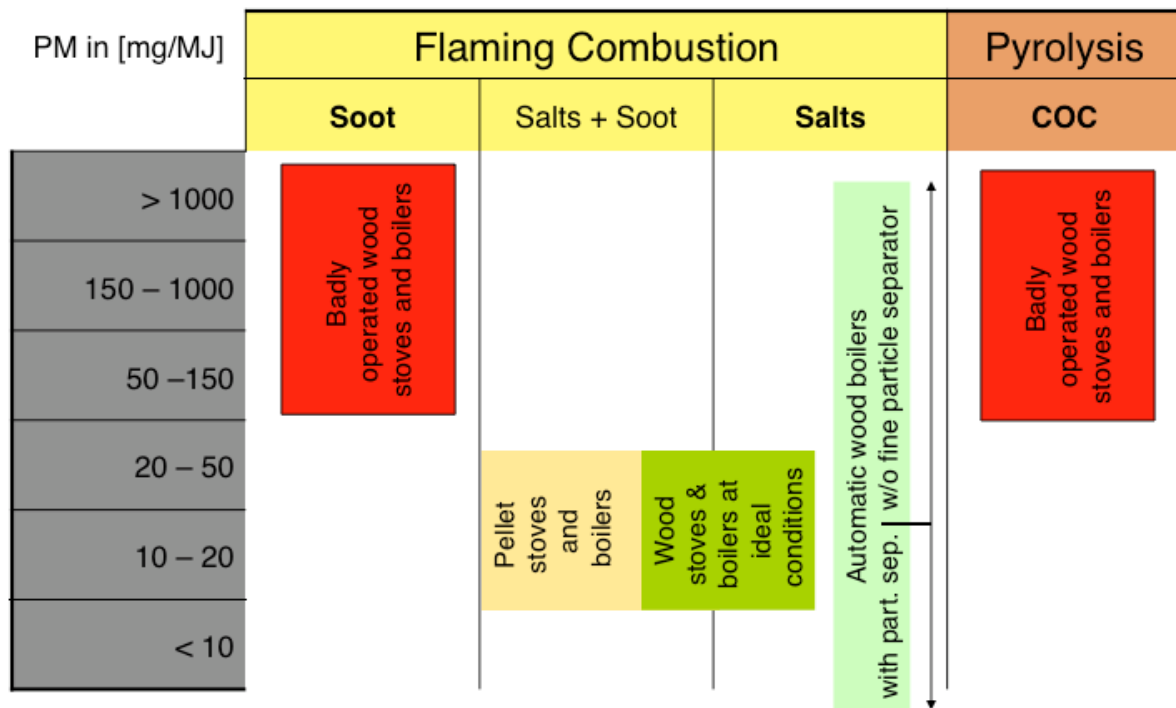


Figure 2.4 Visualisation of combustion regimes enabling different particle types and emission levels (qualitative comparison only).

2.3 Primary measures to reduce airborne pollutants

2.3.1 Primary measures to achieve complete combustion

The main needs for complete burnout are temperature, time, and turbulence (TTT). The mixing between combustible gases and air is often a limiting factor for the burnout quality. The demands for temperature (around 850°C) and residence time (around 0.5 s) can usually be ascertained in large boilers, but can be critical in residential applications.

If *staged combustion* is applied, the excess air can vary in different sections. *Two-stage combustion* is applied with primary air injection in the fuel bed and consecutive secondary air injection in the combustion chamber. This allows good mixing of combustion air with the combustible gases formed by devolatilization and gasification in the fuel bed. If good mixing occurs, an operation at low excess air is possible (i.e., excess air $\lambda < 1.5$), thus enabling high efficiency and high temperature (Figure 2.6) with complete burnout (Figure 2.8). If good mixing is achieved, the concentrations of uncombusted pollutants can be reduced to levels close to zero (e.g. $\text{CO} < 50 \text{ mg/m}^3$ and $\text{C}_x\text{H}_y < 5 \text{ mg/m}^3$ at 11 vol.-% O_2). However, an accurate process control (e.g. CO/lambda-controller with use of sensors for CO and lambda) is needed to ensure optimum excess air in practice. For this purpose, self-adjusting control systems with use of sensors for CO and lambda (CO/lambda-controller) or for CO and temperature have been developed.

Sufficient mixing quality can be achieved in fixed-bed combustion by the above-described two-stage combustion. In a fluidized bed, good mixing is achieved in the bed and the freeboard, while also dust combustion allows good mixing. For further improvements in furnace design, computational fluid dynamics (CFD) is applied to calculate flow distributions and gas phase reactions in the combustion (Figure 2.9).

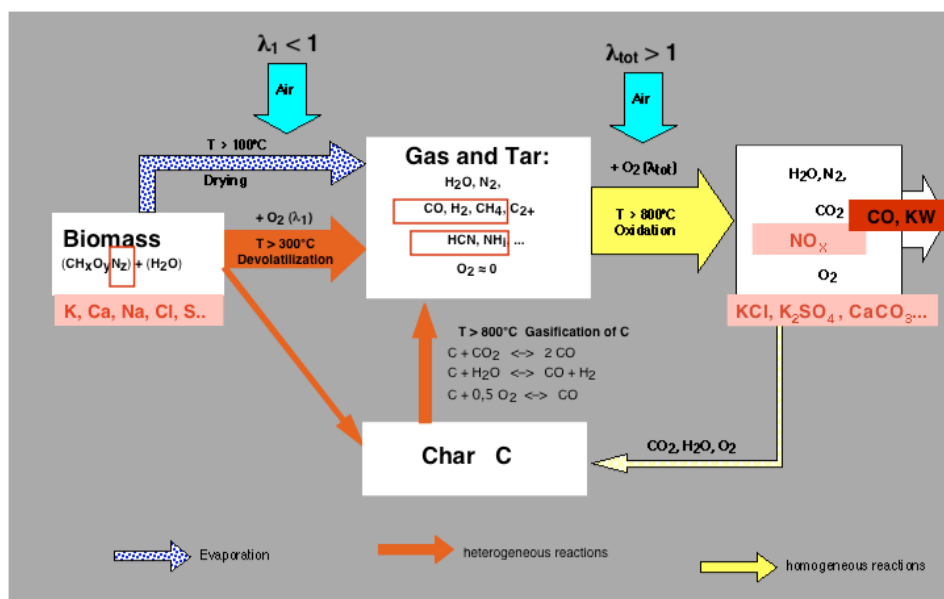


Figure 2.5 Reactions during biomass combustion by injection of primary air for gasification and secondary air for gas-phase burnout, introducing the principle of two-stage combustion [Nussbaumer 2003].

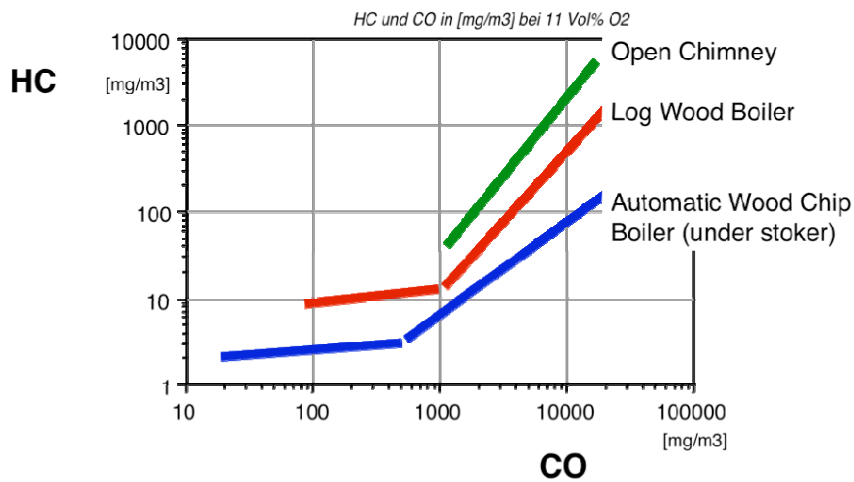


Figure 2.6 Hydrocarbons (HC) as function of carbon monoxide for different combustion types [Nussbaumer 1989].

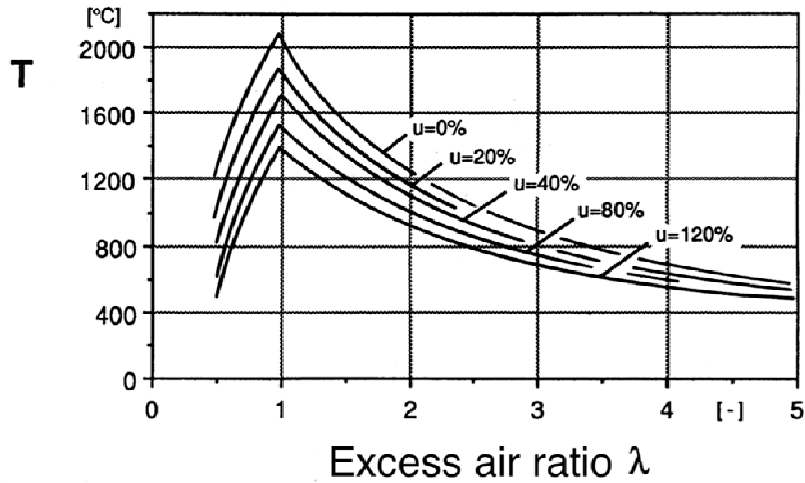


Figure 2.7 Adiabatic flame temperature for the combustion of wood with different humidity u (u is based on dry fuel, hence $u = 100\%$ corresponds to a moisture content $w = 50\%$).

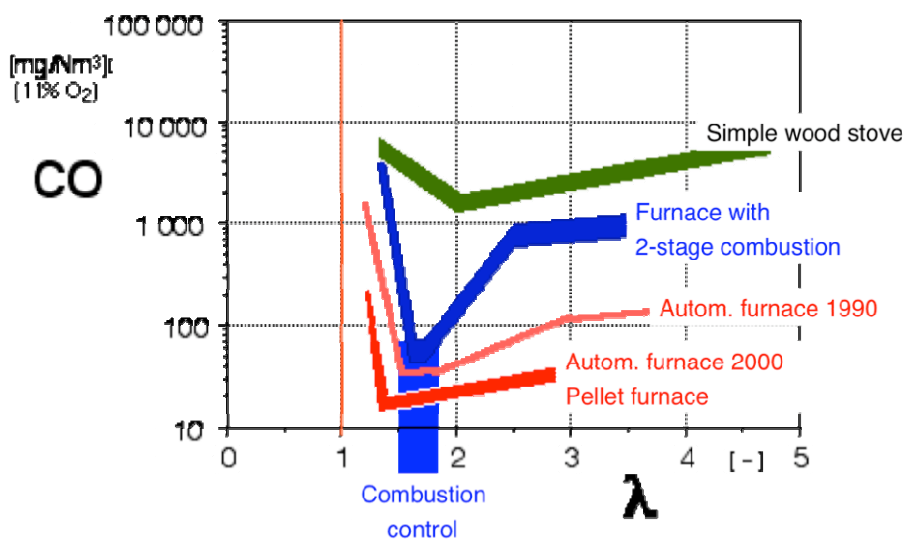


Figure 2.8 Carbon monoxide emissions as function of excess air ratio for different furnace types [Nussbaumer 2003].

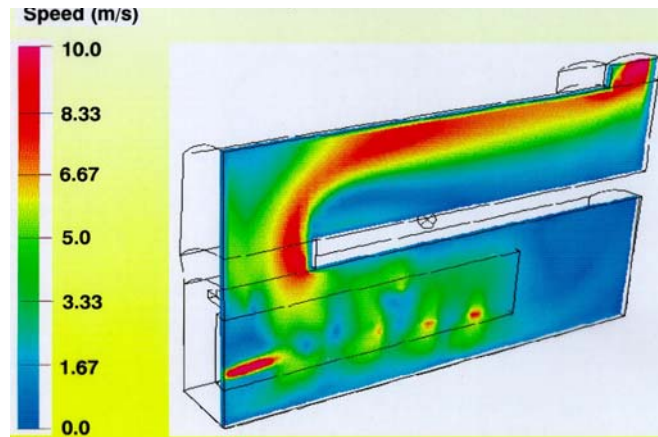


Figure 2.9 CFD modelling for optimization of furnace design shown by the example of a moving grate boiler. [Nussbaumer 2003].

2.3.2 Primary measures to reduce NO_x emissions

In combustion processes, NO and NO₂ (summarized as NO_x) can be formed in three different reactions. Thermal NO_x and prompt NO_x are formed from nitrogen in the air at high temperatures and in the case of prompt NO_x in the presence of hydrocarbons. Fuel NO_x can be formed from nitrogen containing fuels. For biomass combustion, fuel-bound nitrogen is the main source of NO_x emissions, while thermal and prompt NO_x are not relevant due to relatively low temperatures, as has been shown by theoretical and experimental investigations. Fuel nitrogen is converted to intermediate components such as HCN and NH_i with $i=0, 1, 2, 3$. These can be oxidized to NO_x if oxygen is available, which is the case in conventional combustion. If no oxygen is present, intermediates can interact in the reduction zone and form N₂ in reactions such as $\text{NO} + \text{NH}_2 = \text{N}_2 + \text{H}_2\text{O}$ (Figure 2.10). During the past 10 years, staged combustion technologies have been developed as a primary measure for internal NO_x reduction based on this concept, thus leading to the above-described techniques of air staging and fuel staging (Figure 2.11). Both measures allow a NO_x reduction of up to 50% for wood with low nitrogen content and up to 80% for bio fuels with high nitrogen content. However, different specific conditions have to be met accurately to exhaust this reduction potential.

In the case of air staging, a primary air excess around 0.7, a temperature in the reduction zone of 1150°C, and a residence time of 0.5 s are needed. The relatively high temperature can limit the application in practice due to undesired ash softening and deposit formation. For fuel staging, similar results are achieved at lower temperatures (i.e., at temperatures as low as 850°C). However, the furnace concept and operation is more complex due to the need of two independent fuel feeding systems. Nevertheless, a pilot plant based on this concept has been successfully designed with a combination of understoker furnace and entrained flow reactor. For both types of staged combustion, accurate process control is needed to ensure an operation at the excess air ratio needed in the different zones.

Beside primary measures, secondary measures are available for NO_x abatement. The most relevant techniques are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) using the same reaction as mentioned for staged combustion, i.e., $\text{NO} + \text{NH}_2 = \text{N}_2 + \text{H}_2\text{O}$. However, urea or ammonia is injected as a reducing agent and as a source of NH₂. SNCR has to be applied in a narrow temperature window of around 820°C to 940°C, thus allowing a NO_x reduction up to 90%. SCR is typically applied in the flue gas in a temperature range of 250° to 450°C and allows a NO_x reduction of

more than 95%. However, relevant concentrations of undesired side products such as HNCO, N₂O, NH₃, HCN, and others can be formed in both types of secondary measures under unfavorable conditions. Primary measures are preferable if they can achieve sufficient emission reduction.

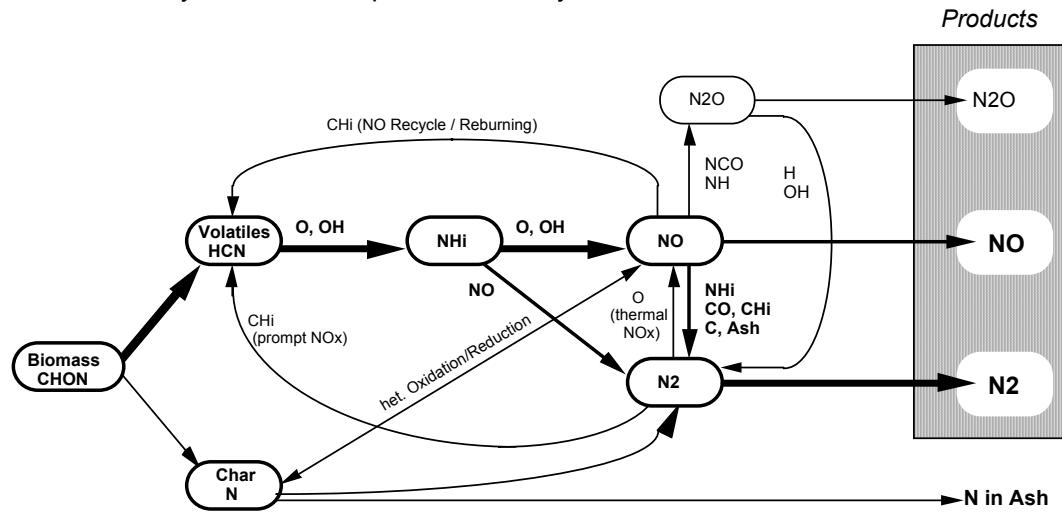


Figure 2.10 Conversion of fuel nitrogen in biomass combustion [Nussbaumer 2003].

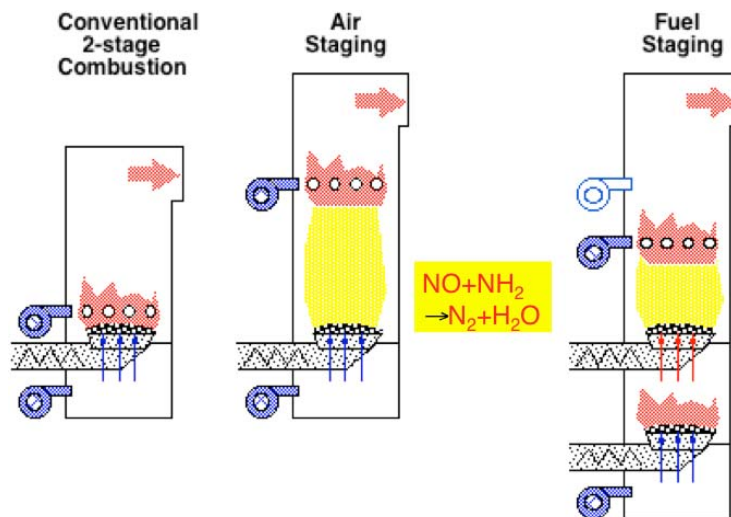


Figure 2.11 Principle of conventional two-stage combustion, air staging with reduction zone, and fuel staging with reduction zone [Nussbaumer 2003].

2.3.3 Primary measures to reduce inorganic particulate emissions

In case of near-complete combustion of wood and other biomass, significant concentrations of inorganic particulates are found in the flue gas resulting from ash components such as K, Cl, S, Ca, Na, Si, P, Fe, and Al. The conversion of mineral constituents in the fuel to the flue gas can be reduced to a certain extent by application of gasification conditions as described as “low-particle-concept” in the next chapter. Nevertheless, inorganic particles cannot be quantitatively avoided by primary measures and hence secondary measures remain necessary for many applications.

2.4 Combustion technologies

Biomass combustion is mainly used for heat production in small and medium scale units such as wood stoves, log wood boilers, pellet burners, automatic wood chip furnaces and straw fired furnaces. District heating systems range in size from 0.5 MW_{th} to 5 MW_{th} with some applications up to 50 MW_{th}. Combined heat and power production (CHP) with biomass is applied by steam cycles (Rankine cycle) with steam turbines, steam engines, and organic Rankine cycles (ORC) that have typical power outputs between 0.5 MW_e and 10 MW_e. Stirling engines (10 kW_e to 100 kW_e) and closed gas turbines are in development or demonstration mode. Co-firing in fossil fired power stations allows the advantages of large size plants (> 100 MW_e), which are not applicable for dedicated biomass combustion due to limited local biomass availability.

Table 2.1 gives an overview of the most frequently used furnace types for biomass combustion. The various types can be distinguished by the flow conditions in the furnace. There are three different flow conditions: fixed-bed, fluidized-bed, and entrained flow or dust combustion (Figure 2.12). To achieve complete burnout and high efficiencies in small-scale combustion, downdraft boilers with inverse flow have been introduced, which apply the two-stage combustion principle described above (Figure 2.13). An operation of log wood furnaces at very low load should be avoided, as it can lead to high emissions of uncombusted pollutants. It is recommended to couple log wood boilers to a heat storage tanks.

Since wood pellets are well suited for automatic heating at small heat outputs as needed for today's buildings, pellet furnaces are an adequate application with growing propagation. Thanks to the well-defined fuel at low water content, pellet furnaces can easily achieve high combustion quality. They are applied both as stoves and as boilers.

Understoker furnaces are mostly used for wood chips and similar fuel with relatively low ash content (Figure 2.15), while grate furnaces can also be used for high ash and water content (Figure 2.16).

Figure 2.17 shows the principle of a the "low particle concept", which consists of a primary zone acting as a gasification section at very low primary excess [Oser & Nussbaumer 2006]. This principle allows the reduction of particle emissions by 50% to 80%. The following mechanisms are relevant for particle reduction:

- Reduced temperature in the glow bed reduces evaporation of ash constituents and formation of salts such as KCl in the flue gas
- Reduction of gas velocity through the fuel bed reduces entrainment of fuel particles that enter the hot section in the flame, where released vapours from ash constituents remain in the flue gas. This leads to salts in the stack instead of grate ash
- A reduction of the oxygen content in the fuel bed reduces the tendency to form oxides from the ash constituents, which reduces evaporation because oxides exhibit lower evaporation temperatures
- Finally, the high fuel bed may act as a filter for initially released particles.

