



Swedish Environmental Emissions Data

Emission factors and emissions from residential biomass combustion in Sweden

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Sammanfattning

Småskalig förbränning är en betydande utsläppskälla för växthusgaser, förorenande ämnen, NMVOC, partiklar, tungmetaller, PAH och dioxiner.

Varje år har Sverige som krav att rapportera utsläppen av flera ämnen till olika internationella instanser. I tidigare rapporteringar så har för varje ämne bara en emissionsfaktor använts för småskalig bibränsleanvändning, inkluderat alla tekniker och bränslen. En noggrannare undersökning av SCB av den nationella energistatistiken för småskalig förbränning har gjort det möjligt att dela upp emissioner från småskalig biomassa användning efter bränsletyp (ved, pellets, flis) och teknik (panna, kamin och öppen spis).

Syftet med föreliggande studie har varit att förbättra rapporteringen av emissioner från småskalig bibränsleledning genom att revidera emissionsfaktorer för N₂O, NO_x, CO, NMVOC, SO_x, NH₃, partiklar (TSP, PM₁₀, PM_{2.5}, metaller, dioxiner och PAH. Vidare har tidsserien 1990-2004 för alla dessa ämnen uppdaterats. De reviderade emissionsfaktorerna är till stor del baserade på resultat från Energimyndighetens forskningsprogram ”Biobränsle, hälsa och miljö”. Data har även samlats in från andra svenska och internationella studier. Resultat från ett stort antal nya mätningar tillsammans med en uppdelning av emissionsfaktorer efter teknik och bränsle, gav stora skillnader mellan tidigare använda emissionsfaktorer och reviderade emissionsfaktorer för vissa ämnen. De nya emissionsfaktorerna för NMVOC och partiklar är väsentligt lägre, medan emissionsfaktorer för CO och dioxiner är något högre.

Summary

Small scale biomass combustion can be a major source of air pollutants like emissions of greenhouse gases, acidifying pollutants, NMVOC, particulate matter, heavy metals, PAH and dioxins.

On a yearly basis Sweden is obliged to report air emissions of these pollutants to different international bodies. Until submission 2005, covering data for 1990-2003, only one emission factor for each pollutant was used for the reporting of emissions from residential biomass combustion. The results from a closer examination by Statistics Sweden of existing national energy statistics for residential heating has enabled a disaggregation of the fuel consumption of biomass by fuel type (wood logs, pellets, wood chips), as well as by technology (boiler, stoves, and open firing places). This study aimed at improving the reporting of emissions from small-scale combustion of biomass by revising the emission factors for N_2O , NO_x , CO, NMVOC, SO_x , NH_3 , total suspended particles (TSP, PM_{10} , $PM_{2.5}$, metals, dioxins and PAH. Furthermore, the time series 1990-2004 for these emissions were updated.

In this work the revised emissions factors were to a large extent based on results from the Swedish Energy Agency research program "Biofuel, Health and Environment". In addition a literature review was carried out to collect data from other Swedish studies as well as relevant international studies.

Results from several recent measurement studies, together with disaggregation of emissions factors by technology and fuel type, lead to quite large differences between previously used emission factors and the revised emission factors presented. In particular the new emission factors for NMVOC and particles are much lower, whereas the new emission factors for CO and dioxin are higher.

1 Background and objective

The Swedish air emission inventories are prepared on an annual basis and the results are reported to the UN Framework Convention on Climate Change (UNFCCC or Climate convention), the European Union's Mechanism for Monitoring Community greenhouse gas emissions, the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP Convention), and to the EU NEC (National Emissions Ceiling) Directive.

The emissions are calculated from emission factors and activity data. Current emission inventories from residential biomass combustion are quite uncertain, primarily due to uncertainties in emission factors. One of the difficulties is that emissions from stoves and domestic boilers very much depend on combustion technology, fuel quality and operation conditions. Thus, to increase the quality of the emission estimates, these parameters need to be considered.

Statistics Sweden (2004) publishes activity data for biomass combustion in the official statistics. Annual surveys on energy consumption in one- and two dwelling buildings, multi-dwelling buildings, agricultural residences and summer cottages are performed. The survey has been relatively similar over the years, using more or less the same questionnaire design for all surveys. Respondents have been asked to fill in what type of heating system the house is equipped with, as well as their consumption of biomass. From 1998 wood pellets/briquettes and wood chips/sawdust were included in the survey. In a recent study these activity data were revised, improved and the time series 1990-2003 was recalculated for methane (Paulrud, 2005).

In Sweden the most commonly used biomass fuel for residential combustion is dry wood log fuels. However, in recent years the use of refined fuels such as pellets and briquettes has increased. Wood chips or sawdust are also used, although they are mainly used in agricultural residences and in multi-dwelling buildings.

In the residential sector different kinds of boilers, stoves and fireplaces are used with a variety of models and designs. Residential wood boiler systems are most common for water-based heating and hot water production. To increase the combustion efficiency the boiler may also be connected to a heat storage tank (a water tank for storage of heat). Different types of stoves and fireplaces are also used, mainly as secondary heating source.

Systems that are used for pellets combustion are pellets boilers, special burners, adapted to wood or oil boilers, and pellets stoves used as primary heating replacing heating with electricity. Wood chips and sawdust are usually combusted in small grate boilers with a continuous feeding, or in special pre-furnaces connected to a boiler.