The low particle concept is being investigated in research projects in Switzerland. It exhibits a potential for improvement. However, particle separation is still needed to achieve very low particle emissions for large-scale application. For medium-scale combustion (100 kW to 500 kW), the low particle principle may achieve emission limits of smaller than 50 mg/m³ at 13 vol.-% O₂ without secondary measures. Furthermore, it allows a reduction of the filter ash if applied for large-scale combustion equipped with

particle removal. This allows a cost reduction for the particle separation and a reduction of filter ash, which needs to be disposed as hazardous waste.

Special types of furnaces have been developed for straw that has very low density and is usually stored in bales. Beside conventional grate furnaces operated with whole bales, cigar burners and other specific furnaces are in operation.

Similar technologies are applied to residential pellet boilers (Figure 2.18). However, due to the higher fuel density and the homogeneous fuel properties, smaller auxiliary equipment such as stokers and electric motors can be used. Pellet boilers are smaller in size and exhibit lower cost than wood chip boilers of the same nominal heat output.

Stationary or bubbling fluidized bed boilers (SFB) as well as circulating fluidized bed boilers (CFB) are applied for large-scale applications and often used for waste wood or mixtures of wood and industrial wastes from the pulp and paper industry (Figure 2.19, Figure 2.20). In CFB boilers, nearly homogeneous conditions of temperature and concentrations can be achieved, thus allowing high burnout quality at low excess air. The choice of different bed materials in CFB offers additional opportunities for catalytic effects. In addition, the option of heat removal from the bed allows control of the combustion temperature and allows an operation at low excess air without excessive ash sintering. Since similar conditions for nitrogen conversion with air and fuel staging are attained, relatively low NO_x emissions are achieved.

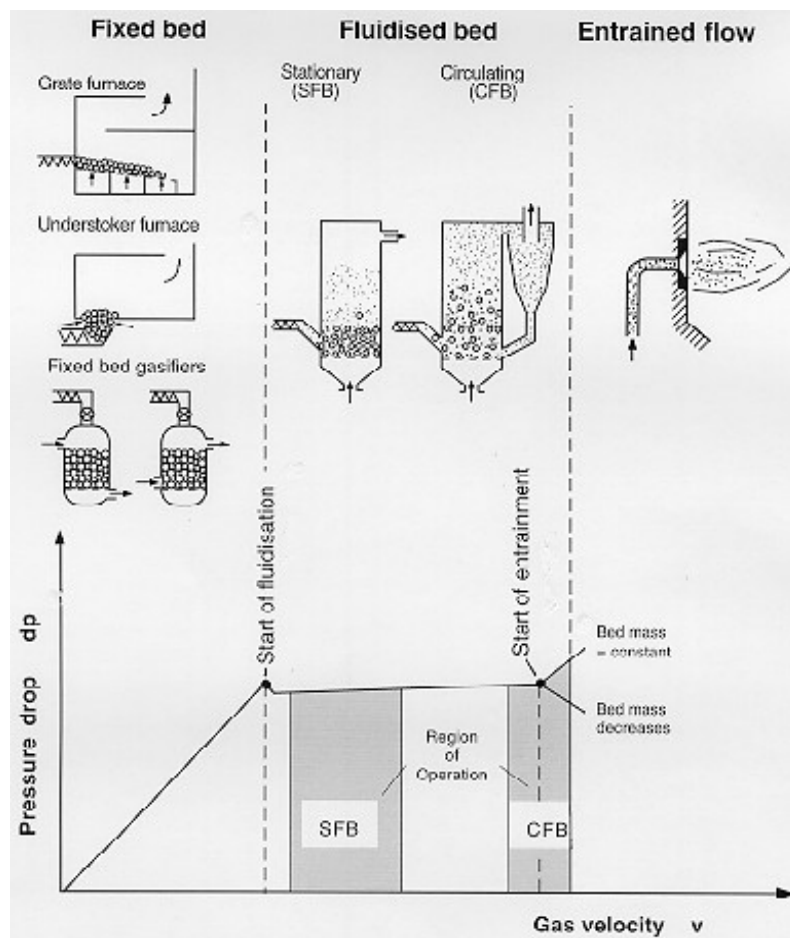


Figure 2.12 Furnace types and flow conditions: Fixed bed, fluidized bed, and entrained flow reactor.

Table 2.1 Types of biomass furnaces with typical applications and fuels. *Biomass covers typically less than 10% of the total fuel input. a = ash content (wt.-%), d = typical fuel size (diameter)

Application	Type	Typical size range	Fuels	Ash	Moisture content
Manual	Wood stoves	2 kW – 10 kW	dry wood logs	< 2%	5% – 20%
	Log wood boilers	5 kW – 50 kW	log wood, sticky wood residues	< 2%	5% – 30%
Pellets	Pellet stoves and boilers	2 kW – 25 kW	wood pellets	< 2%	8% – 10%
Automatic	Understoker furnaces	20 kW – 2.5 MW	wood chips, wood residues	< 2%	5% – 50%
	Moving grate furnaces	150 kW – 15 MW	all wood fuels and most biomass	< 50%	5% – 60%
	Pre oven with grate	20 kW – 1.5 MW	dry wood (residues)	< 5%	5% – 35%
	Understoker with rotating grate	2 MW – 5 MW	wood chips, high water content	< 50%	40% – 65%
	Cigar burner	3 MW – 5 MW	straw bales	< 5%	20%
	Whole bale furnaces	3 MW – 5 MW	whole bales	< 5%	20%
	Straw furnaces	100 kW – 5 MW	straw bales with bale cutter	< 5%	20%
	Stationary fluidized bed	5 MW – 15 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Circulating fluidized bed	15 MW – 100 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Dust combustor, entrained flow	5 MW – 10 MW	various biomass, d < 5 mm	< 5%	< 20%
Co-firing*	Stationary fluidized bed	total 50 MW – 150 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Circulating fluidized bed	total 100 – 300 MW	various biomass, d < 10 mm	< 50%	5% – 60%
	Cigar burner	straw 5 MW – 20 MW	straw bales	< 5%	20%
	Dust combustor in coal boilers	total 100 MW – 1 GW	various biomass, d < 2 – 5 mm	< 5%	< 20%

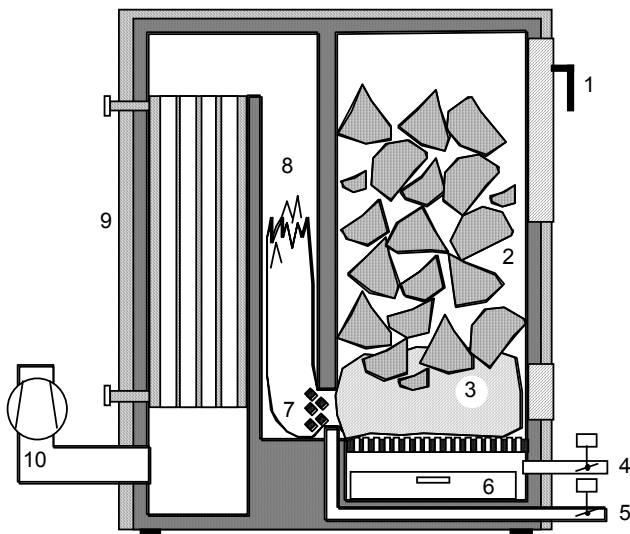
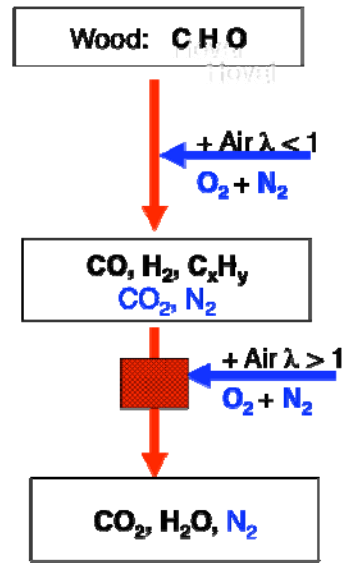
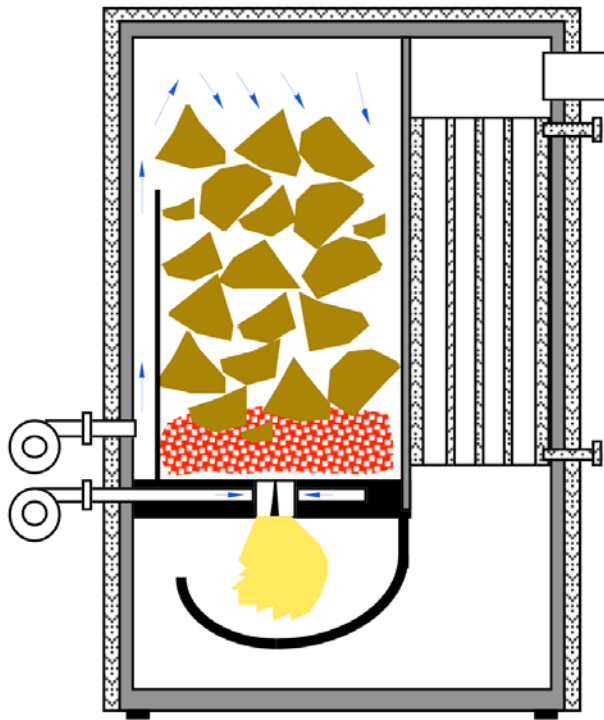


Figure 2.13 Downdraft boilers with inverse combustion of log wood and with enforced air flow and air supply with primary and secondary air. Graphs: [Nussbaumer 2003], bottom right: Schmid AG Eschlikon.

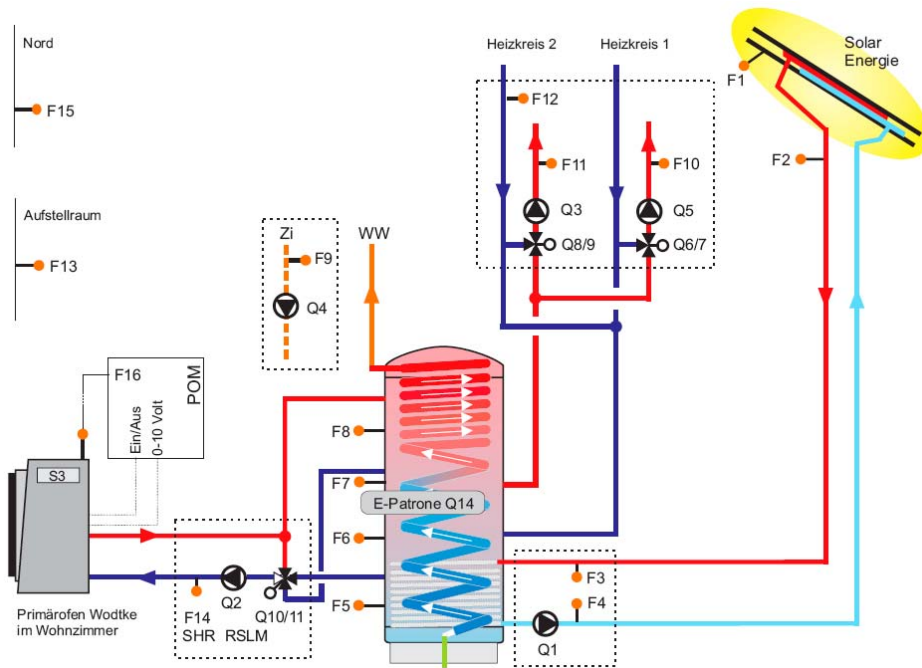


Figure 2.14 Wood boilers for residential heating should be combined with a heat storage tank to safely avoid part-load operation at less than 50% of nominal heat output. [Tiba AG].

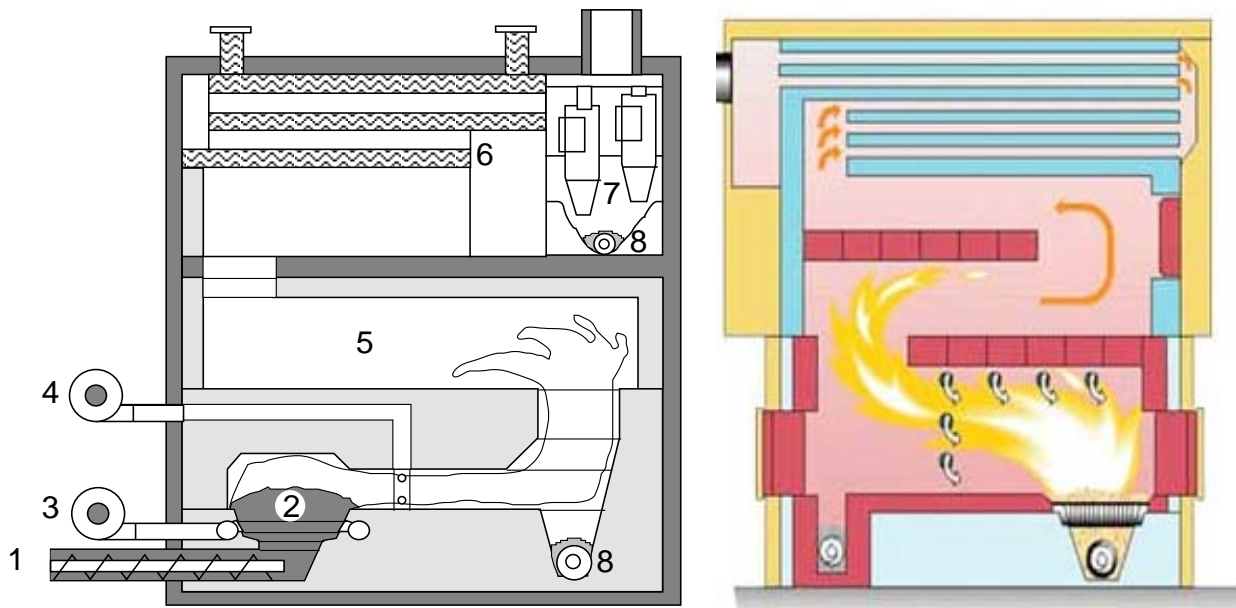


Figure 2.15 Understoker boiler with primary and secondary air, mixing zone and post combustion chamber. 1 Screw feeder, 2 understoker zone with glow bed, 3 primary air, 4 secondary air, 5 post combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal. (Right: Müller AG).

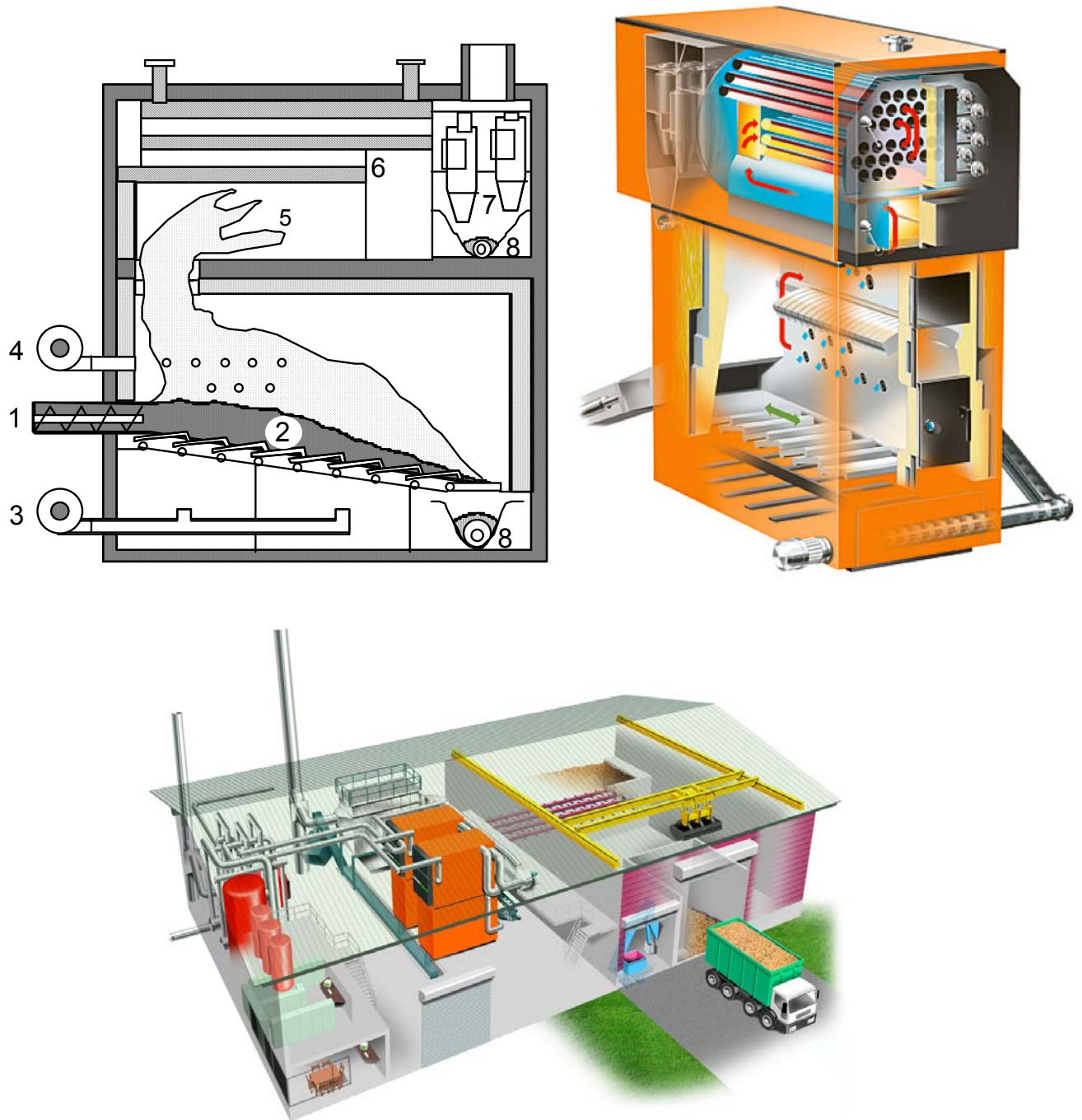


Figure 2.16 Moving grate boiler with primary air in two stages in the grate and secondary air.
 Top: 1 Screw feeder, 2 moving grate, 3 primary air, 4 secondary air, 5 post-combustion chamber, 6 heat exchanger, 7 cyclone, 8 ash removal.
 Bottom: Example of a district heating plant with two boilers and electrostatic precipitator in Switzerland (approx. 6 MW, Schmid).

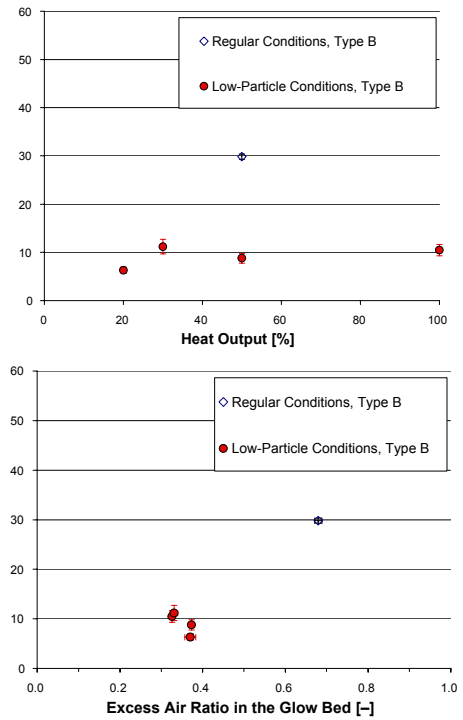
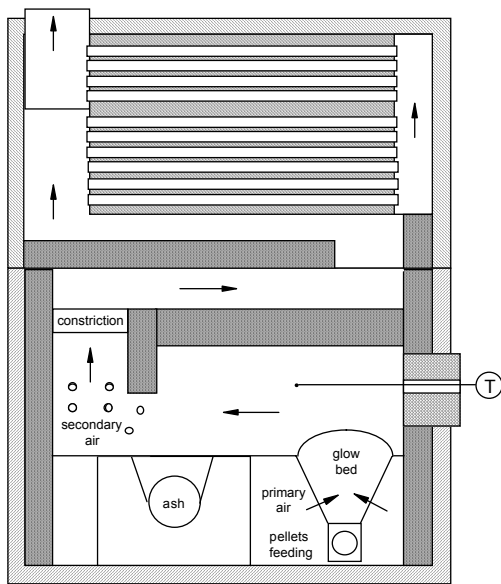


Figure 2.17 Schematic of an understoker boiler with “low particle concept”. The figure shows a 100 kW prototype pellet boiler. The cross-section of the combustion chamber is reduced from both sides in the section “constriction”, to improve the gas mixing by acceleration and subsequent velocity reduction. The influence of low-particle conditions on the particle mass concentration is shown in the graphs. The reduction of the particle emissions at very low primary excess air (comparable to gasification conditions) amounts to more than 50%. The particle emissions remain constant at varying load, which is an important advantage for practical applications. [Oser & Nussbaumer 2006].