Small-scale biomass combustion can be a major source of air pollutants. The concentrations of N, S, and Cl in different biofuels are important because they may cause emissions of NO_x , SO_2 , HCl and increased emissions of chlorinated aromatic compounds such as dioxins. Using non-contaminated wood such as wood log and wood pellets, emissions of dioxins, chlorine, SO_2 , NO_x and heavy metals are not considered a major problem. However, contaminated wood and non-wood biomass may give considerable emissions of these compounds.

Other pollutants formed during combustion are products of incomplete combustion, such as particles, carbon monoxide (CO), hydrocarbons including volatile organic compounds (VOC), and polycyclic aromatic hydrocarbons (PAH). These pollutants are mainly influenced by the combustion equipment, process and physical fuel properties (Jenkins et al. 1998; Werther, 2000).

In Sweden a national research program financed by the Swedish Energy Agency, entitled “Biofuels, Health and Environment”, was carried out during the period 2001-2004. The overall objective of this program was to describe the influence of small-scale biomass combustion on emissions, air quality and human health. In this program extensive quantification and characterisation of gases and particulate emissions were performed for a wide range of residential biomass combustion appliances during different fuel and operation conditions (Boman et al. 1995, Johansson, et al. 2005, Johansson et al. 2003).

1.1 Objective

This study aimed at improving Sweden's reporting of emissions from small-scale combustion of biomass by revising the emission factors for N_2O , NO_x , CO, NMVOC, SO_x , NH_3 , total suspended particles (TSP, PM_{10} , $PM_{2.5}$), metals, dioxins and PAH. Furthermore, the time series 1990-2004 for these emissions were updated.

2 International emission reporting requirements and guidelines

2.1 General reporting requirements and guidelines

On a yearly basis Sweden is obliged to report emissions to air of a number of pollutants to several international bodies:

- EU's National Emission Ceiling directive and CLRTAP (United Nation's Convention on Long-Range Transboundary Air Pollution) which follows "draft guidelines for estimating and reporting emissions data", (UNECE EB.AIR/GE.1/2002/7) and EMEP/CORINAIR Air Emission Inventory Guidebook.
- UNFCCC (United Nations Framework Convention on Climate Change) and the EUs climate gas directive "Monitoring Mechanism", which follows revised 1996 IPCC Guidelines for National Greenhouse gas Inventories (IPCC Guidelines), IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse gas inventories (IPCC Good Practice Guidance), and UNFCCC Reporting Guidelines on annual inventories (FCCC/CP/2002/8).

3 Revision of emission factors

3.1 Methods

The general method for calculating emissions from a certain source is to multiply relevant activity data with an emission factor, according to the equation:

$$E=AD*EF$$

Where E=emission, AD=activity data and EF= emission factor

Until submission 2005, covering data for 1990-2003, only one emission factor for each pollutant was used when reporting emissions from residential biomass combustion. The results from a closer examination by Statistics Sweden of existing national energy statistics for residential heating has enabled a disaggregation of the fuel consumption of biomass by fuel type (wood logs, pellets, wood chips), as well as by technology (boiler, stoves, and open firing places) (Paulrud et al. 2005). These are also the categories that are used for the revised emission factors in this report.

In this work the revised emissions factors are to a large extent based on results from the Swedish Energy Agency research program “Biofuel, Health and Environment”. In addition a literature review was done to collect data from other Swedish studies and relevant international studies. Information was also obtained from discussions with experts. The international emission factors were necessary to use as a supplement to the Swedish measurements or as best estimate, as in the Swedish measurements there are in some cases combustion appliances with too few, non-reliable measurements or no measurements at all. Studies on wood chips combustion in small appliances are scarce and these emission factors are mainly based on older studies and international studies. It should also be considered that there is always an uncertainty introduced when interpreting literature data since different sampling methods and different fuels (raw material from other countries) may affect the result.

The emission factors are based on experiments and measurements carried out in the laboratory as well as in the field. In adopting literature data it has been assumed to be more correct to also compare minimum and maximum figures instead of just average figures, as average figures generally give false impression of the accuracy of the estimates presented. In the results section the variability of the emission factors are presented as well as the average value used for the emission factor calculations.

Since there is often a large variation in the emission factors, and data from several studies were used, it was not considered correct to only calculate an average value from all measurements. The emission factors in this study were estimated using measured data in combination with expert judgement and some assumptions. The method used was to find an average value for each emission factor that pro-

vides a good measure of "typicalness". Mean and median are two types of "averages" or measures of central tendency. For a given set of data, these measures of center may be very close or may be quite different, depending on how the data are distributed, and either of the measures of center may or may not provide a good measure of "typicalness". The mean and median each have advantages and disadvantages when used to describe data sets. Changing one data value usually not affects the median, but every change in a data value affects the mean. Thus, the mean is affected by a few extremely large or extremely small values outside the range of the rest of the data, but the median is not. In this study the median was primarily used for skewed distributions, which it represents more accurately than the arithmetic mean.

When calculating the time series the same emission factors from 1991-2004 have been used. The reason for this is that few emission factors from 1991 could be found, especially for the pollutants NMVOC, PAH, dioxins and particles. Further, a recent study (Johansson, 2006) shows that the differences in emissions between the group of boilers not fulfilling the emission limits according to the Swedish National Board of Housing Building and Planning and fired without a thermal heat storage tank (IBG) on the one hand, and the group of boilers that fulfil the emissions and are connected to a heat storage tank (BGA) on the other hand, are small.

3.2 Results

3.2.1 Dioxins

Combustion is a major source of emissions of polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofuranes (PCDF) into the environment. The dominant source is municipal waste incineration. Other significant sources include private wood boilers, stoves and other smaller plants for biomass combustion as well as PCP-treated wood and fires, both accidental fires and others.

Polychlorinated dioxins and furans, referred to as dioxins in this report, are formed unintentionally in several industrial and combustion processes. The production of dioxins is strongly dependent on certain physical and chemical conditions. PCDD/PCDF in thermal processes are formed in trace quantities in combustion processes when carbon, oxygen, hydrogen, and chlorine are present in a temperature range between 200 °C and 650 °C. For residential biomass appliances PCDD/PCDF are formed usually as a result of incomplete combustion. While many investigations have been performed to study the emissions of PCDD and PCDF from municipal waste combustion, there are only few Swedish reports on dioxin emissions from residential wood combustion. In the present work, data from mainly two Swedish studies and six international studies have been used (Table 1). The chemical content, for example the chlorine content of the fuel, is a parameter of major significance (Hedman, 2005). In the present work it is assumed that most wood boilers and stoves in Sweden are fired with local wood, i.e. uncontaminated wood.

When evaluating the occurrence of dioxins, information on their toxic effects is often required. The dioxin levels are often presented as a sum of different dioxins species in a combined value, toxic equivalents (TEQs). Each of the species has been attributed a toxic equivalent factor (TEF) which corresponds to its toxicity relative to that of the most toxic dioxin congener (2,3,7,8-TCDD). A number of different TEF scales have been developed during the past decades, as more information on toxicity of different species has become available, and varying measures of species related toxic effects have been applied. Lately, the scale promoted by the World Health Organization (WHO) in 1997 (Hedman, 2005) has been the most commonly used. Unfortunately, if a value is presented in one system, it cannot be recalculated to another system without access to data on all congeners. In this report the international system (ITEQ) is used, mainly because most data reported follow this system and it is also the scale that is used for the international reporting. However, the two Swedish studies use the WHO-scale but according to Hedman, (2005) the values for PCDD/F WHO-TEQ is approximately 10-20 % higher compared to the ITEQ scale when dealing with low-chlorinated dioxins as in this work. Thus, this approach was adopted in the present work.

Emission factors from the literature are compiled in Table 1. The emission factors for PCDD/F varied in the range of 0.012-2.6 ng/MJ for the wood log boilers, 0.02-1.18 ng/MJ for the wood log stoves, 0.002-0.84 ng/MJ for the pellets burners, 0.003-0.11 ng/MJ for the wood chips boilers and 0.005-4.5 ng/MJ for the open fire places. Some of the combustion experiments with pellets showed surprisingly high values. There were no explanations for these high values and in this work it was assumed that combustion of pellets in general have more similar levels of PCDD/F as wood log boilers.

A recent Danish study (Glasius et al, 2005) on in-field measurements of PCDD/F emissions from wood stoves showed in some cases high values. This was also the case in a recent in-field study from Austria (Hubner 2005), and several explanations for these high values were presented. A common practice in Austria is to use paper, paperboard, wood shavings and plastic for ignition and to speed up the combustion. One explanation may be that combustion of waste on previous days or weeks might have had an effect on the PCDD/F concentrations in certain samples, as contaminated soot can be expelled days after its formation. Other reasons for high emissions were the inappropriate operation of certain appliances or that the combustion equipment was in poor conditions due to lack of maintenance.

The revised emissions factors adapted to the available activity data are presented in Table 2. The previously used single emission factor is also shown. The emission factors are based on measured emission data from combustion experiments in the laboratory as well as in the field. Since the Swedish measurements are few, the revised emission factors are also based on data from international studies.

Table 1. Example of variability of emission factors for dioxin from small scale combustion of wood logs, pellets and wood chip using different combustion technologies. All data presented as nb/MJ fuel.

Fuel/appliance	WTEQ/ITEQ PCDD/F ng/MJ	Reference
Wood boiler	0.03-0.79 (WTEQ) (1)	Bergqvist et al, 2005
Wood boiler	0.012-0.022 (ITEQ)	Schtowitz et al 1994
Wood boiler	0.018-2.6 (ITEQ)	Hubner et al. 2005
Wood stove	0.18-0.31 (WTEQ) (1)	Bergqvist et al. 2005 ¹
Wood stove	0.02-1.18 (ITEQ)	Glasius et al 2005
Wood stove	0.023-0.15 (ITEQ)	Hubner et al 2005
Wood Stove	0.04-0.34 (ITEQ)	Schleicher et al 2001
Wood stove	0.02-0.25 (ITEQ)	Hansen et al 1994
Wood stove	0.04-0.06 (ITEQ)	Bröcker et al 1992
Wood stove	0.1 (ITEQ)	UNEP 2001
Pellets burner	0.07-0.82 (WTEQ) (1)	Bergqvist et al, 2005
Pellets burner	0.05-0.25 (WTEQ)	Johansson, 2005
Open fire place	0.041-0.066 (ITEQ)	Schtowitz et al, 1994
Open fire place	0.005-0.08 (ITEQ)	Bröcker et al 1992
Open fire place	0.045-4.5 (ITEQ)	Hubner et al 2005
Wood chips boiler	0.042-0.11 (ITEQ)	Schtowitz et al 1994
Wood chips boiler	0.003-0.006 (ITEQ)	Hubner et al. 2005
Stoker pellets	0.01-0.03 (ITEQ)	Schleicher et al 2001
Pellets boiler	0.002 (ITEQ)	Hubner et al 2005

*The emission factors expressed as ng TEQ/MJ have been calculated using an energy value of 15-16 MJ/kg for wood log and 17 MJ/kg for wood pellets.