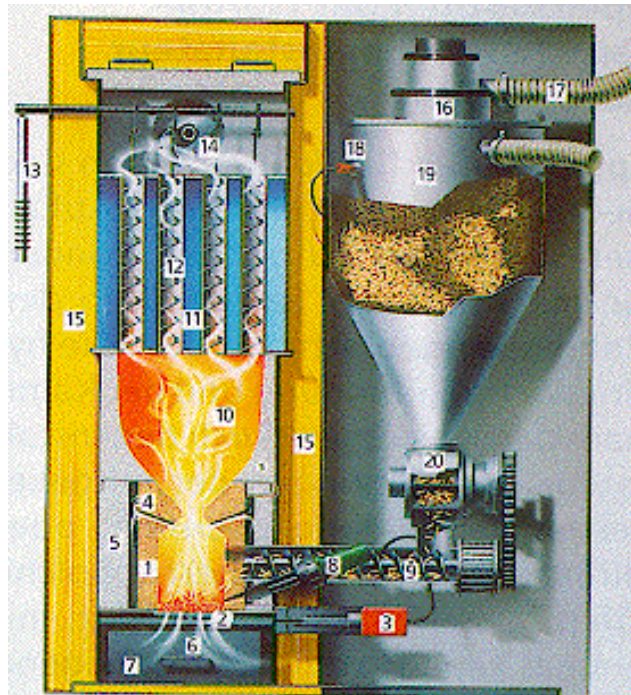
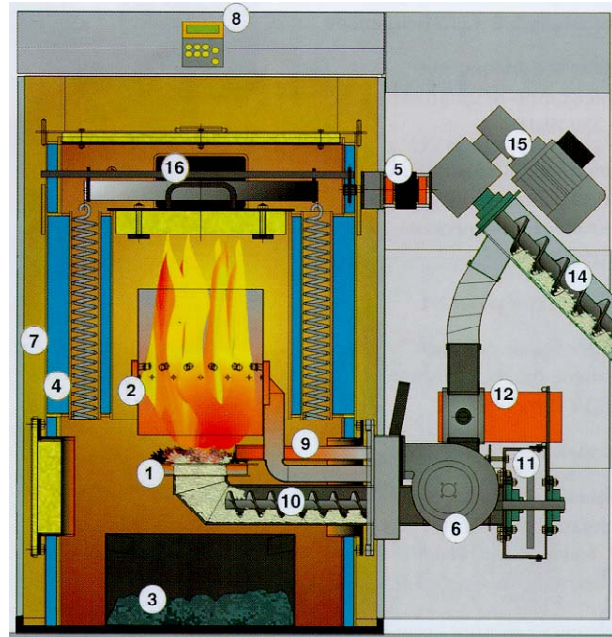


Figure 2.18 Examples of pellet boilers.
 Top: Understoker boiler with small grate and primary air inlet (1) and subsequent secondary air inlet in the combustion chamber (2) (Oekofen).
 Bottom: Screw feeder on top of the grate with primary air inlet (6) and subsequent secondary air inlet (4) prior to the combustion chamber (10) (Hargassner).

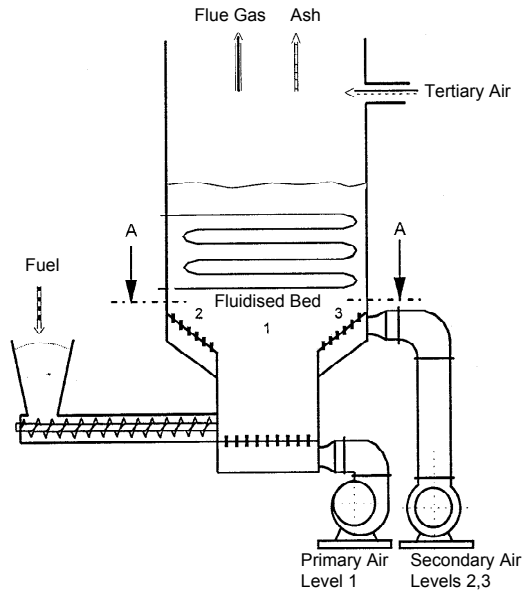


Figure 2.19 Stationary fluidized bed combustor with staged combustion. (Lurgi, 5 MW).

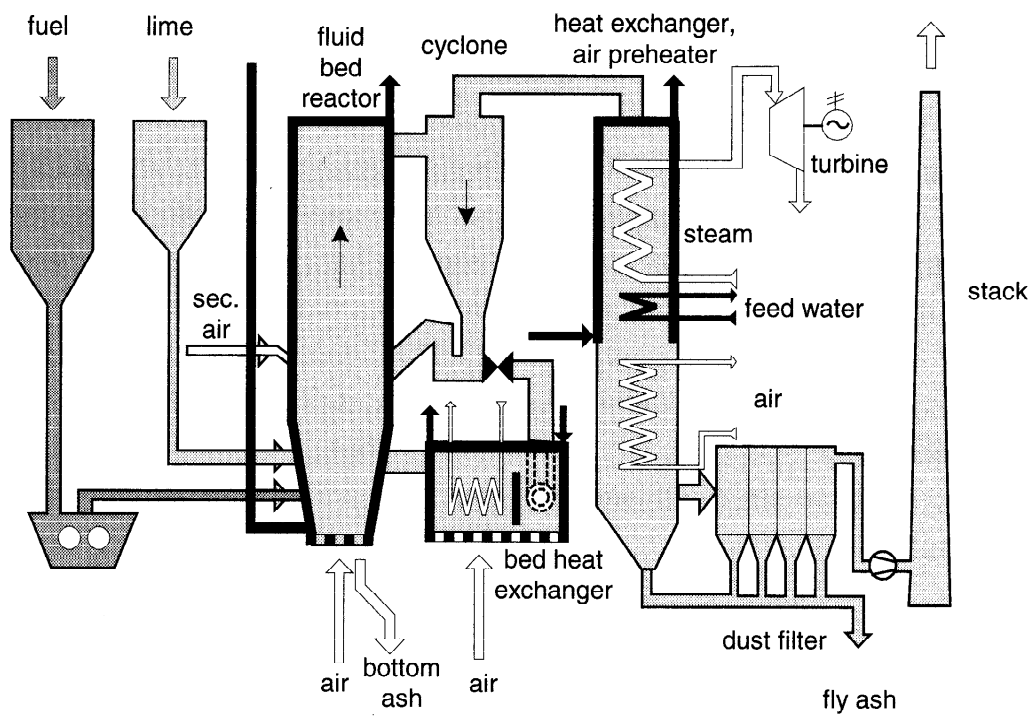


Figure 2.20 CFB plant with steam boiler for coal and biomass (Lurgi).

2.5 Co-combustion

A co-utilization of biomass with other fuels can be advantageous with regard to cost, efficiency, and emissions. Lower specific cost and higher efficiencies of large plants can be used for biomass, and emissions of SO_x and NO_x can be reduced by co-firing. However, attention must be paid to increased deposit formation in the boiler and limitations in ash use due to constituents in biomass, especially alkali metals, which may disable the use of ash in building materials. Due to undesired changes of ash compositions, the share of biomass is usually limited to approximately 10% of the fuel input. Other opportunities are of interest, and the following three options for co-utilization of biomass with coal are applied:

1. **Co-combustion or direct co-firing:** The biomass is directly fed to the boiler furnace (fluidized bed, grate or pulverized combustion), if needed after physical pre-processing of the biomass such as drying, grinding, or metal removal.
2. **Indirect co-firing:** The biomass is gasified and the product gas is fed to a boiler furnace (a combination of gasification and combustion).
3. **Parallel combustion:** The biomass is burned in a separate boiler for steam generation. The steam is used in a power plant with the main fuel.

Co-combustion of biomass leads to a substitution of fossil fuels and to a net reduction of CO_2 emissions. In many countries co-firing is the most economical technology to achieve the target of CO_2 reduction. Biomass co-firing can therefore be motivated by savings of CO_2 taxes.

3 Secondary measures for particle removal

3.1 Overview

Figure 3.1 gives an overview on the technologies for particle removal from gases. For biomass combustion, cyclones are commonly applied if relatively high clean gas emissions are accepted as e.g. 150 mg/m³ at 11 Vol.-% O₂ or more. Cyclones are not capable to reduce fine particle emissions with particle sizes < 5 to 10 microns significantly. For this purpose, electrostatic precipitators (ESP) are widely applied in biomass plants nowadays in the size range > 1 to 2 MW. In case of dry fuels or very stringent emission limit values, fabric filters are often applied. Wet scrubbers achieve typically only a limited separation efficiency for biomass particles. Since wet gas cleaning is relatively complex due to the additional need of water management or even waste water treatment, it is rarely applied except in plants burning wet biomass, where flue gas condensation is applied to enable significant energy recovery. Figure 3.2 shows the typical precipitation efficiencies as function of the particle size. Figure 3.3 shows the influence of the electric field strength on the separation efficiency in an ESP.

Coarse particle dedusting		Fine particle separation					
1. Precipitation by inertia		2. Filter		3. Electrostatic precipitator ESP (≠ Filter !)		4. Wet scrubber + Inertia	
> 50 μm	> 5 μm	> 0.01 μm		> 0.01 μm		> 1 μm	
Inertia	Centrifugal force	Accumulating filter	Surface filters	Dry ESP	Wet ESP	Gas injection	Droplet injection
Sedimentation chamber	Cyclone	e.g. one-way clean air filters	Cloth filters Packed bed filters	Plate ESP (Tube ESP)	Tube ESP Plate ESP	Packed Column Base Column	Venturi Jet Column

Figure 3.1 Overview on particle separation technologies.

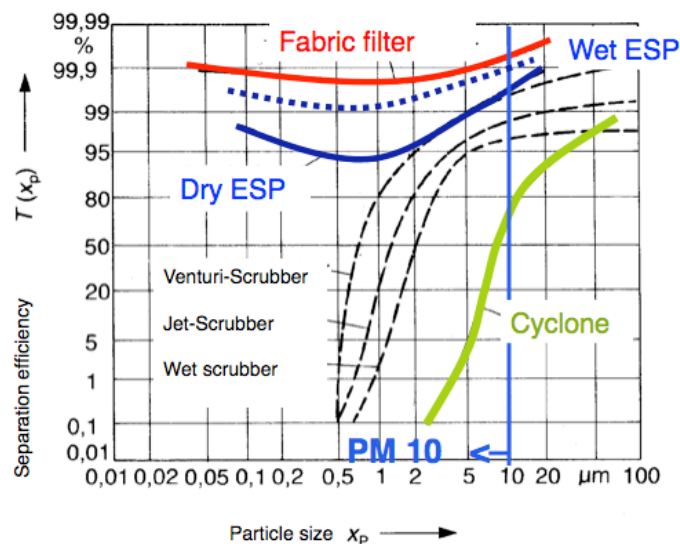


Figure 3.2 Precipitation efficiency for different gas cleaning systems (by [Fritz & Kern 1990], adapted).

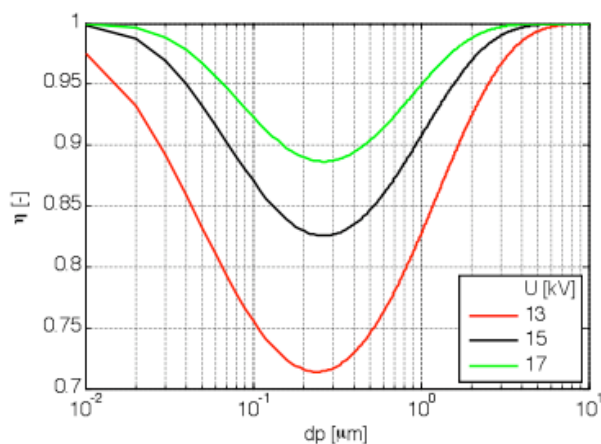


Figure 3.3 Influence of the electric field strength on the precipitation efficiency [Nussbaumer & Lauber 2010].

3.2 Relevance of particle properties

As described in chapter 2.2, three particle types can be distinguished from biomass combustion summarized as salts, soot, and condensable organic compounds (COC).

The three combustion regimes – among other parameters – are related to the level of excess air available in the combustion chamber. Figure 2.3 shows the particles found in a laboratory device at different excess air ratios:

- At low excess air ratio (regime C), soot is formed in hot zones in the flame as a synthesis product through the release of hydrocarbons containing primary tars from wood pyrolysis, formation of secondary tars in an atmosphere with lack of oxygen, PAH formation, and finally release of hydrogen during particle growth thus resulting in a high C/H ratio as indicated in Table 1.
- At optimum excess air (regime B), near complete combustion is achieved, if good mixing of combustible gases with air is guaranteed and quenching of the flame is avoided. Consequently, carbonaceous matter in solid and liquid phase is emitted in very small concentrations, while

inorganic particles formed from ash constituents are available as particulate matter (PM) in the flue gas and predominantly found as salts.

- At high overall excess air (regime A), the combustion temperature decreases, resulting in incomplete combustion. Due to low temperature, the formation of soot and the release of hydrogen is suppressed, resulting in high concentrations of primary and secondary tars formed during pyrolysis consequently leading to condensable organic compounds (COC) in the flue gas with low C/H ratio.

Since ESP operation is ideal at operation at optimum excess air, nowadays applications are often limited to such combustion conditions, while the ESP is often shut-off during unideal combustion conditions.

According to the chemical composition and the physical properties, salts are expected to be suitable for ESP operation, while soot may result in re-entrainment and COC may be related to back-corona. Due to the release of hydrogen during soot formation, a significantly different molar ratio of soot and COC is expected, thus enabling to identify and distinguish the two types of aerosols from incomplete combustion.

Since the electrical conductivity influences the formation of dust layers in the electric field, different dust layers may be formed depending on the particle properties. Soot leads to dendritic build-up with a weak adhesion of the agglomerates, which can cause re-entrainment of agglomerated soot particles. Salt forms a homogeneous layer, which can be safely removed by state-of-the-art dedusters. COC may form a homogeneous, but sticky layer, which is difficult to be removed and may cause operational problems.

Consequently, salts are expected to be uncritical for particle removal in ESP but also in fabric filters. Soot can lead to re-entrainment in ESP, while this does not occur in fabric filters. Most critical are COC since they may form a sticky layer which can hardly be removed in ESP and also coat fabric filters. In addition, COC can limit the efficiency of ESP due to back-corona. Furthermore, all elemental and organic carbon is a potential fire risk in particle separators as well as in chimneys. For this reason, commercial ESP and fabric filters are restricted to low carbon content. Typically the restrictions are:

< 5% carbon for ESP and

< 2% carbon for fabric filters.

These requirements underline that near-complete combustion is crucial and cannot be subsidised by particle removal. The requirements are demanding, but they can often be achieved in industrial boilers at stationary operation. Residential biomass combustion is typically related to far higher carbon contents, which needs to be considered for secondary measures.

3.3 Industrial scale applications > 200 kW

3.3.1 Technology

Automatic biomass combustion plants exhibit usually particle emissions in the raw flue gas of more than 100 mg/m^3 at 11 or 13 vol.-% O_2 and in some cases up to several 100 mg/m^3 , depending on fuel type and combustion type. If a target value of safely below 20 mg/m^3 is aimed at, a significant removal efficiency is needed, i.e., at least > 90% to 95% for particles smaller 10 microns and even more for particles smaller than 1 micron. For automatic biomass combustion plants, the following technologies are commonly applied for particle removal:

- Cyclones
- Dry electrostatic precipitators (ESP)
- Fabric filters.

Cyclones do not achieve a relevant removal efficiency for fine particles smaller than 5 microns. If emission limit values of e.g. 150 mg/m^3 at 11 or 13 vol.-% O_2 are aimed at, cyclones are often applied as only particle removal system. If ESP or fabric filters are applied, cyclones are often used as a pre-separators for the removal of coarse fly ash and glowing particles which might lead to a destruction of the fabric material. However, a pre-separator by cyclone causes not only additional investment cost, but also significant operation cost due to the additional pressure drop.

ESP exhibit a high precipitation efficiency for all particle sizes except for particles in the size range from approx. 0.2 to 0.8 micron, where the precipitation efficiency exhibits a typical minimum. Due to the precipitation principle, the removal efficiency depends on the residence time or the space velocity in the ESP and hence can be improved by increasing the precipitation area, thus leading to increased size and cost of the ESP. Due to this situation, ESP are nowadays often designed to achieve e.g. 50 mg/m^3 at 11 vol.-% O_2 and hence the size and cost increase, if far lower emission limit values are demanded.

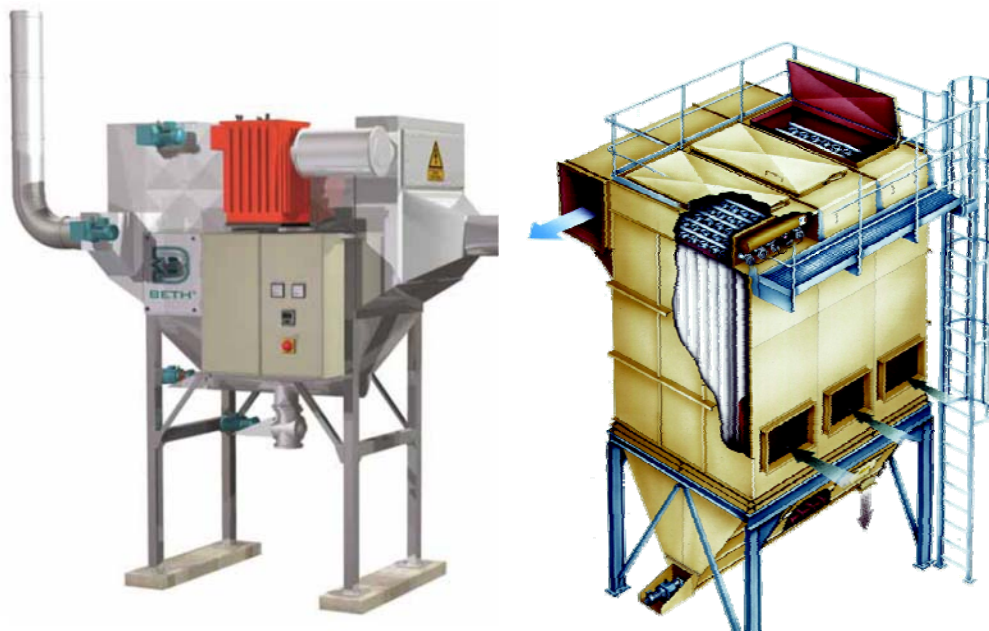


Figure 3.4 ESP (Aerob-Beth) and fabric filter (Scheuch) for biomass boilers in the size range of approx. 400 kW to 1 MW.

Fabric filter enable typical removal efficiencies of > 99%. The periodic cleaning of the fabric filter causes a temporary reduction of the filtration efficiency, since the filter layer is needed for a maximum precipitation of fine particles. In addition, gaseous substances such as HCl and PCDD/F can be removed by absorption in the filter layer. For this purpose, limestone can be added for HCl removal and active coke can be added for PCDD/F removal. Hence, fabric filters are advantageous in case of contaminated wood. However, fabric filters exhibit a significant energy consumption due to the relevant pressure drop and the utilisation of pressurised air for the periodic cleaning. In addition, fabric filters are well suited for dry flue gases, while high water content in the fuel and consequently in the flue gas are critical, since condensation of water vapour and other substances may lead to filter clogging and thus to a destruction of the filters, which may lead to interruption of the plant operation and to high cost. In addition, fabric filters can be destroyed by glowing particles, which need to be avoided, removed, or detected and extinguished in front of the fabric filter.

To avoid condensation in the filter, fabric filters need to be heated up to a minimum operation temperature, which can be performed by electric heating. However, fabric filters in small plants are often equipped with a by-pass and hence not in use during the critical start-up phase of the combustion plant. Typically, fabric filters are only operated at temperatures higher than 120°C for dry fuels and higher than 140°C for wet fuels. In ESP, condensation should also be avoided and hence in some systems, the electric current is reduced or shut off during operation periods below a minimum temperature. Consequently, automatic combustion plants which are equipped with particle precipitation should be operated during long operation periods, while on/off operation should be avoided. Furthermore, a minimum availability for the precipitation should be claimed and the operation of the precipitation should be monitored. Since condensation is more critical in fabric filters, fabric filters are most often used for dry fuels only, while ESP are also used for wet fuels.

Beside ESP and fabric filters, flue gas condensation and wet electrostatic precipitation (wet ESP) are also used for automatic biomass combustion plants. However, flue gas condensation alone does not achieve a high efficiency (i.e., typically less than 50% if the raw gas concentrations are below 100 mg/m³), while wet ESP with or without separate flue gas condensation is more complex and hence usually applied in larger scale, e.g. for blue haze reduction (organic aerosols) in wood industry.