¹The values are corrected by Hedman, Umeå University (Hedman, 2005).

Table 2. Revised emission factors for dioxin determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as ng/MJ fuel.

Appliance type	Fuel	PCDD/F, ng/MJ (average)
Boilers	Wood logs	0.07
	Wood chips	0.07
	Pellets	0.07
Stoves	Wood logs	0.07
	Wood chips	
	Pellets	0.07
Open fire places	Wood logs	0.07
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	0.05 (previous value)

3.2.2 Particles

Combustion is a major source of fine particulate matter, and in urban areas traditional residential wood combustion can be a major contributor. There are two main sources of primary combustion particles from small-scale biomass combustion; particles from incomplete combustion and ash particles. Emission of gaseous hydrocarbon compounds, soot, condensable organic particles and char particles result from incomplete combustion, while ash particles originate from the inorganic part of the fuel and remain as a by-product of combustion.

There are different sampling methods for particle measurements which may affect the particle concentration. The sampling is carried out either in a flue gas channel or in a dilution tunnel. The purpose of a dilution tunnel is to simulate what happens to the flue gas when it reaches the ambient air, and the flue gas is diluted with large amounts of room-tempered air prior to sampling. In Sweden sampling in a flue gas channel is the most common approach, and in this study the result is based on this sampling method.

The current estimates for residential wood combustion cover emissions of TSP (total suspended particulate matter), PM₁₀ (particles of size <10 µm) and PM_{2.5} (<2.5µm). In this report the new emission factors are based on results from mainly Swedish measurements (see Table 3) in combination with expert judgement. Emission factors from the literature are compiled in Table 3.

The revised emissions factors adapted to the available activity data are presented in Table 4. The previously used single emission factor is also shown. The emission factors are based on measured emission data from Swedish combustion experiments in the laboratory as well as in the field. In most measurements the entire firing cycle was included: sample start during ignition and stop when the wood charge had burnt out. No Swedish data for open fire places could be found, and the same level as for older stove inserts according to Paulrud (2006) were used.

Several studies have shown that small-scale wood combustion typically leads to particle emissions dominated by submicron particles (<1 µm), and no significant emissions of particles larger than 10 µm will normally be found (Johansson, 2004, Boman, 2005, Ohlström, 2005). These studies have also shown that all particulate matter from biomass consists of particles <2.5 µm, meaning that TSP = PM₁₀ = PM_{2.5}. This result has been adopted in this study and the same emission factor is used for TSP, PM₁₀ and PM_{2.5}.

Table 3. Example of variability of emission factors for particulate matter determined from small scale combustion of wood logs, pellets and wood chip using different combustion technologies. All data presented as mg/MJ fuel.

Fuel/appliance	PM mg/MJ	Reference
Wood boiler	26-450	Johansson, 2005
Wood boiler	23-2200	Johansson, 2003
Wood boiler	30-700	SNV, 1983
Wood stove	22-181	Paulrud, 2006
Wood stove	7-173 (PM2.5)	Hedberg, 2002
Wood stove	37-350	Boman, 2005
Wood stove	120-320 (PM2.5)	MacDonald, 2000
Wood Stove	30-55 (PM2.5)	Johansson, 2004a
Wood Stove	10-1000	SNV, 1983
Wood stove	200-5500	Glasius, 2005
Wood stove	100, 90 (PM1)	Ohlström, 2005
Pellets burner	12-65	Johansson, 2003
Pellets burner	10-60 (PM2.5)	Johansson, 2004a
Pellets burner	35, 25 (PM1)	Ohlström, 2005
Pellets boiler	30-40	SNV, 1983
Pellets boiler	15, 10 (PM1)	Ohlström, 2005
Pellets stove	30-60 (PM2.5)	Johansson, 2004a
Pellets stove	11-81	Boman, 2005
Pellets stove	17-46	Boman, 2005
Open fire place	170-780 (dilution tunnel)	Purvis, 2000
Open fire place	100-150	SNV, 1983
Open fire place	130-1200	Dasch, 1982
Open fire place	150-420 (PM2.5)	McDonald, 2000
Open fire place	330-630 <PM10	Schauer et al 2001.
Open fire place	180-760 (PM2.5)	Fine, 2001
Wood chips boiler	30-1600	SNV, 1983
Wood chips boiler	20, 10 (PM1)	Ohlström, 2005
Wood chips boiler	50, 30 (PM1)	Ohlström, 2005

Table 4. Revised emission factors for particles determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	TSP=PM10=PM2.5 mg/MJ (average)
Boilers	Wood logs	150
	Wood chips	100
	Pellets	30
Stoves	Wood logs	100
	Wood chips	100
	Pellets	30
Open fire places	Wood logs	150
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	previous value TSP 650 PM10 585, PM2.5 520