3.3.2 Economy

The influence of ESP and fabric filters on the economy of automatic wood heating plants was investigated in Switzerland [Nussbaumer 2007]. Data on investment cost were collected from existing heating plants and from manufacturers of ESP and fabric filters. Special focus was given on installations smaller than 1 MW, since ESP and fabric filters in this size range were rare at this time and the introduction of more stringent national emission limits was under discussion. The assumptions for investment and operation cost for automatic wood combustion plants without ESP or fabric filters were based on experiences from more than 30 existing plants. In addition, investment cost on ESP and fabric filters for the size range between 100 kW and 2 MW were collected from five different manufactureres from Switzerland, Germany, and Austria. Furthermore, data on investment cost and operation cost of three plants with ESP and fabric filter in the size range between 250 kW and 550 kW

were used to verify the effective cost for real-life applications of such installations. Based on these data, a detailed economic assessment was performed indicating the influence on investment cost and on total heat production cost. For this purpose, the heat production cost were calculated based on the following assumptions:

Interest rate for capital cost:	5.0% p.a.
Payback time for technique/hardware:	15 a
Payback time for buildings:	30 a
Operation of heating plants:	2000 h/a
Life time of filters for fabric filters:	5 a (before filter replacement)
Fuel price for wood chips at the gate:	3.0 Euro Ct./kWh
Fuel price for light fuel oil:	6.0 Euro Ct./kWh

The fuel cost for wood chips and light fuel oil were typical at this time e.g. for Switzerland or Germany, while significantly higher or lower fuel cost are found in other European countries. Hence the results are of indicative value for similar economic conditions, while the trends shown here can be invalid for differing economic conditions.

Effect on investment cost

For the given assumptions, the specific investment cost for the heat production plant without precipitation exhibit a strong economy of scale as shown in Figure 3.5. The same is true for the total cost for a plant with particle precipitation. However, ESP and fabric filters exhibit a stronger economy of scale than the boiler for applications smaller than 500 kW, since for this size range, the same ESP and fabric filters are applied independently of the size. Consequently, the relative increase in investment cost sharply increases in this size range as is shown in Figure 3.6. ESP exhibit higher investment cost than fabric filters, as can be seen from Figure 3.7

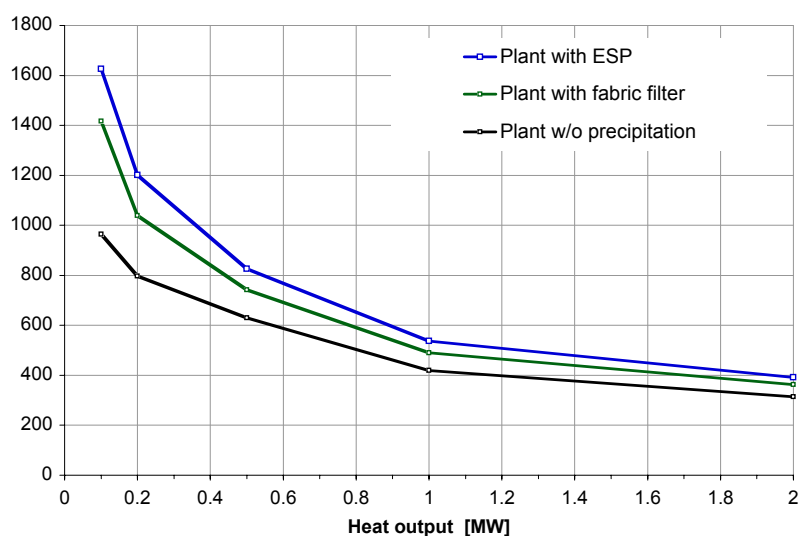


Figure 3.5 Specific investment cost for hardware (technique without building) with and without precipitation.

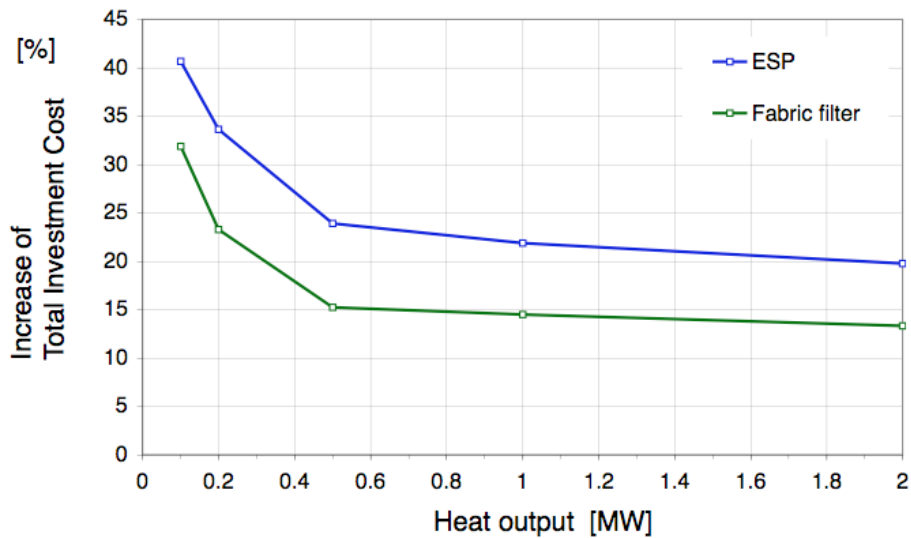


Figure 3.6 Increase of investment cost for hardware caused by an ESP or a fabric filter.

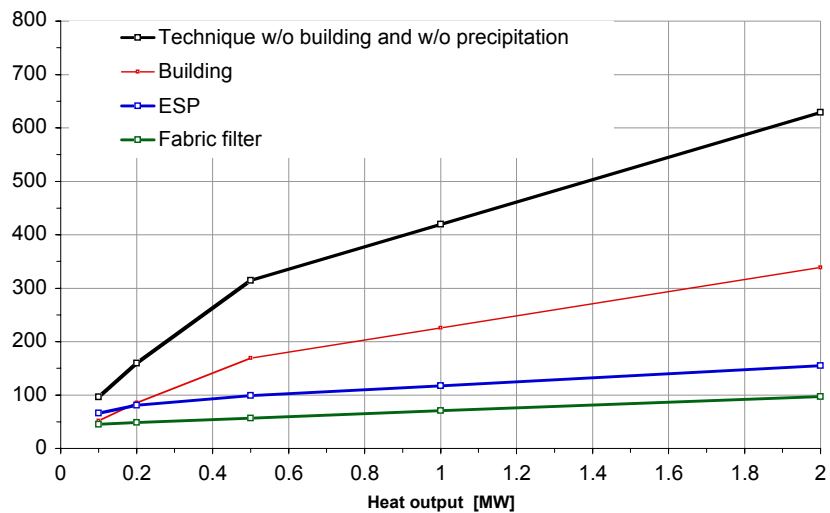


Figure 3.7 Investment cost for hardware (technique), building, ESP, and fabric filter as function of heat output.

Effect on heat production cost

Figure 3.8 and Figure 3.9 show the additional heat production cost caused by application of an ESP and a fabric filter respectively to an automatic biomass heating plant indicated in Euro Cents per kWh produced heat. Due to the relatively high investment cost and fairly low operation cost, the total cost for the ESP are mainly caused by the capital cost. The fabric filter exhibits significantly higher operation cost and lower capital cost. Consequently, the total cost for ESP and fabric filters are fairly similar with slightly lower cost for fabric filters. However, this comparison does not take into account different restrictions for the fuel and the plant operation for the two types of separators. Since fabric filters are not suited for fuels with high water content and need to meet stronger restrictions with respect to the burn out quality of the fly ash, ESP might also be economically more favourable in practice.

For an interest rate of 5% p.a. and wood fuel prices of 3 Euro Ct./kWh, the application of particle removal systems influences the total heat production cost for new plants as shown in Table 1, Figure 3.10 and Figure 3.11 as follows:

- For 2 MW, the heat cost increase by 6%,
- for 1 MW by 7% to 8%,
- for 500 kW by 9% to 12%,
- for 200 kW by 17% to 21% and
- for 100 kW by 28% to 30%.

The lower values are valid for fabric filters, while the higher values refer to ESP without considering the restrictions for fabric filter applications.

A comparison with the heat production cost from light fuel oil at 6 Euro Ct./kWh reveals that the size for equal heat cost for wood and light fuel oil is shifted from 0.7 MW to 0.9 MW. However, the comparison between wood and light fuel oil does not take into account the heat distribution cost in case of district heat or the higher specific heat production cost in case of residential heating instead of district heating and hence can be used as a qualitative comparison only.

While the absolute cost of particle removal is independent of the fuel price, the relative increase of heat production cost are strongly influenced by the fuel price. When the wood fuel price is less than 3 Euro Ct./kWh, the relative increase of heat production cost is higher, while for higher fuel prices it is lower.

Particle removal technologies for automatic biomass combustion from 100 kW to 2 MW is in principle available. However, stronger quality requirements will be needed for the plant planning and plant operation to ensure highly efficient flue gas cleaning in practice and to avoid damages of the particle removal system or increased operation cost. On/off operation should be avoided and a high burnout quality of the fly ash needs to be guaranteed. Depending on the specific applications, electrostatic precipitators or fabric filters can be favourable, since ESP exhibit higher investment cost, while fabric filters lead to higher operation cost. For applications smaller than 500 kW, nowadays particle precipitation exhibit a much stronger economy of scale than the combustion plant.

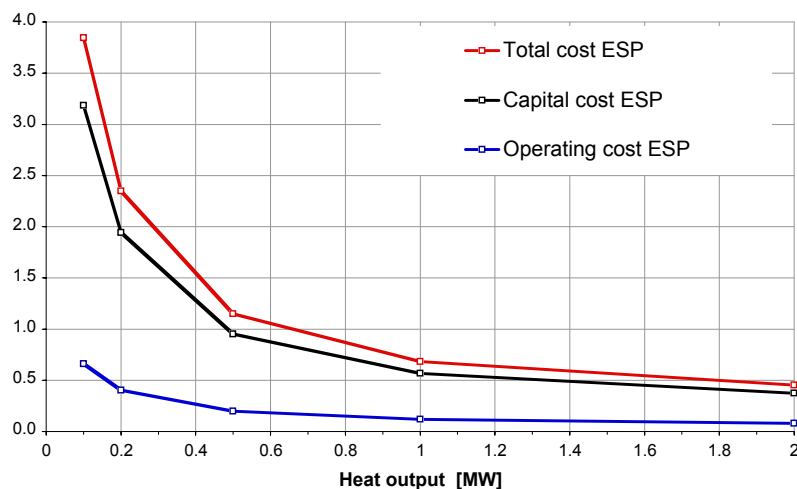


Figure 3.8 Increase of heat production cost by an ESP.

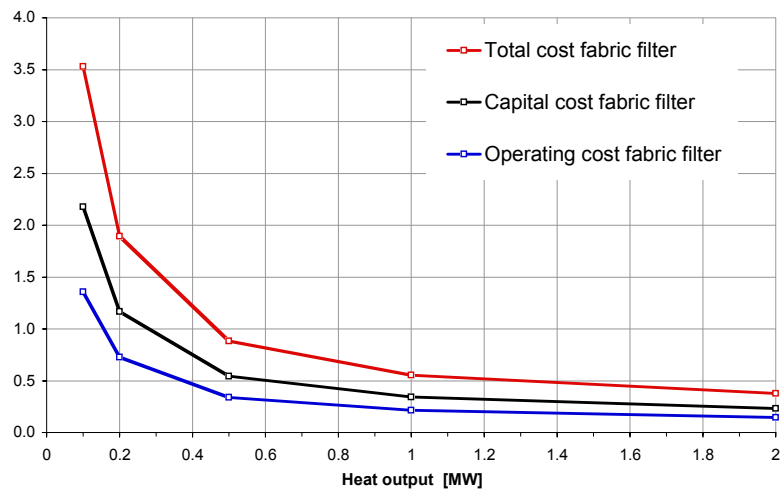


Figure 3.9 Increase of heat cost by a fabric filter.

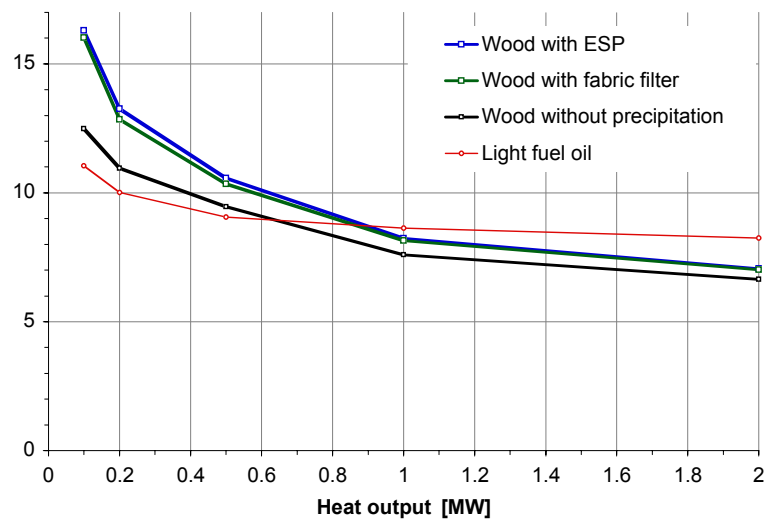


Figure 3.10 Total heat production cost for light fuel oil and for wood with and without particle removal. Fuel prices: 3 Euro Ct./kWh for wood and 6 Euro Ct./kWh für light fuel oil. Interest rate: 5% p.a.

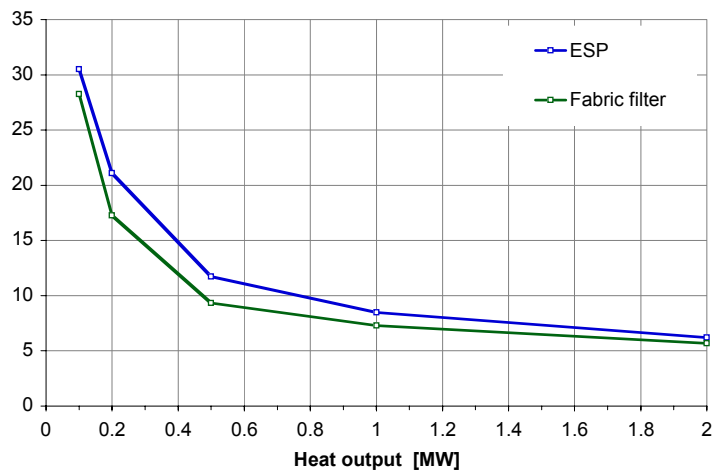


Figure 3.11 Percentage increase of the heat production cost.

3.4 Residential scale applications < 100 kW

Since residential biomass combustion has been identified as an important source to local PM emissions, there is an increasing interest in small-scale systems for particle removal from wood stoves and wood boilers. Several products have been developed or are currently being developed. Most of them are based on the ESP principle. However, due to cost reasons and size limitations, some of the small-scale ESP exhibit a simplified application principle, e.g. by utilising a metal chimney tube as collecting electrode. In addition, limited high voltage is often applied for cost reasons, and finally, the dedusting needs to be done manually by the operator or the chimney sweeper, since no mechanical dedusting is applied. The reported separation efficiency vary in a broad range from approx. 50% to more than 95%. In case of relevant separation efficiencies, i.e., safely greater than maybe 80% – 90%, small-scale ESP might become a very useful technology to reduce PM in residential areas. However, the following consequences need to be considered for a broad implementation:

- A sufficiently frequent periodic cleaning needs to be ascertained. The cleaning frequency strongly depends on the utilisation of the wood stove or boiler, indicated by the operational hours, which are usually not controlled so far. Experience is needed to define the cleaning period.
- ESP is well suited for the precipitation of particles from almost complete combustion which consist mainly of inorganic material. Soot can lead to re-entrainment of coarse particles due to its high electrical conductivity, while condensable organic compounds are related to back-corona since they lead to an electrically insulating layer [Nussbaumer & Lauber 2010].
- To avoid condensation, small-scale ESP might only be in use at reasonably high operation temperature. In such applications, the emissions during the start-up phase, which are most relevant with respect to health effects [Nussbaumer 2005 b], are not reduced.
- In addition, safety aspects need to be considered. In industrial ESP, a low carbon content of the particles need to be guaranteed to prevent fires of combustible particle layers. In case of residential combustion, the particles exhibit a high content of elemental and organic carbon. The precipitation of such particles is related to a potential fire risk. If carbon containing particles are not precipitated, the function of the ESP is limited.

Beside small-scale ESP, wet scrubbers are also proposed for residential wood boilers. It is assumed, that the separation efficiency is rather limited, however, there are only few data available.

The following figures show some examples of recently introduced small-scale ESP.

Figure 3.12 shows an ESP which can be added to a boiler as additional equipment similar to industrial ESP. Although manual cleaning is needed, a separate ash box is available for this purpose. However, the cost are relatively high for residential applications and additional space is needed.

Figure 3.13 shows an ESP which acts as an insert into a metal chimney tube. Hence the chimney tube acts as precipitation electrode, which needs to be manually cleaned by the chimney sweeper.

Figure 3.14 and Figure 3.15 show two systems which can be added on top of the chimney, thus enabling retrofitting to any existing residential heating device.

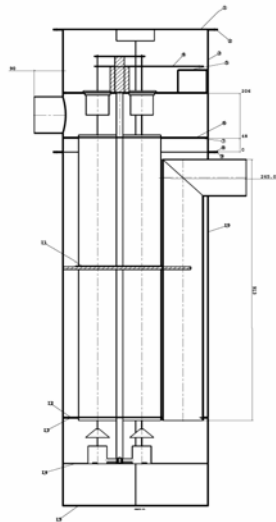


Figure 3.12 Small scale ESP (Spanner GmbH, GER).

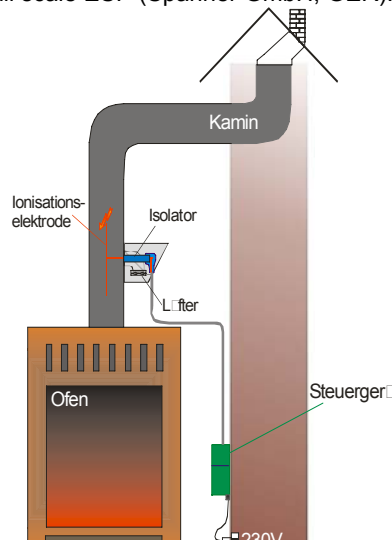


Figure 3.13 Small scale ESP (Rüegg, SWI).



Figure 3.14 Small scale ESP (APP, NOR).

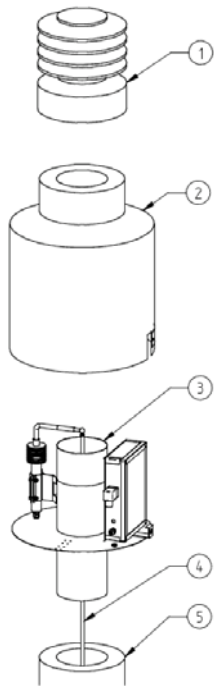


Figure 3.15 Small scale ESP (Oekotub, SWI).

4 Particulate Matter (PM)

4.1 Characteristics of particulate matter (PM)

Particulate matter describes the sum of airborne solid particles and droplets. Particle size is an important parameter for the characterization of particulate matter. According to different size ranges, coarse particles $> 10 \mu\text{m}$, fine particles ($0.1\text{--}1 \mu\text{m}$ or $0.1\text{--}2.5 \mu\text{m}$) and ultrafine particles $< 0.1 \mu\text{m}$ are distinguished. PM_{10} defines particles as having an aerodynamic diameter $< 10 \mu\text{m}$. This includes both coarse and fine particles. The size and density affects the retention period and travel distances in the atmosphere. Coarse particles tend to settle to the ground within hours, while fine particles can remain in the atmosphere for several weeks. Furthermore, limit values for both particle emissions and ambient PM standards are indicated as mass concentrations. This does not account for the large surface area of fine particles, which can act as a potential carrier for toxic substances. Beside mass concentrations, additional parameters are relevant for the potential impact of particles on environment and human health. In particular, the particle size, the particle shape, the morphology, and the chemical composition are important parameters that need to be considered. For typical conditions, approximately 90% of PM consists of fine and ultrafine particles [UBA 2005]. Since PM indicates only mass concentrations, there are considerations for further parameters such as particle number and toxicity, which might be considered for future limit values.

Particulate matter in the ambient air is a mixture of directly emitted primary aerosols and secondary aerosols formed in the atmosphere. PM is partially of natural origin, while anthropogenic emissions lead to additional PM in the ambient air. Coarse particles from primary aerosols originate mainly from mechanical processes (construction activities, road dust, re-suspension, and wind), whereas fine particles are particularly produced through combustion [WHO 2006]. Main sources of primary particulate matter are Diesel engines and biomass combustion. Secondary aerosols are formed in the atmosphere through conversion of gaseous precursors such as sulphur oxides (SO_2 , SO_3), nitrogen oxides (NO , NO_2), ammonia (NH_3), and Non-Methane Volatile Organic Compounds (NMVOC). Reaction products are ammonium sulphates and ammonium nitrate. Aldehydes and ketones are oxidation products of NMVOC. The greatest producer of secondary aerosols are combustion processes (thermal power stations, industry, domestic heating: SO_2 , SO_3 and NO_x), agriculture (NH_3), Diesel engines (NO_x and SO_2), use of solvents, chemical industry and petro chemistry (NMVOC) [UBA 2005]. Beside secondary aerosols that originate from NO_x and SO_x , secondary organic aerosols (SOA) can also contribute significantly to PM in the ambient air. Among other sources, incomplete combustion of wood is a potential source of SOA.

PM in the ambient air can be influenced by the following secondary reactions:

1. High molecular organic compounds (organic condensables, such as tar components) can be available in the vapour phase at flue gas temperature in the stack but can subsequently form additional particles or droplets by nucleation and condensation. This leads to an increase in particle number and mass or an increase in the particle mass concentration by adsorption on existing particles in the stack or in the ambient air.

2. Low molecular organic compounds (VOC) can form SOA by photochemical oxidation in the atmosphere and/or can increase the particle mass by adsorption on existing particles. Due to the added mass of oxygen, the total particle mass is additionally increasing.
3. PM in the ambient air can be reduced by evaporation of particles and droplets and by desorption of semi-volatile compounds adsorbed on the particles due to dilution in the ambient air, thus resulting in a reduced partial pressure of the respective compounds in the surrounding atmosphere.

Consequently, organic PM from residential wood heating in the ambient air can be underestimated if only solid particles detected on hot filters in the stack at 160°C (as by VDI norms) are taken into account. Investigations from diesel and wood combustion show a distinctive increase in PM concentration by dilution with ambient air at low dilution ratios. For wood stoves, an increase of 2.5 to 9 was found in a dilution tunnel (Figure 4.24) [Rhyde & Johansson 2007] where dilution ratios up to 10 are commonly applied. Investigations from diesel exhaust also show a significant initial increase of detected particles by dilution with ambient air with a dilution ratio of 20 (Figure 4.1) [Lipsky & Robinson 2006, Robinson 2007].

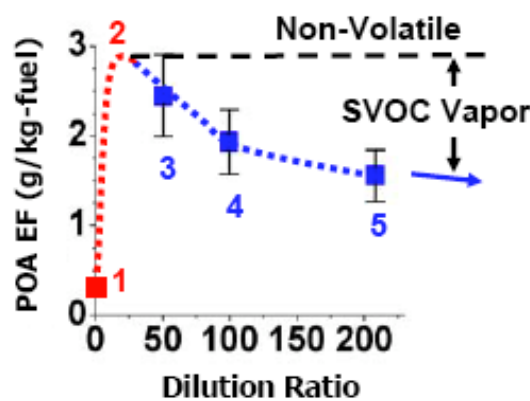


Figure 4.1 Primary organic aerosol (POA) in diesel exhaust as function of dilution ratio [Robinson 2007].
 1: Measurement in undiluted exhaust (tail pipe).
 2: Measurement with dilution with cold air at dilution ratio = 20.
 3, 4, 5: Measurement with further increased dilution.

Cooling with subsequent condensation and adsorption is essential in the first dilution step and leads to a significant increase in particle mass. while The further dilution of the flue gas, evaporation, and desorption of volatile and semi-volatile compounds due to a reduction of the partial pressure in the surrounding gas phase becomes relevant. This leads to a reduction of the particle mass. Consequently, the partitioning of semivolatile organics is a crucial factor with respect to the conversion of stack emissions from wood combustion or from diesel engines to the ambient air. Figure 4.2 illustrates the conversion mechanisms from emissions in the stack to ambient conditions by an initial rapid dilution and consecutive secondary reactions. This leads to additional secondary organic aerosols. The graph describes a fictitious example. However, the illustrated increase of detected solid particles in the hot flue gas to the particle mass sampled at a dilution ratio of approximately 10, corresponding to typical conditions in a dilution tunnel, is assumed to be 3.3 in the given example, which is in the range of results reported from wood stoves. The example describes a resulting PM₁₀ concentration in

the ambient, which is 2.8 times the mass of primary solid particles detected in the stack (i.e. in undiluted flue gas at a flue gas temperature of 160°C). The difference is due to secondary organic aerosols that result from organic compounds available as condensables at ambient conditions and additional particle mass resulting from secondary oxidation of volatile and semivolatile compounds. The sum of PM₁₀ and VOC can exceed the mass of particles and condensables detected in the stack or immediately after an initial dilution, which is due to the added mass of oxygen available by secondary oxidation. To illustrate the potential effect of added oxygen, Figure 4.3 shows a fictitious example, where the resulting mass of PM₁₀ exceeds the mass of solid particles and condensables in the stack.

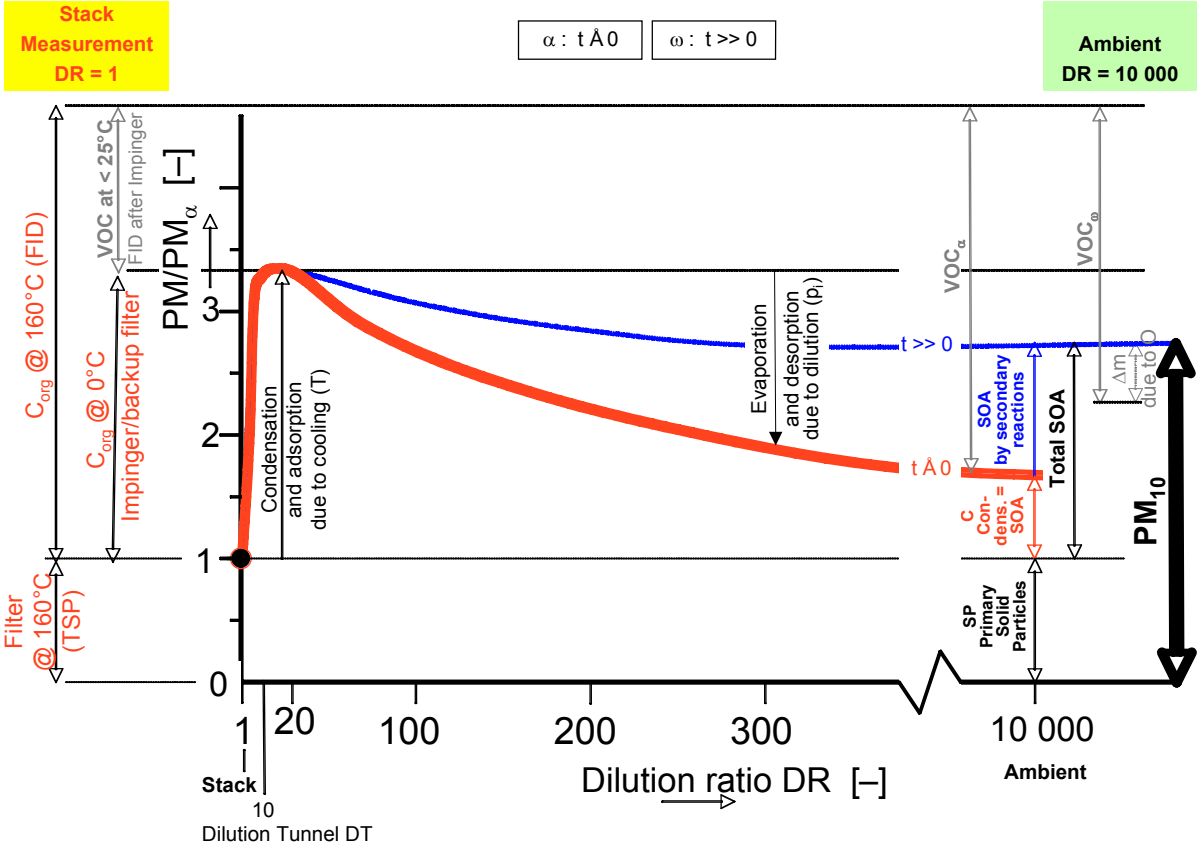


Figure 4.2 Conversion of stack emissions to PM₁₀ in the ambient. The graph shows a virtual example with total SOA = 1.8 TSP as measured in the stack and consequently PM₁₀ = 2.8 TSP.

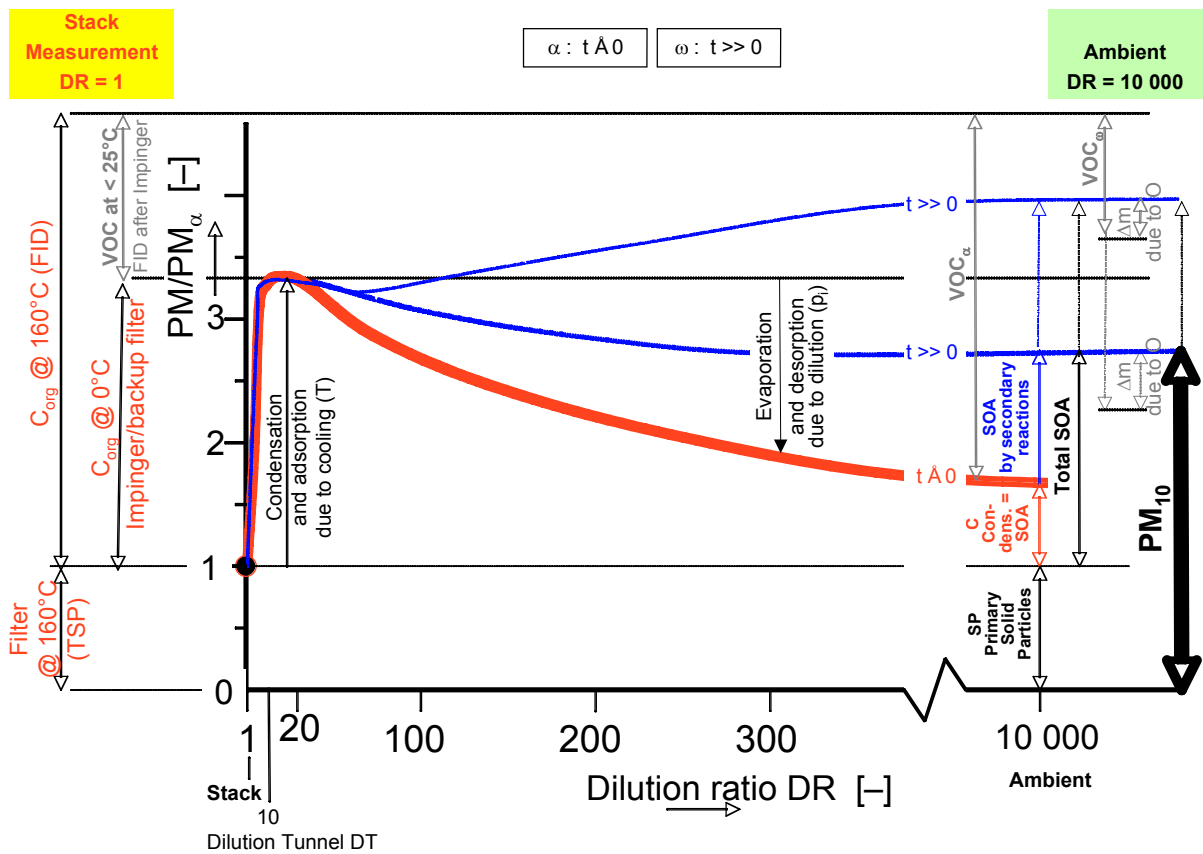


Figure 4.3 Conversion of stack emissions of PM and organics to PM_{10} in the ambient. The graph shows a virtual example with total SOA = 2.8 TSP as measured in the stack and consequently PM_{10} = 3.8 TSP. Here, the mass of PM_{10} in the ambient exceeds the total mass of solid particles and condensables as sampled in the stack due to the additional mass of oxygen added by secondary oxidation.

4.2 Partitioning and measurement of particulate matter

4.2.1 Partitioning of carbon from biomass combustion

The conversion of carbon during combustion and its final partitioning in the atmosphere is crucial with respect to the net contribution of biomass combustion to health effects and to climate change. Figure 4.4 shows the conversion of carbon during combustion and consecutive partitioning of VOC. The carbon conversion is strongly influenced by the combustion conditions. Local lack of oxygen at high temperatures enforces the formation of PAH and finally soot, while at lower temperatures, the release of hydrogen from the initial organic compounds is suppressed resulting in COC in the air emissions.

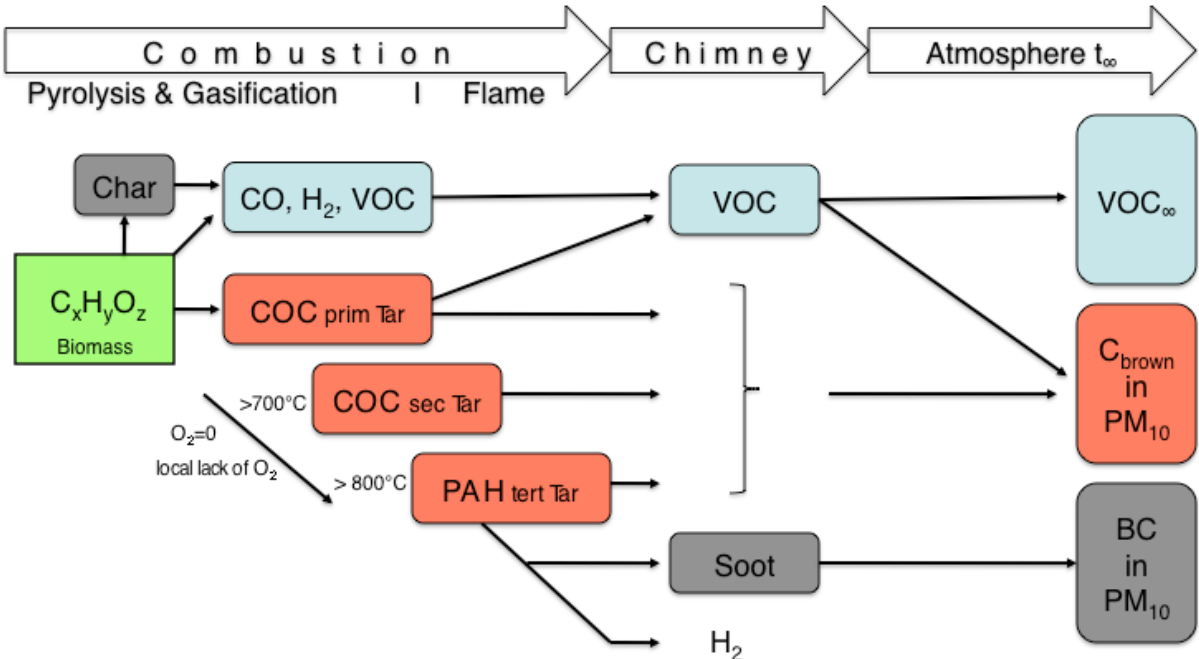


Figure 4.4 Conversion of carbon during combustion and consecutive partitioning of VOC.

Figure 4.5 shows the partitioning of VOC in the chimney and the atmosphere to remaining VOC and secondary organic aerosols resulting in brown carbon. Beside VOC, COC contribute to brown carbon as primary organic aerosols, while soot from the combustion is found as Black Carbon in the atmosphere. The partitioning of VOC to methane and NMVOC is described by an initial partitioning factor. Preliminary investigations performed in residential wood stoves and boilers revealed a typical methane factor of 30%. NMVOC [Nussbaumer & Boogen 2010]. NMVOC was found to be typically partitioned into COC by roughly 34% with 66% remaining as non-condensable NMVOC (NCNMVOC) which is partly found as remaining NCNMVOC and partly converted to secondary organic aerosols. POA and SOA are assumed to form brown carbon, while Black Carbon stems from soot from the combustion.

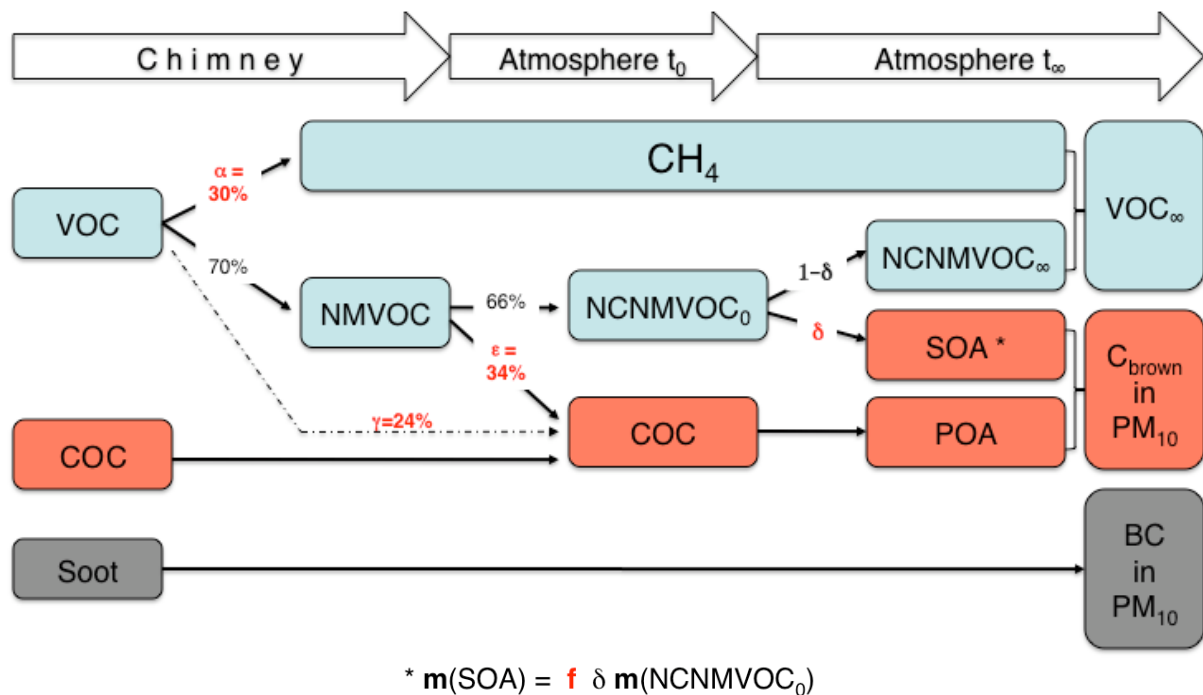


Figure 4.5 Partitioning of organic compounds from biomass combustion.

The partitioning factors α , ϵ , and γ shown in the graph are indicative values from preliminary investigations in wood stoves and boilers [Nussbaumer & Boogen 2010].

Typical conversion factors f to SOA (on mass basis) are reported by [Turpin & Lim 2001]:

- $f = 1.6 \pm 0.2$ for urban aerosol,
- $f = 2.1 \pm 0.2$ for non-urban aerosol,
- $f = 2.2 - 2.6$ (**2.4**) for wood smoke.

4.2.2 Influence of particle sampling methodology

Combustion particles are a mixture of solid particles and condensables, containing both organic and inorganic fractions. 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 such as benzo(a)pyrene (BaP) or fluorine. This 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.