3.2.3 NO_x

Emissions of NO_x predominantly arise from nitrogen in the fuel since most commercial biomass users operate at temperatures low enough that thermal formation of NO_x is relatively insignificant (Olanders & Gunnars, 1994; Jenkins et al. 1998; Winter, Wartha & Hofbauer, 1999; Salzman & Nussbaumer, 2001). A higher content of N in the fuel is likely to increase the NO_x emissions. The conversion of fuel nitrogen to NO_x also depends on the operation conditions and combustion equipment (Olanders & Gunnars, 1994; Van der Lans, Glarborg & Dam-Johansen, 1997; Jenkins, 1998; Winter, Wartha, Hofbauer, 1999; Salzman & Nussbaumer, 2001). In this work it was assumed that fuel nitrogen was the dominating N-source for NO_x formation. For the revision of emission factors, data from mainly six Swedish studies have been used (Axell, 1996, Boman, 2005, Dasch, 1982, Johansson, 2004, Johansson, 2003, Karlsson, 1992).

The emission of NO_x for pellets varied between 30-80 mg/MJ and for wood logs between 20-120 mg/MJ. The average values presented in Table 5 were slightly higher for the combustion technologies using wood log. One explanation for this is that wood log contains slightly more nitrogen due to higher content of bark compared to pellets. However, the variation is large. Usually there is also interdependence between NO_x and CO. Lower NO_x-emissions due to poor combustion often results in increased unburned pollutants. For example, the average value for boilers with a storage tank was 90 mg/MJ compared to boiler without a storage tank, for which the average value was 60 mg/MJ.

Table 5. Revised emission factors for NO_x determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	NO _x mg/MJ (average)
Boilers	Wood logs	80
	Wood chips	80
	Pellets	65
Stoves	Wood logs	80
	Wood chips	80
	Pellets	65
Open fire places	Wood logs	80
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	60 (previous value)

3.2.4 N₂O and NH₃

Combustion of biomass plays a significant role in global atmospheric chemistry due to the non-CO₂ (carbon dioxide) GHGs (greenhouse gases), and its potential for global warming due to an enhanced greenhouse gas effect. Much of the CO₂ from the biomass does not result in a net increase in atmospheric concentration because the plants absorb it during photosynthesis. In developing countries, a large quantity of biomass is burnt in small inefficient combustion devices which emit non-CO₂ GHGs such as methane (CH₄) and nitrous oxide (N₂O). During combustion, nitrous oxide is produced as a result of chemical interactions between nitrogen oxides (mostly NO₂) and other combustion products. With most conventional stationary combustion systems, high temperatures destroy almost all nitrous oxide, limiting the quantity that escapes; therefore, emissions from these systems are typically small. In this inventory no new studies on N₂O from small scale wood combustion could be found. A thesis by Skreiberg (1997) show measurements of N₂O in different wood stoves. The result from this study showed that the emission factor for N₂O was <5 mg/MJ for all wood stoves. The previous used value for N₂O (5 mg/MJ) for wood combustion is therefore not revised, and the same value is used for all fuels and techniques.

The NH₃ emissions from wood combustion is generally low and since no new information on NH₃ emission factors was found the emission factors for NH₃ were not revised (Table 6).

Table 6. Emission factors for N₂O and NH₃ determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	N ₂ O mg/MJ	NH ₃ mg/MJ
Boilers	Wood logs	5	2
	Wood chips	5	2
	Pellets	5	2
Stoves	Wood logs	5	2
	Wood chips	5	2
	Pellets	5	2
Open fire places	Wood logs	5	2
	Wood chips	not relevant	
	Pellets	not relevant	
All technologies	All biomass	5 (previous value)	2

3.2.5 CO

CO is a product of incomplete combustion and it is mainly influenced by the combustion technique, combustion process and physical fuel properties. The variation in CO emissions is usually large and the levels may sometimes be very high, especially from wood log combustion. Emission factors from literature are compiled in Table 7.

The revised emissions factors adapted to the available activity data are presented in Table 8. The previously used single emission factor is also shown. The emission factors are mainly based on measured emission data from Swedish combustion experiments carried out in the laboratory as well as in the field.

Table 7. Example of variability of emission factors for CO determined from small scale combustion of wood logs, pellets and wood chip using different combustion technologies. All data presented as mg/MJ fuel.

Fuel/appliance	CO mg/MJ	Reference
Wood boiler	160-8900	Johansson, 2005
Wood boiler	500-16400	Johansson, 2003
Wood boiler	100-3000	SNV, 1983
Wood boiler	670-9700	Axell, 1996
Wood boiler	540-4300	Hubner, 2001
Wood boiler	1100-23700	Karlsson, 1992
Wood stove	1200-1900	Johansson, 2004a
Wood stove	1200-7700	Boman, 2005
Wood stove	5400-9400	MacDonald, 2000
Wood Stove	700-5000	Paulrud, 2006
Wood Stove	5-8000	SNV, 1983
Wood stove	200-5500	Gladius, 2005
Wood stove	170-6500	Purvis, 2000
Pellets burner	36-1100	Johansson, 2003
Pellets burner	31-1700	Johansson, 2004a
Pellets boiler	600-800	SNV, 1983
Pellets stove	92-200	Johansson, 2004a
Pellets stove	110-810	Boman, 2005
Open fire place	4000	SNV, 1983
Open fire place	3900-12000	Dasch, 1982
Open fire place	2100-4700	Hubner, 2001
Wood chips boiler	3-1500	SNV, 1983
Wood chips boiler	790-1400	Hubner, 2001
Pellets boiler	120	Hubner, 2001