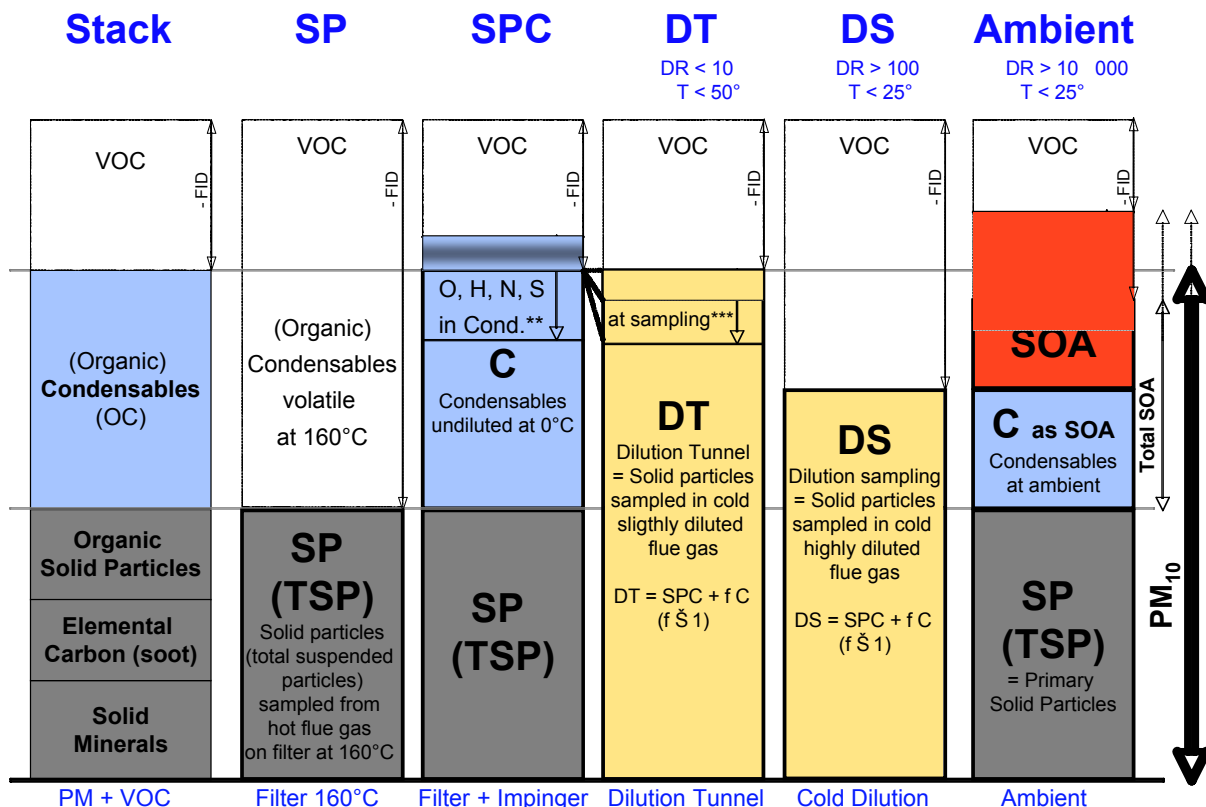


Figure 4.6 Comparison of PM sampling with PM in the ambient.
SP: Filter (Method a) resulting in solid particles SP (total suspended particles TSP).
SPC: Filter + Impinger (Method b) resulting in solid particles and condensables SPC.
DT: Dilution Tunnel (Method c) with typical dilution ratio (DR) in the order of 10 resulting in a PM measurement including SPC and most or all C. 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.

*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 that 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.

The emission of inorganic particles can be slightly influenced by the combustion conditions. However, this depends on different formation mechanisms than organic particles. High temperature enhances the conversion of ash material to the gas phase and consequently, the emission of inorganic particles. Under typical conditions, organic particles are 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 for product testing and health studies. In the present survey, four types of particle sampling are distinguished, as illustrated in Figure 4.6:

- A Sampling of particles on a heated filter, through a probe, from undiluted flue gas in the chimney at gas temperatures of 160°C (German norms by Verein Deutscher Ingenieure, VDI 2066) or 120°C (US EPA method 5H). These particles are defined as **solid particles (SP)** in the study and consist of filterable particles and droplets at the indicated temperature. If not otherwise indicated, 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 constituted a large part of K_2SO_4 and KCl (depending on the fuel composition) at favorable combustion conditions, while soot (elemental carbon, EC) and organic particles are also emitted as solid particles if the combustion conditions are poor.

- B Sampling of particles as described in method A, and subsequent sampling of **condensable organic matter (C)** in impinger traps at temperatures less than 20°C. Typically condensable particulate emissions are sampled in a series of impinger flasks 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 SO_2 . In the case of a considerable 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, the inorganic PM is sampled in the filter, while condensable inorganic matter in the impinger bottles is assumed to be negligible.
- C Sampling of filterable particles in a dilution tunnel with a filter holder gas temperature less than 35°C (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 insignificant for residential combustion of wood. 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) (typically DR has a magnitude of 10). For a comparison and interpretation of results from dilution tunnel measurements it needs to be considered that the dilution ratio may vary during one 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 volatile compounds.
- D Dilution can also be performed at high dilution ratios (100 or more), which is defined as **dilution sampling (DS)** in the present study. To mimic conditions in the ambient air, sampling can be

performed in cold, highly diluted flue gas. Dilution with cold air at high dilution ratios is applied by analyzing 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 particle number concentrations, a hot dilution stage followed by a cold dilution stage is usually applied resulting in a total dilution ratio of 100. The hot dilution avoids condensation and allows 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 particle mass.

For residential combustion devices, all methods can be applied, while for large combustion devices, sampling in a dilution tunnel is not applicable.

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 the health impact as well.

Measurements in dilution tunnel by method C may over-estimate the particle mass in the ambient air, since evaporation by subsequent dilution in the ambient air 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.

4.2.3 Conclusions on partitioning and measurement methods

PM from biomass combustion in the ambient air results from the following sources:

1. Solid particles emitted as primary aerosols and sampled on hot filters in the chimney (e.g. at 160° acc. to VDI 2066 or at 120°C acc. to EPA method 5H).
2. Condensable organic compounds contained as primary aerosols in the flue gas. COC are dominantly in the vapour phase in the hot flue gas and hence not contained in the solid particles sampled on hot filters. However, COC can be sampled separately by flue gas quenching in impinger bottles at < 20° or < 5°C or together with primary solid particles on cold filters by dilution of the flue gas with cold air in a dilution tunnel.
3. Secondary organic aerosols are formed in the atmosphere from VOC present as precursors in the flue gas. On the other hand, COC identified as primary aerosols in cooled flue gas by quenching or dilution can partially re-evaporate during further dilution in the ambient air thus resulting in VOC and consequently reduction the PM in the ambient.

Consequently, the sampling and measurement method need to be considered for the comparison of emission factors and for the estimation of the resulting PM in the ambient air from different sources. This is specifically important in case of residential biomass combustion or open burning with high concentrations of products from incomplete combustion, while in case of near-complete combustion as in automatic boilers, COC and VOC are on a low level. For residential applications, data from different measurement methods cannot be directly compared thus leading to the following recommendations for future measurements:

1. Measurements of solid particles only do not enable a reliable assessment of the final PM contribution to the atmosphere, since they do not consider COC and SOA. Consequently, parallel measurement of solid particles on hot filters *and* VOC in the hot flue gas is regarded as a valuable option to capture all relevant air emissions, since VOC are a precursor for COC, SOA, and resulting VOC in the ambient.
2. As an option, quenching in impinger bottles can be applied (e.g. by US EPA method 5H or CEN TS 15439) if COC shall be identified separately. This method provides an additional distinction between combustion devices with low condensables and products where the condensable fraction is higher than the solid fraction. However, separate measurement of COC is related to significant additional expenditures and not necessary in case of low VOC emissions.
3. Measurement of solid particles in diluted, cold flue gas is applied as an option to capture primary aerosols in sum, i.e., primary solid particles and COC. However, gravimetric analysis of the particulate matter trapped on the cold filter does not enable a discrimination between primary solid particles and COC. In addition, the sampling in the dilution tunnel does not replace the additional measurement of VOC needed to estimate the potential of SOA and final VOC in the atmosphere.

4.3 PM emission factors

4.3.1 Data basis

Emission factors on particulate matter from biomass combustion have been collected recently in an overview performed on behalf of the International Energy Agency (IEA), Bioenergy Task 32 [Nussbaumer et al. 2007]. A total of 17 institutions from seven IEA countries, i.e., Austria, Denmark, Germany, Norway, The Netherlands, Sweden, and Switzerland, participated in the survey. In addition, data for national emission factors were collected from literature. For the emission inventory, a range was requested for best results at ideal operation, typical results as expected in real-life operation and worst results at very bad handling. To enable a comparison of different data, the sampling and measurement techniques was documented. Hence solid particles collected on filters in the hot flue gas, condensables collected by quenching in impingers, and particles collected in a dilution tunnel are distinguished. The detailed information and a full literature list is given in [Nussbaumer et al. 2007], which is the basis for chapter 4.3 in the present report.

4.3.2 Open fireplaces

Figure 4.7 shows the PM emission factors for open fireplaces found in [Nussbaumer et al. 2007]. 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). While open fireplaces are of minor importance in countries with relevant heat demand, they are assumed to be most relevant in countries with warmer climate such as e.g. Italy. However, in the cited IEA study, only data from countries north of Italy were participating and hence more detailed data was collected for wood stoves and boilers.

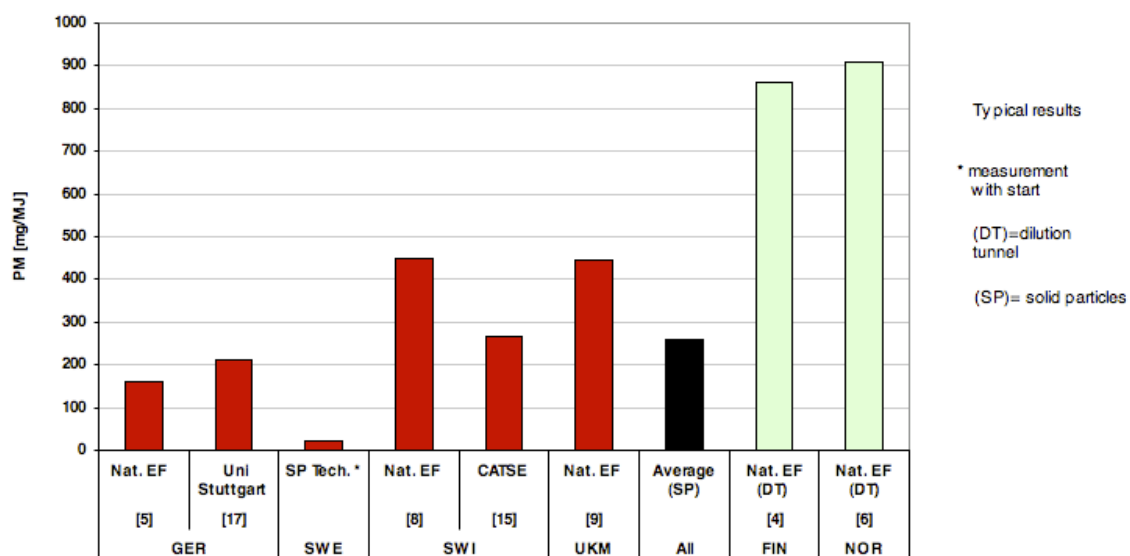


Figure 4.7 Emission factors for PM in mg/MJ for solid particles (red) and for particles measured in dilution tunnel (green) [Nussbaumer et al. 2007].

4.3.3 Closed inset appliances (closed fireplaces)

For closed inset appliances (closed fireplaces according to EN 13229:2001), only few data were available from the countries participating in the IEA study [Nussbaumer et al. 2007]. 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. However, due to the limited data basis, these values are regarded as indicative values only and they do not reflect the range expected from good operation to very bad operation as presented for other categories such as wood stoves in the survey.

4.3.4 Wood stoves

Within the survey, most data was delivered for the category of wood stoves, so 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, which range from 340 to 544 mg/MJ.

National emission factors are the basis 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 order of magnitude. The emission factor for solid particles ranges 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. Factors vary from 750 mg/MJ (Finland) to 1932 mg/MJ (Norway).

The Finnish value is a revised number, which will apply soon, while currently the old value of 400 mg/MJ is still in use. The Norwegian emission estimate is based on an aggregated emission factor for traditional/conventional stoves, new stoves, and open fireplaces [Nordic Council of Ministers 2004]. An explanation of the high Norwegian emission data is that the Norwegian standard for wood stoves includes measurements at low thermal output with throttled air supply. Thus, the data should represent real use of wood stoves in Norway.

Figure 4.8 shows the emission factors for wood stoves with an indication of ranges from best, typical to worst type of operation or combustion type. Figure 4.9 summarizes the same data with indication of the typical data only.

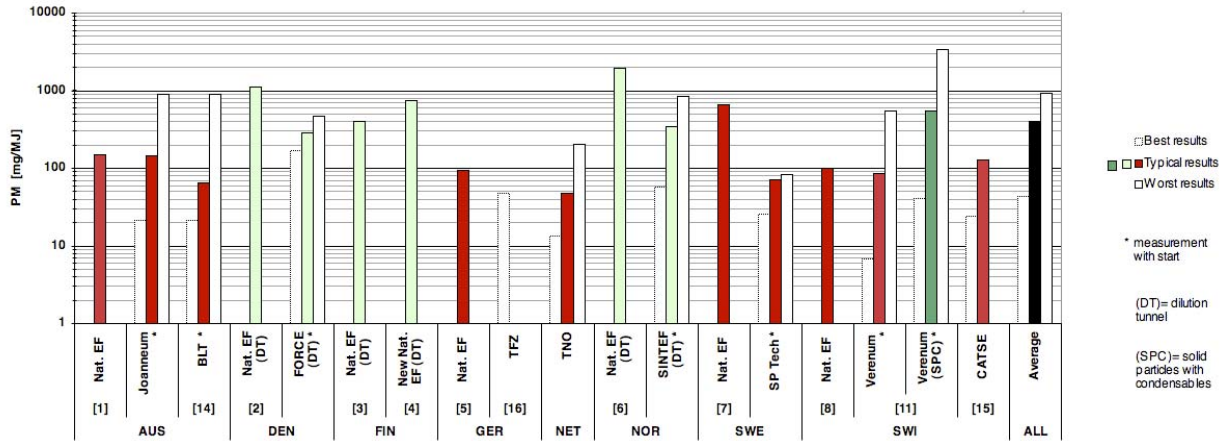


Figure 4.8 Range of emission factors from worst to best (where available) for wood stoves depending of type of operation and/or equipment [Nussbaumer et al. 2007].

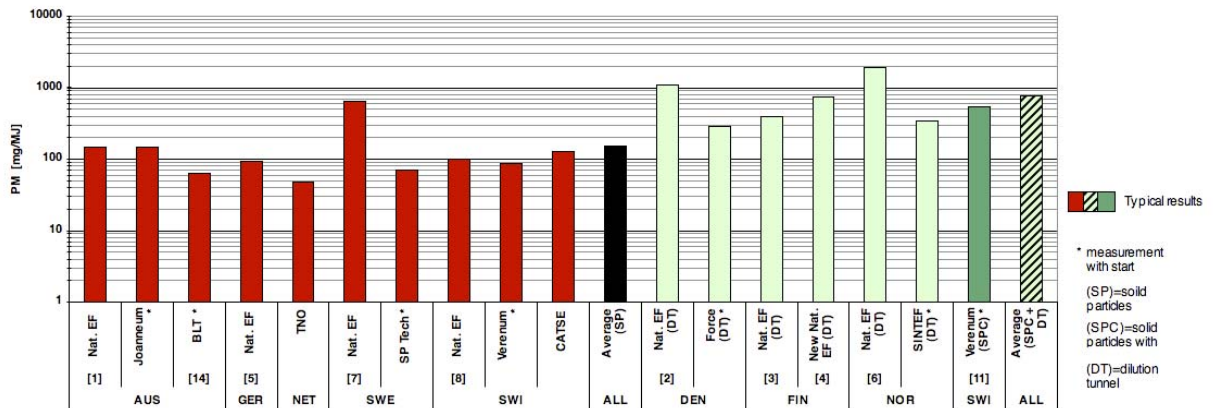


Figure 4.9 Average emission factors for wood stoves [Nussbaumer et al. 2007].

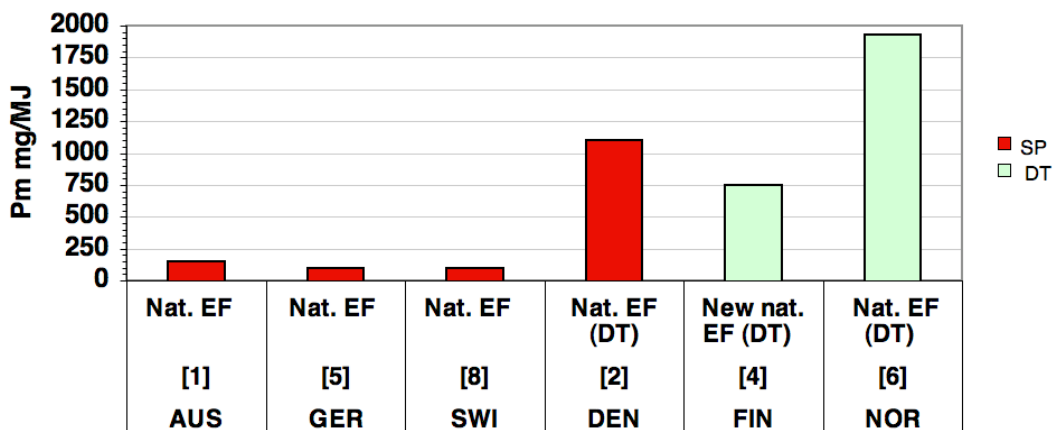


Figure 4.10 National emission factors for wood stoves [Nussbaumer et al. 2007].

4.3.5 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 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 the heat exchanger in the boiler section [Nussbaumer 2003]. Such boilers are usually designed by the downdraft principle and most commonly operated with forced draft, 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 4.11 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 4.12 shows emission data from log wood boilers with forced draft. Under typical operation conditions, boilers with downdraft principle allow significantly lower emissions than updraft boilers.

In addition to the combustion principle, the hydraulic implementation of the boiler in the heating system, and the application and management of a heat storage tank can significantly influence the emissions in practical operation. Figure 4.13 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 allows 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 tanks may be used with throttled air inlet, thus leading to excessively high emissions of uncombusted carbon and particles.

Figure 4.14 shows an overview of data from log wood boilers. No information about the combustion principle was available.

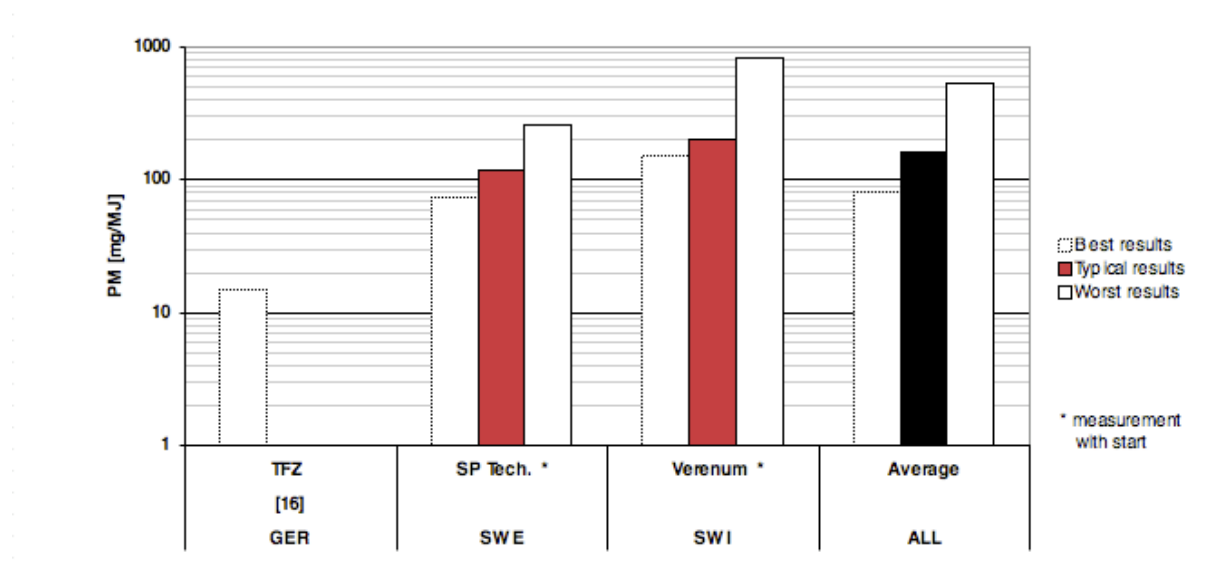


Figure 4.11 Range of emission factors from worst to best (where available) for log wood boilers with updraft combustion without ventilator [Nussbaumer et al. 2007].

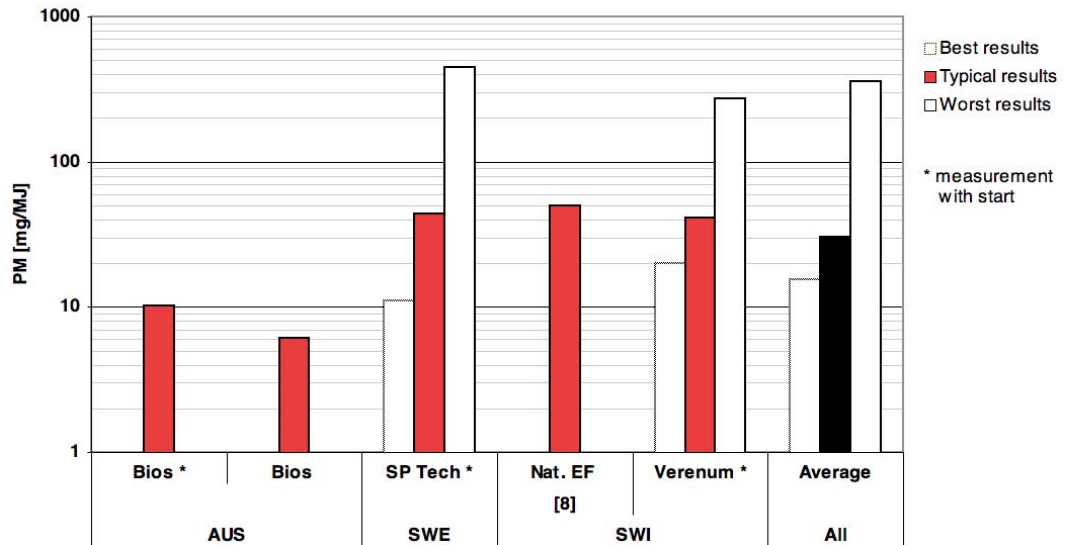


Figure 4.12 Range of emission factors from worst to best (where available) for log wood boilers with forced downdraft combustion [Nussbaumer et al. 2007].

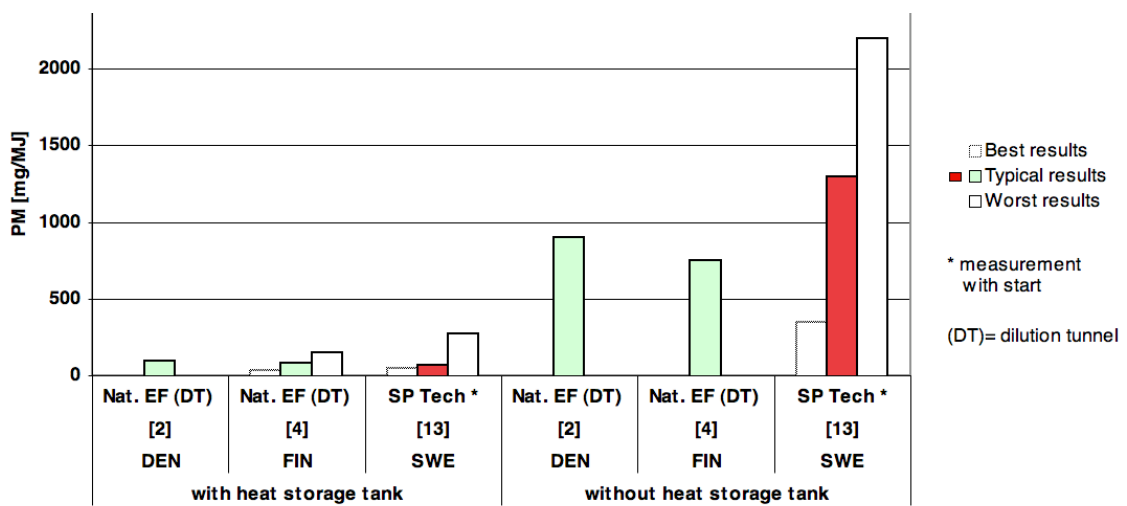


Figure 4.13 Emission factors for log wood boilers with and without heat storage tank [Nussbaumer et al. 2007].

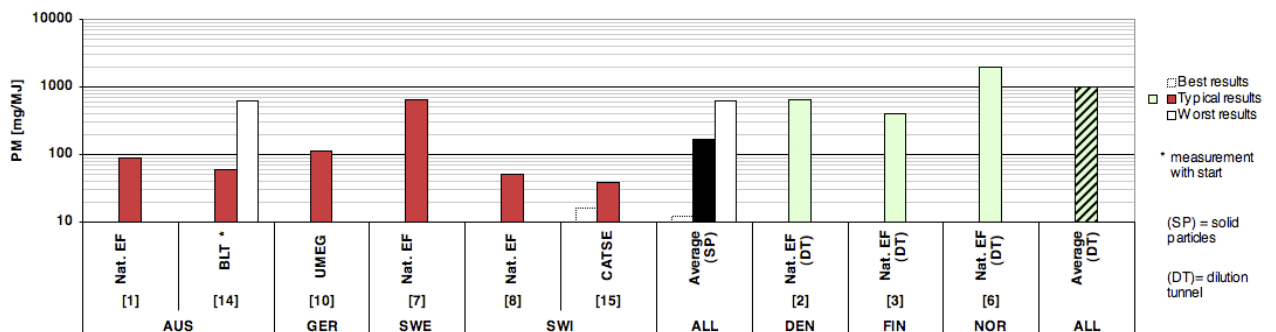


Figure 4.14 Emission factors for log wood boilers, where combustion type is not specified [Nussbaumer et al. 2007].

4.3.6 Pellet stoves and boilers

Figure 4.15 and Figure 4.16 show the emission factors of pellet stoves and pellet boilers, respectively. For both 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 are comparable to the best results achieved by log wood combustion. If the 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 a magnitude lower, which is regarded as the main advantage of pellet combustion. However, many investigations have shown that the use of biomass other than wood, with low amounts of bark for pellet combustion, in residential heating appliances results in significantly increased emissions of particulate matter (typically by a factor of more than 3), as well as in emission of NO_x. The reported data are valid for wood pellets with low ash content only.

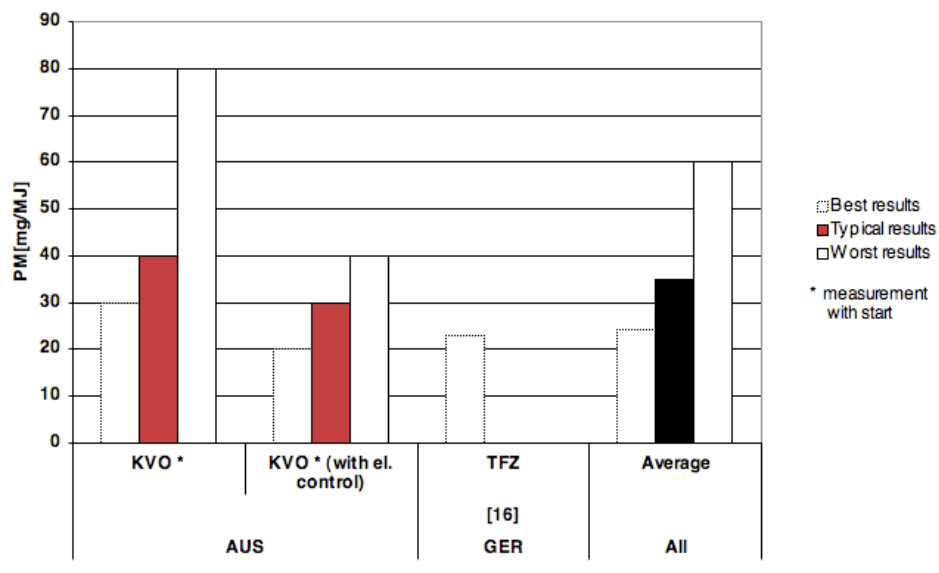


Figure 4.15 Range of emission factors from worst to best (where available) for pellet stoves with natural draft [Nussbaumer et al. 2007].

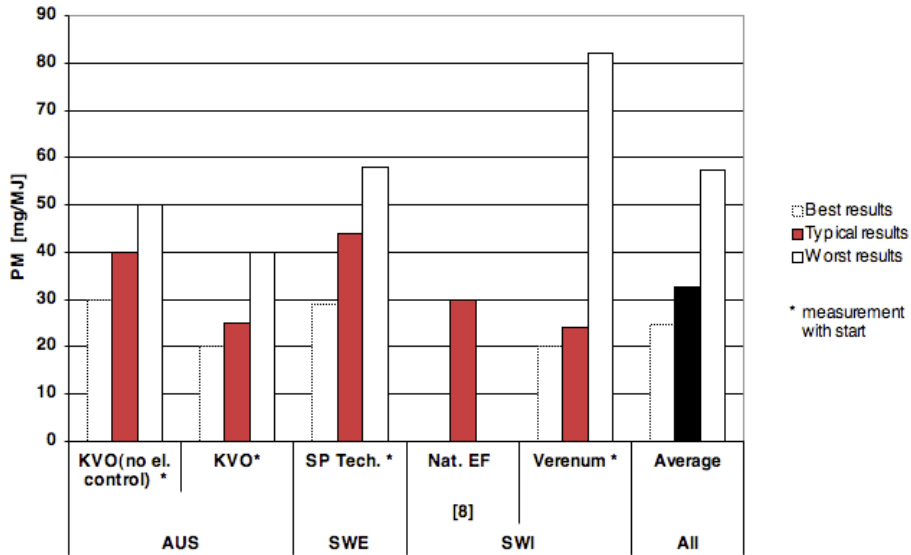


Figure 4.16 Range of emission factors from worst to best (where available) for pellet stoves with forced draft and electronic combustion control [Nussbaumer et al. 2007].

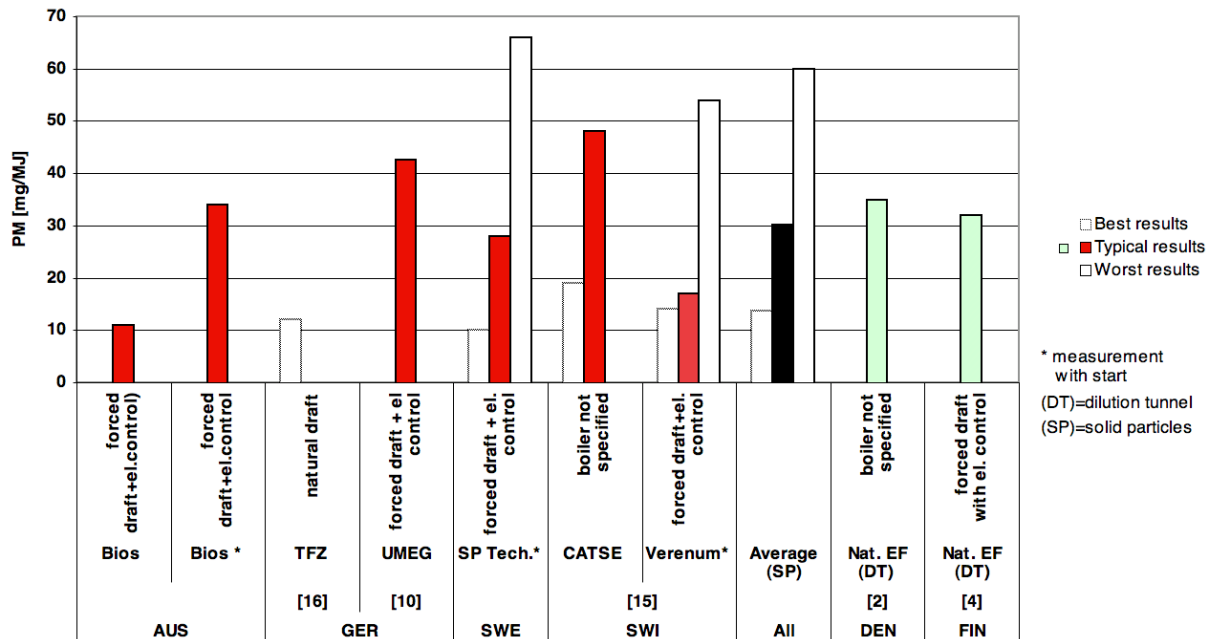


Figure 4.17 Range of emission factors from worst to best (where available) for pellet boilers [Nussbaumer et al. 2007].

4.3.7 Overview on residential wood combustion

Figure 4.18 gives a summary of the average emission factors for pellet combustion, log wood boilers, and wood stoves.

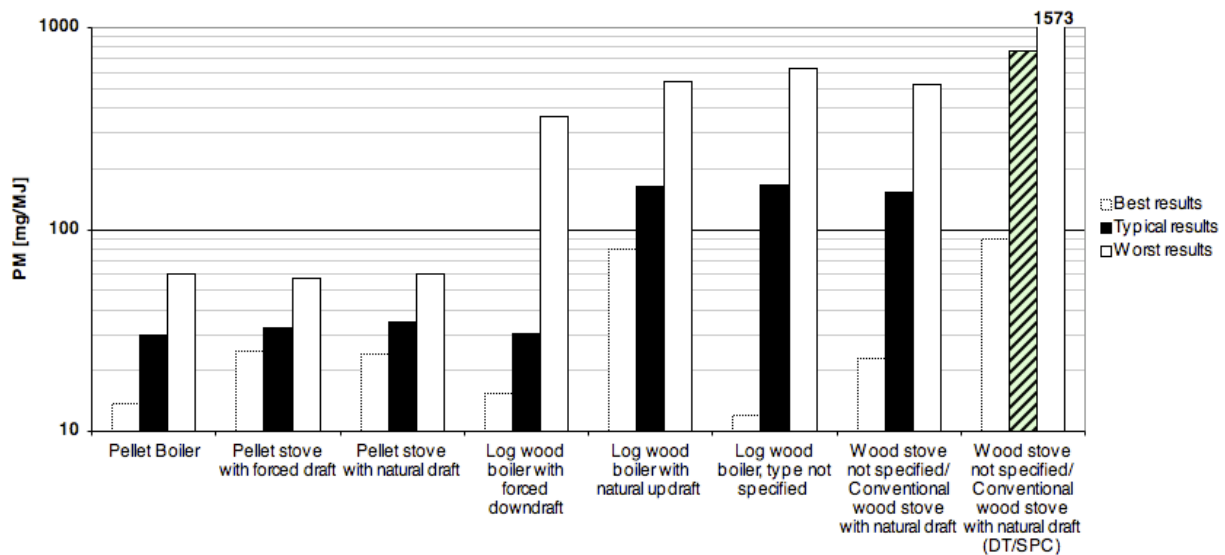


Figure 4.18 Average emission factors (best, typical, worst) for pellet boilers, pellet stoves, log wood boilers, and wood stoves. All data indicated as solid particles SP except for wood stoves, where data including condensables (SPC) or measured in dilution tunnel are given in the last column [Nussbaumer et al. 2007].

- 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 that 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. This is 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 only, while significantly higher emissions are found for other fuels such as bark, straw pellets, wet log wood and other inappropriate fuels.
- Under poor operation conditions, an increase of roughly a factor of 2 is expected for pellet combustion, although this value is uncertain due to limited investigations and might be underestimated. For downdraft boilers, an increase by a factor of 10 is expected under poor operation conditions. The main advantage of pellet combustion is that very poor operation is assumed to be very rare because of the homogeneous fuel and the continuous fuel feeding. Especially for log wood combustion, the effect of the start-up may significantly increase the average emissions. However, information on this issue is scarce and 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 small batches of small and dry logs, which leads to a constant and low heat output by continuous manual feeding in short periods and assumes an optimized 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 for solid particles.

- Similar values are expected for old-type wood boilers with natural updraft combustion. 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 a heat storage tank is usually needed to avoid 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. A comparison of these data with measurements of solid particles reveals significantly higher average emission factors. Since the data shown in Figure 4.18 are derived from different investigations and different combustion devices, they do not allow a direct comparison between the different measurement methods. However, the significantly higher (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 highly volatile organic condensables found during poor combustion conditions. The influence of the sampling method is discussed separately, since the data in Figure 4.18 do not allow a direct comparison of the sampling types.

4.3.8 Automatic biomass combustion plants

Figure 4.19 and Figure 4.20 show the reported emission factors for automatic combustion plants from 70 kW to 500 kW for under stoker and grate boilers, respectively. Average emission factors of this category range from 50 – 100 mg/MJ, which is in line with the typical emission limit values valid today (e.g. 150 mg/m³ at 11 or 13 Vol.-% O₂).

However, an investigation of field measurements in Switzerland for a large number of installations revealed a relatively broad range of emissions from 30 to 350 mg/MJ, which demonstrates 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, as shown in Figure 4.21 and Figure 4.22. However, emission factors of installations in this category strongly depend on the type of flue gas cleaning and on the imposed emission limit values. In combustion plants greater than 500 kW in Switzerland¹, significant changes are expected. New emission limit values in this category were introduced by 1.1.2008 which make the application of fine particle removal systems necessary and lead to a significant reduction of PM emissions.

For the comparison of different particle sources it needs to be recognized that the presented emission factors are indicated as particle mass concentrations and do not respect the health relevance of different particle types. Particles and condensables found from wood burned under very poor combustion conditions, such as 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 at good operation conditions consist mainly of salts

¹ 20 mg/m³ at 11 Vol.-% O₂ are valid for plants > 1 MW from 9.1.07 instead of formerly 150 mg/m³,
20 mg/m³ at 13 Vol.-% O₂ are introduced for plants > 500 kW in 2008 instead of formerly 150 mg/m³.

with lower toxicity and carcinogenity [Klippel & Nussbaumer 2007]. Nevertheless, also inorganic particles need to be avoided, since they exhibit an inflammatory potential [Kelz et al. 2010].

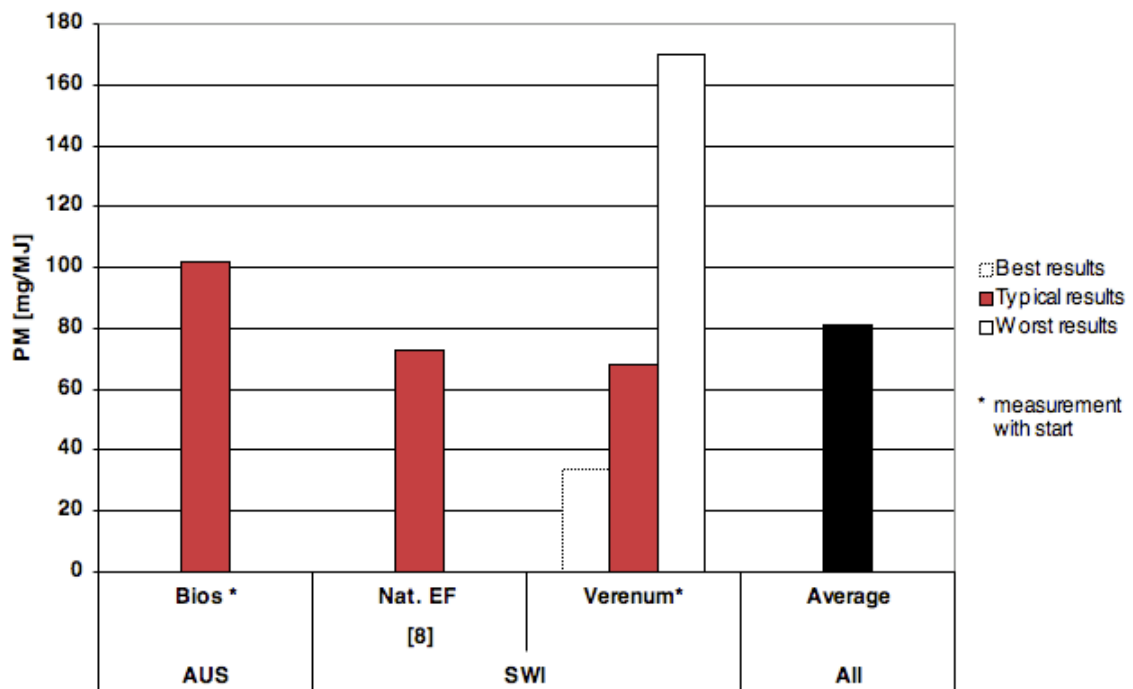


Figure 4.19 Emission factors for under stoker boilers from 70 – 500 kW [Nussbaumer et al. 2007].

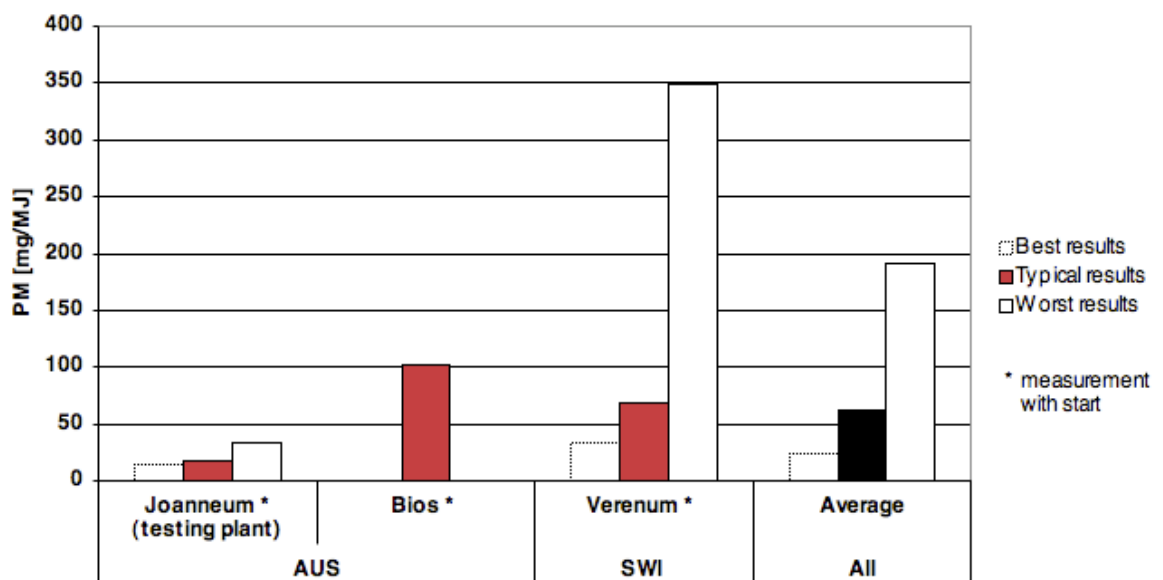


Figure 4.20 Emission factors for grate boilers from 70 – 500 kW [Nussbaumer et al. 2007].