Table 8. Revised emission factors for CO determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	CO mg/MJ (average)
Boilers	Wood logs	4000
	Wood chips	1000
	Pellets	300
Stoves	Wood logs	2500
	Wood chips	1000
	Pellets	300
Open fire places	Wood logs	4000
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	2000 (previous value)

3.2.6 SO_x

Emissions of SO_x arise predominantly from sulphur in the fuel and since the content of sulphur is low in wood fuels, the emissions of sulphur dioxide from wood fuel combustion are also low.

Previous Swedish emission inventories were based on a S-content of (0.07 wt % dry fuel). This is higher than the S-content used in this study (0.01 wt %). The explanation for this is that in previous inventories, only one emission factor was used, which included all types of wood fuels (wood residue, bark, wood log etc.).

The sulphur content in wood pellets and wood log is normally <0.01 wt-% dry fuel which will result in low SO₂ emissions. There are no new studies on SO₂ from small scale wood combustion, and no information on how much sulphur that will be emitted could be found. Therefore the same calculations as in Boström, (2003) were used. However, in this study no account was taken to how much sulphur that is emitted and how much that is bound to the ash. Doing so resulted in a new emission factor of 10 mg/MJ, as compared to the previous of 30 mg/MJ.

$$\frac{(0,1 \text{ g S/kg dry wt})}{19 \text{ MJ/kg dry wt}} = 0,005 \text{ g S/MJ} = 0,01 \text{ g SO}_2/\text{MJ}$$

It should be considered that there are always variations and generally some of the sulphur is bound to the ash. On the other hand there is also a variation of the sulphur content in the fuel depending on the fuel quality. A higher content of bark will increase the sulphur content.

The revised emissions factors adapted to the available activity data are presented in Table 9. The previously used single emission factor is also shown.

Table 9. Revised emission factors for SO₂ determined from small scale combustion of wood logs, pellets and wood chip/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	SO ₂ mg/MJ
Boilers	Wood logs	10
	Wood chips	10
	Pellets	10
Stoves	Wood logs	10
	Wood chips	10
	Pellets	10
Open fire places	Wood logs	10
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	30 (previous value)

3.2.7 Metals

The major part of biomass ash consists of nutrients like Ca, K, Mg, Na and P, with minor amounts of trace elements like Zn, Cu, Cd, Pb and Cr. During combustion these elements will be distributed between bottom ash, fly ash particles and gaseous compounds. Most of the metals are emitted as particles or adsorbed to particles while mercury and partly arsenic are emitted in gaseous form. During combustion of different wood biomass fuel, zinc has been identified as a major trace element in the fine (<1 µm) particulate emissions (Boman, 2005). Besides Zn significant amounts of Cd, Pb and Cr have been found in fine particles in large-scale combustion.

Table 10 shows the previously used values and emission factors from three different studies. There are very few recent studies conducted on metal emissions from small scale biomass combustion. Heberg (2001) presents emission factors for metals from a wood stove. In this inventory, the emission factors for Zn, Cr and Cu are revised. Due to few Swedish measurements and no available data on a more detailed level, the same emission factors are used for all fuels and all technologies. The emission factors from literature are compiled in Table 10 and the revised emission factors adapted to the available activity data are presented in Table 11.

Table 10. Example of variability of emission factors for metals determined from small scale combustion of wood logs, pellets and wood chips using different combustion technologies. All data presented as mg/MJ fuel.

Elements	Wood Stove Average, 7 samples (Hedberg, 2001) mg/MJ	Fireplace Schauer, 2001 mg/MJ	Wood stove (SNV PM), 1982 mg/MJ	Pellets boiler SNV PM), 1982 mg/MJ	Previous mg/MJ
Zn	(0.1-0.8)0.5	0.36	0.33	0.63	0.1
Cd	0.04 (0.00-0.1)		0.003	0.003	0.003
Cr	(0.003-0.1)0.04		0.002	0.004	0.001
Cu	0.005(0.005-0.0053)		0.001	0.014	0.01
Hg	<0.1				0.0005
Ni	0.004 (0.0007-0.02)		0.0025	0.0035	0.0025
Pb	(0.005-0.06) 0.020		0.02	0.032	0.015
Se	(0-0.001) 0.006		-	-	0.0022

Table 11. Revised emission factors for metals determined from small scale combustion of wood logs, pellets and wood chips/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Elements	Boiler wood/pellets mg/MJ	Stove wood/pellets mg/MJ	Open fire place wood log mg/MJ	Wood chips/saw dust boiler mg/MJ
Zn*	0.4	0.4	0.4	0.4
Cd	0.003	0.003	0.003	0.003
Cr*	0.003	0.003	0.003	0.003
Cu*	0.005	0.005	0.005	0.005
Hg	0.0005	0.0005	0.0005	0.0005
Ni	0.0025	0.0025	0.0025	0.0025
Pb	0.015	0.015	0.015	0.015
Se	0.0022	0.0022	0.0022	0.0022

*Revised

3.2.8 NMVOC

NMVOCs (Non Methane Volatile Organic Compounds) are organic compounds which may differ widely in their chemical composition. These organic compounds are often grouped under the NMVOC label as the majority display similar behaviour in the atmosphere. NMVOCs are emitted to air as products from incomplete combustion.

Emission factors from literature are compiled in Table 12 and the revised emission factors adapted to the available activity data are presented in Table 13. The emission factors are based on measured emission data from Swedish combustion experiments in the field and in the laboratory. In most of the measurements for wood logs the entire firing cycle was included, sample start during ignition and stop when the wood charge had burnt out. No data for wood chips boilers could be found and the same value as for wood logs in stoves were used. No data for open fire places could be found and the same level as for older stove inserts according to Paulrud (2006) were used.

The previously used value for NMVOC is high, 1975 mg/MJ, in comparison to the emission factor for methane, 250 mg/MJ. According to Johansson(2004b) the fraction of methane in VOC (sum of methane and NMVOC) is approximately 20-40 mass % for pellet boilers and 30-70 mass % for wood boilers.

The revised emission factors now show significantly lower values compared to the previously used value. This is due to that the new emission factors are based on data from more measurements.

Table 12. Example of variability of emission factors for NMVOC determined from small scale combustion of wood logs, pellets and wood chips using different combustion technologies. All data presented as mg/MJ fuel.

Fuel/appliance	NMVOC mg/MJ	Reference
Wood boiler	25-930	Johansson, 2005
Wood boiler	1-2000	Johansson, 2003
Wood stove	17-180	Paulrud, 2006
Wood Stove	18-2500	Boman, 2004
Pellets burner/stove	1-20	Johansson, 2003
Pellets stove	1-22	Boman, 2004

Table 13. Revised emission factors for NMVOC determined from small scale combustion of wood logs, pellets and wood chips/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	NMVOC mg/MJ
Boilers	Wood logs	300
	Wood chips	150
	Pellets	6
Stoves	Wood logs	150
	Wood chips	150
	Pellets	6
Open fire places	Wood logs	200
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	1975 (previous value)

3.2.9 PAH

Polycyclic aromatic hydrocarbons (PAHs) is the collective name of a large group of chemicals, which all have in common that they consist of two or more ring structures, where at least one ring has the structure of benzene. Just like dioxins, PAHs are predominantly formed during incomplete combustion processes. Historically, it has not been possible to separate different PAHs from each other, due to analytical difficulties. Thus they have been reported as “total PAH” or “sum of PAH”, without any further information about which substances were included in the chemical analysis. Today, broad knowledge exists on the different toxic and physical-chemical properties of different PAH substances, and it is generally conceived that separation of individual substances is necessary. The UNECE POPs Protocol specifies that the following four PAHs should be used as indicators for the purposes of emission inventories:

- benzo(a)pyrene (BaP)
- benzo(b)fluoranthene (BbF)
- benzo(k)fluoranthene (BkF)
- indeno(123cd)pyrene (Ind)

These four substances belong to the heavier molecules in the PAH group and to those regarded as the most carcinogenic. The current emission inventory comprises the four substances specified in the UNECE POPs protocol (BaP, BbF, BkF and Ind, hereafter referred to as PAH-4). It should be noted, however, that the selected substances often occur at low concentrations when compared to more volatile PAHs. Thus, calculating emissions of PAH-4 should not be regarded as a complete emission inventory for PAHs. Emission factors from literature are compiled in Table 14.

Table 14. Example of variability of emission factors for NMVOC determined from small scale combustion of wood logs, pellets and wood chips using different combustion technologies. All data presented as mg/MJ fuel.

Fuel/appliance	PAH-4 mg/MJ	Reference
Wood boiler	0.005-1.25	Johansson, 2005
Wood boiler	0.005-0.80	Johansson, 2003
Wood stove	0.04-3.7	Hedberg, 2001
Wood stove	0.003-0.47	Gladius et al 2005
Wood Stove	0.01-0.91	Paulrud, 2006
Wood Stove	0.07-7.4	Boman, 2005
Wood stove	0.02-0.04	Johansson, 2004a
Fire place	0.06-0.16	Schauer, 2001
Fire place	0.06-0.12	Gullet, 2003
Pellets burner	<0.001-0.11	Johansson, 2004a
Pellets burner/stove	0.004-0.39	Johansson, 2003
Pellets stove	<0.001-0.016	Boman, 2005

The revised emissions factors adapted to the available activity data are presented in Table 15. The emission factors are based on measured emission data from Swedish combustion experiments conducted in the laboratory as well as in the field. In most measurements for wood logs the entire firing cycle was included: sample start during ignition and stop when the wood charge had burnt out. No data for wood chips boilers could be found and therefore the same value as for wood logs in stoves were used.

Table 15. Revised emission factors for NMVOC determined from small scale combustion of wood logs, pellets and wood chips/saw dust using different combustion technologies. All data presented as mg/MJ fuel.