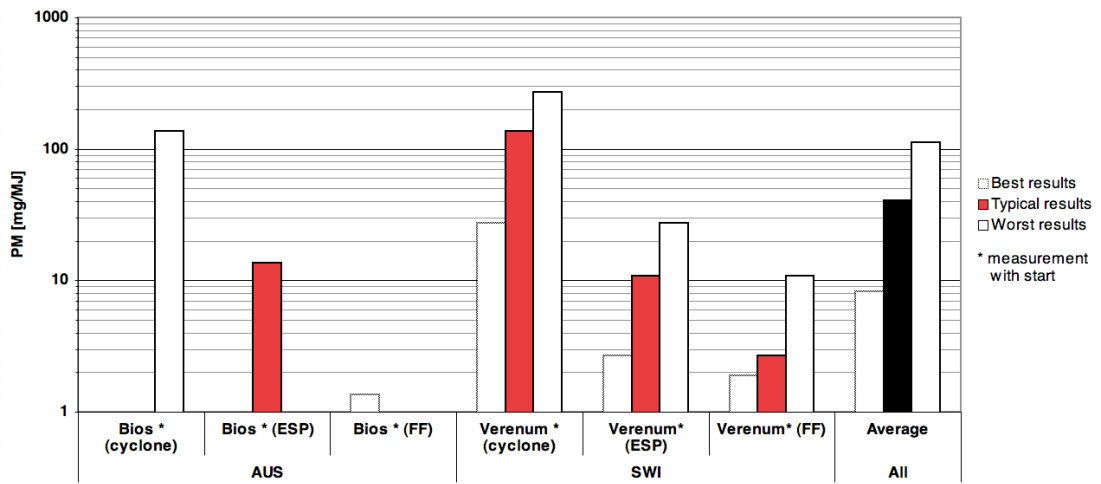


Figure 4.21 Emission factors for under stoker boilers from 500 kW – 10 MW [Nussbaumer et al. 2007].

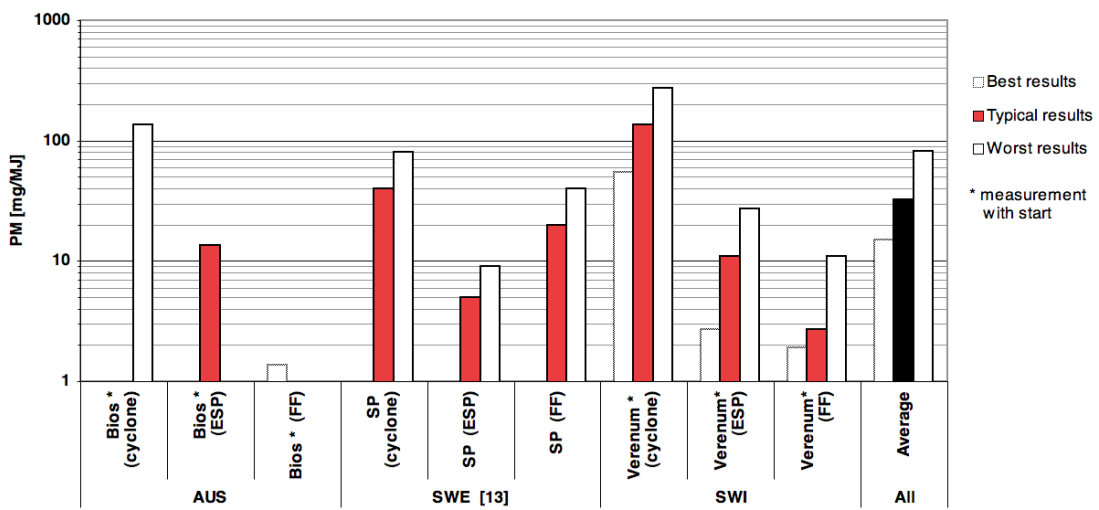


Figure 4.22 Emission factors for grate boilers from 500 kW – 10 MW [Nussbaumer et al. 2007].

4.4 Particle sampling

For the emission factors from wood stoves, a limited number of data is available from Sweden. [Ryde and Johansson, 2007] Parallel measurements were performed by sampling method A, resulting in solid particles (SP) and sampling method C, resulting in particles found on the filter in the dilution tunnel (DT), as described in chapter 4.2. In addition, data is available from measurements on wood stoves in Switzerland with separate sampling of solid particles and subsequent condensable matter, thus resulting in SP according to method A and SPC according to method B.

Figure 4.23 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.

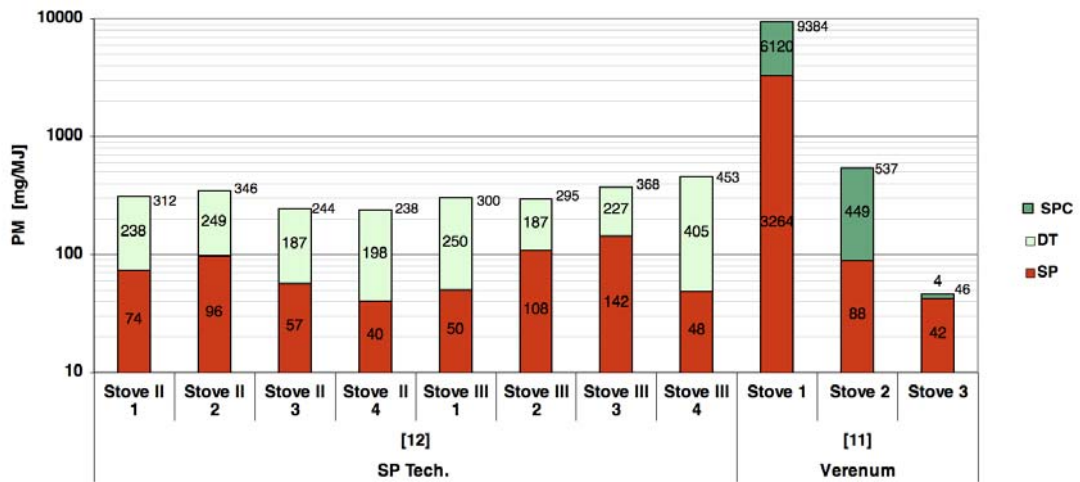


Figure 4.23 Comparison of PM emission factors on solid particles (SP), particles in dilution tunnel (DT), and solid particles plus condensables from impinger (SPC) for wood stoves [Nussbaumer et al. 2007].

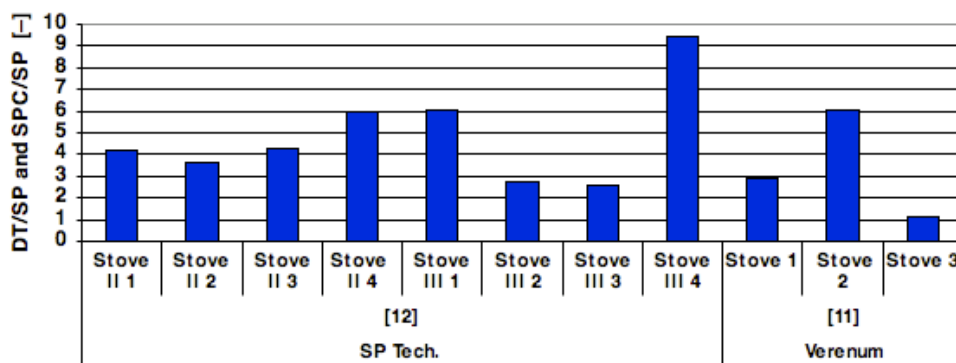


Figure 4.24 Ratio DT/SP and SPC/SP for wood stoves acc. to Figure 4.23.

Figure 4.24 illustrates the ratio of DT/SP, when measured in the dilution tunnel, and of SPC/SP when measured with condensables found in impingers. In one case (Verenum stove 3), which corresponds to a high combustion quality, resulting in low total PM emissions, the ratio SPC/SP is only slightly above one (≤ 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 three and six (Switzerland).

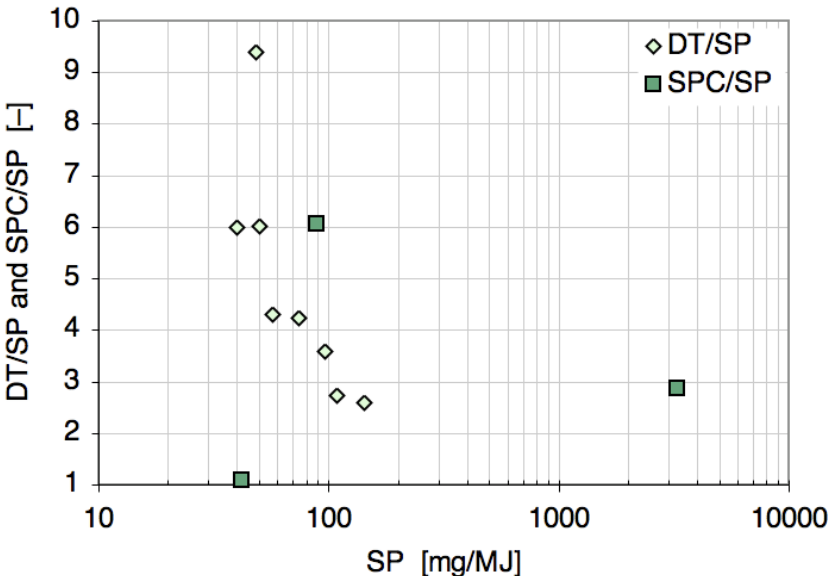


Figure 4.25 Ratio DT/SP and SPC/SP for wood stoves as function of SP.

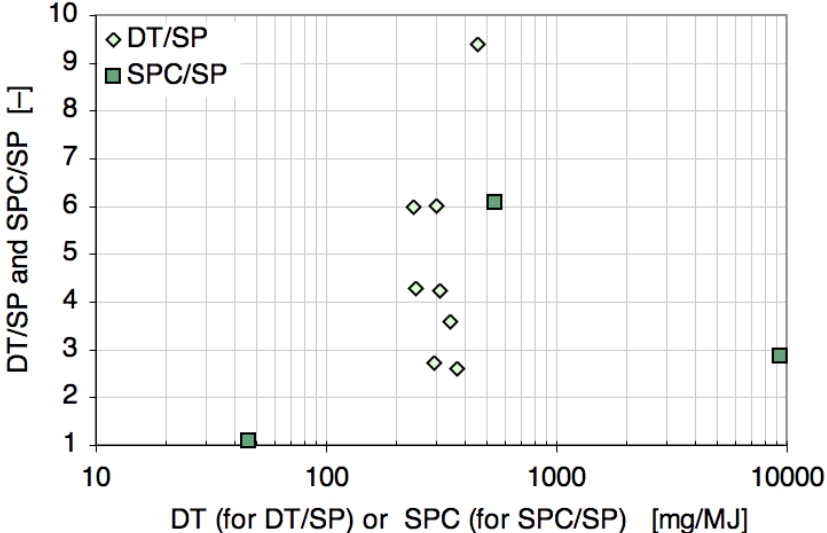


Figure 4.26 Ratio DT/SP and SPC/SP for wood stoves as function of SPC and DT, respectively.

5 Conclusions

5.1 State-of-the-art of biomass combustion in Europe

In many countries in Europe, biomass combustion is widely applied on small and medium scales. Small-scale applications are mainly for residential heating. For this purpose, manually operated stoves and boilers are commonly applied, while pellet combustion is available as an alternative with automatic feeding but does not allow the use of log wood available from forests.

For **log wood boilers**, the technical standard was significantly improved in the past 30 years thanks to the application of the two-stage combustion principle with primary and secondary air, which is injected with mechanical ventilation and followed by a hot combustion chamber. This allows improvements in efficiency and a reduction of pollutant emissions, such as CO, which is often used as an indicator for the carbon burnout, as well as VOC and also carbonaceous particulate matter, which originates from soot and organic condensables and exhibit a serious environmental impact. However, to ensure good combustion conditions in practice, operation at low load needs to be avoided. For this purpose, the application of a heat storage tank is needed. The use of log wood boilers without heat storage tanks and/or with simple combustion technology can lead to excessive pollutant formation.

For **wood stoves**, ideal operation is essential to avoid high-pollutant emissions in practice, such as ignition of the wood from the top instead of ignition from the bottom and use of small batches of small dry logs. As for boilers, throttling the combustion air to achieve low heat loads needs to be strictly avoided. Since the ideal type of operation is related to frequent adding of small logs, wood stoves are often non-ideally operated. Consequently, residential wood combustion is a relevant source of PM as found in many investigations.

In some countries, **open fireplaces and inset appliances** are widely in use. Modern inset appliances are available with combustion design similar to wood stoves thus enabling similar efficiencies and emission levels. Beside these, simple open fireplaces and simple closed fireplaces are most common today, which achieve very low heating efficiencies and do not enable an efficient energy utilisation of wood. In addition, they exhibit significantly higher PM emission than well designed and operated wood stoves and wood boilers. However, there is only a limited risk of operation at throttled air which in case of boilers or stoves can lead to excessively high emissions.

Cooking stoves for wood exhibit certain limitations with respect to combustion design and operations due to the necessity of heat extraction to the cooking plate. Consequently, cooking stoves usually exhibit higher PM emissions than well designed wood stoves and boilers. However, as for stoves and boilers, the emission level is strongly influenced by the type of operation.

To reduce PM emissions from residential wood combustion, **small-scale electrostatic precipitators** (ESP) and other particle separation technologies are under development and in the market implementation phase. These separators are often based on a design which is simplified compared to industrial applications for cost reasons. In some cases, high separation efficiencies of up to more than 90% are reported, while for other applications, moderate separation efficiencies in the order of only 50% are expected. In addition, the reduction potential in practice especially for soot and condensable organic compounds is uncertain for most applications and hence further experiences are needed.

As an alternative to manual operated devices, **pellet boilers** and **pellet stoves** are applied. Thanks to automatic feeding and small fuel size, improved combustion conditions can be achieved in practical operation. Consequently, pellet combustion instead of manual stoves or badly operated boilers allows

a reduction of PM emissions. However, pellet boilers and stoves are often operated with high excess air and frequent automatic ignition or glow bed maintenance resulting in increased emissions. Due to this, there is still a certain potential of improvement, which is, however, of lower priority than the improvements needed to reduce PM resulting from inappropriate operation of manual wood combustion devices.

For medium scale applications from 100 kW to 10 MW, **automatic boilers** for wood chips, bark and similar fuels are widely applied. Thanks to high combustion temperature, such plants exhibit usually low emissions of uncombusted gaseous and solid carbon emitted as PM, while relevant emissions of inhalable particles result from ash constituents in the fuel during such conditions emitted mainly as salts. For plants greater than 200 kW, or certainly for plants greater than a few MW, depending on national emission limits, efficient particle removal mostly by ESP and in some cases by fabric filters is commonly applied thus enabling low PM levels in the clean gas when properly operated. However, boilers for heating purposes are often operated at part-load or with periodic on/off operation. During such operation modes, the particle removal is often ineffective. Therefore system integration, boiler management, and combustion control need to be improved in future to ensure high availability of the particle separation. For applications greater than 10 MW, biomass is mostly used for steam generation in combined heat and power production plants. Thanks to nearly continuous operation and efficient flue gas cleaning, PM emissions from such applications are usually on a low level.

5.2 PM emission factors and achievable emission levels

Wide ranges of emission factors are found for residential wood combustion in practice today, while emission factors of medium and large scale applications mainly depend on particle removal equipment, related to national or local emission limit values. Compared to real-life emission factors, far lower emission levels are achievable for correctly operated modern combustion devices.

Table 1 Typical PM emission factors for various appliance types for wood combustion indicated as solid particles sampled on hot filters (not including condensable organic compounds) in real-life operation today (left), and achievable best-practice PM emission levels under ideal conditions (right).
*only if operated at full load, which cannot be guaranteed for space heating.

Appliance type	Typical PM emission factors today [mg/MJ]	Achievable PM emission levels [mg/MJ]
Open fireplaces	50 to > 1 000	50 – 100
Wood stoves & closed inset appliances	20 to > 1 000	15 – 25
Log wood boilers without heat storage tank	20* to > 1 000	not recommended
Log wood boilers (with heat storage tank)	20 to > 100	10 – 20
Pellet stoves & boilers	10 – 50	10 – 20
Automatic wood combustion plants ... with cyclone	50 – 300	50 – 100
... with simple ESP	25 – 50	15 – 35
... with advanced ESP	5 – 15	5 – 15
... with fabric filter	< 5	< 5

From a survey of PM emissions [Nussbaumer et al. 2008] and recent experiences from from different boilers and stoves [Doberer et al. 2009, Good & Nussbaumer 2010], the following trends can be found and summarized for typical PM emission factors and achievable best-practice PM emission levels at ideal operation shown in Table 1 and indicated as solid particles sampled on hot filters in the flue gas:

1. The emission factors from manual wood combustion devices exhibit wide ranges from less than 20 mg/MJ under ideal conditions, to more than 1 000 mg/MJ under poor conditions with maximum reported levels of more than 5 000 mg/MJ under certain specific conditions which can occur at least temporarily.
2. For wood stoves, wide ranges are found due to different operation conditions. While low emissions of less than 25 mg/MJ are possible by utilisation of small logs of dry wood being added in small batches and igniting the fuel from the top, excessive PM emissions of up to more than 1 000 mg/MJ can occur due to smoldering conditions at reduced load and throttled air supply or due to inappropriate fuel such as wet wood. Consequently, high priority should be given to avoiding inappropriate operation.
3. Closed inset appliances with advanced design are available today with comparable combustion characteristics as wood stoves. However, closed inset appliances with simple design as well as open fireplaces typically exhibit higher emissions than well designed and operated stoves and boilers. Nevertheless, the risk of operation at throttled air is smaller than for wood stoves and boilers, where correct operation and in case of wood boiler heat storage tank is crucial.
4. For residential wood boilers, the type of combustion design influences the PM emission. Modern wood boilers with forced downdraft combustion and electronic combustion control achieve low PM emissions of less than 20 mg/MJ if properly operated, i.e., full load operation and appropriate fuel, while old-type boilers with updraft combustion exhibit significantly higher emissions. However, for all type of wood boilers, excessive PM emissions of more than 1 000 mg/MJ can occur if the boiler is operated without heat storage tank resulting in throttled operation. Consequently, heat storage tanks are highly recommended or should be mandatory for log wood boilers.
5. For pellet boilers and stoves, typical particle emissions of approx. 30 mg/MJ are reported with a relatively narrow variation from 10 to 60 mg/MJ. In average, PM emissions under typical operation conditions are expected to be lower than in manual operated combustion devices since variations are less emphasized. It should be noted that the market for pellets is growing and therefore the production of pellets with higher ash content may increase. The use of such pellets in small-scale equipment without particle removal will result in 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. Domestic scale applications should be restricted for high quality wood pellets with low ash content, while pellets with increased ash content should be reserved for applications in larger plants which are equipped with flue gas cleaning.
6. For automatic combustion plants, the emission factors without electrostatic precipitator (ESP) or fabric filter are relatively high, typically around 100 mg/MJ. Thanks to high temperature and sufficient oxygen availability at good conditions, these PM emissions are mainly attributed to inorganic particles, except if due to inappropriate boiler operation or bad furnace design, incomplete

combustion occurs. Clean gas emissions from automatic boilers usually 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 made stricter. The situation of typical PM emissions will change in many countries in the near future, since particle removal allows clean gas emissions of easily less than 30 mg/MJ e.g. by simple ESP or safely less than 10 mg/MJ, e.g. by application of advanced ESP or fabric filter.

For a comprehensive assessment of the above described figures, two additional issues need to be considered:

1. PM from incomplete combustion as found from badly operated manual combustion devices consists mainly of carbonaceous material, i.e., soot and condensable organic compounds (COC), which exhibit high toxicity and carcinogenicity, while PM from properly operated automatic wood combustion plants consist mainly of salts. This difference with respect to potential health effects is not considered by the particle mass concentration as indicated here and as used for emission limit values today.
2. The concentration of COC from good combustion conditions at high temperature and with sufficient local oxygen availability is low and can usually be neglected e.g. for the assessment of PM from automatic wood combustion plants. However, in case of non-ideal conditions as typically found in wood stoves or similar combustion devices, the concentration of COC in the flue gas can exceed the mass concentration of solid particles collected on hot filters by a factor of 2 to 10. Consequently, in case of incomplete combustion in manually operated stoves, the total PM emissions are significantly higher when COC is taken into account. For such conditions, measurements in dilution tunnels or additional measurements of condensables by liquid quenching results in far higher PM concentrations than measurements of hot solid particles only.

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