Appliance type	Fuel	PAH-4 mg/MJ
Boilers	Wood logs	0.25
	Wood chips	0.20
	Pellets	0.006
Stoves	Wood logs	0.20
	Wood chips	0.20
	Pellets	0.006
Open fire places	Wood logs	0.20
	Wood chips	not relevant
	Pellets	not relevant
All technologies	All biomass	0.325 (previous value)

4 Recalculated time series

Figure 1-7 show the recalculated time series for dioxins, particles, NO_x, CO, SO₂, NMVOC and Zn. These are the time series for which significant differences can be seen compared to the old time series. Results from several new measurements, together with disaggregation of emissions factors by technology and fuel type, lead to quite large differences between previous and revised time series. In particular the new time series for NMVOC and particles show lower values, and the emissions for CO, dioxins and Zn show significantly higher values. In Appendix 1, recalculated data for all pollutants are compiled.

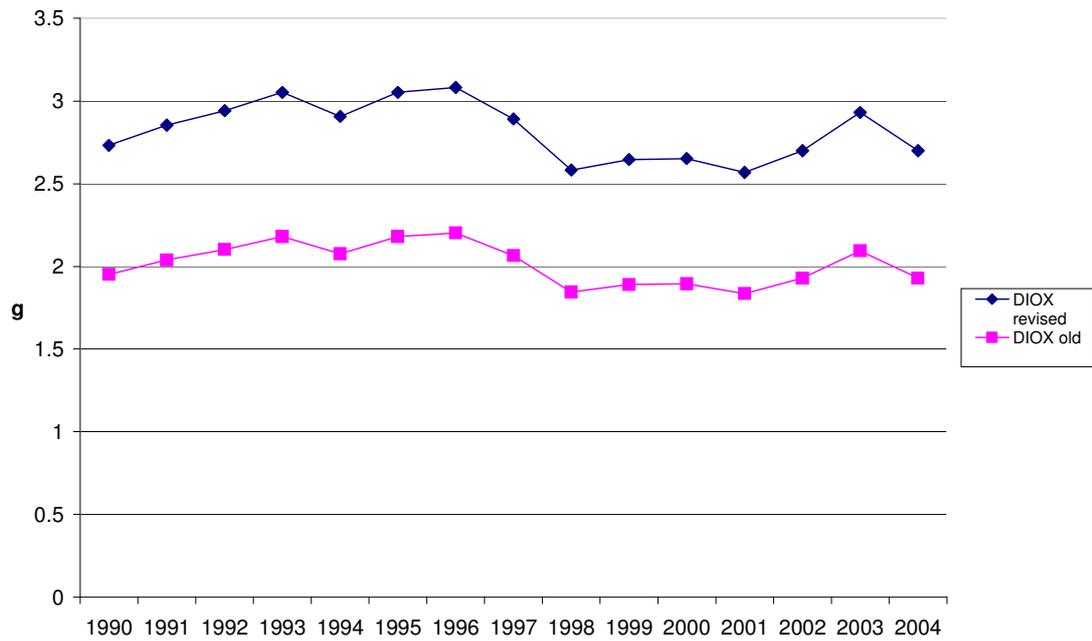


Figure 1. Recalculated dioxin emissions 1990-2004 for wood combustion in the residential sector; total dioxin emissions (gram) before revision and dioxin emissions (gram) after revision.

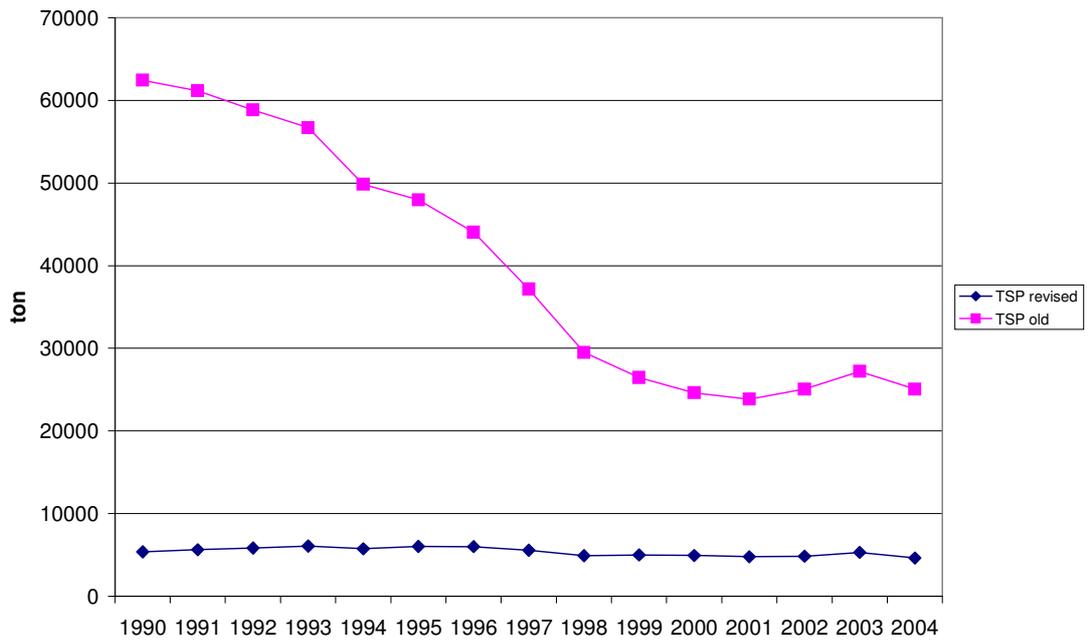


Figure 2. Recalculated particle emissions (total suspended particles, TSP) 1990-2004 for wood combustion in the residential sector; total particle emissions (ton) before revision and particle emissions (ton) after revision.

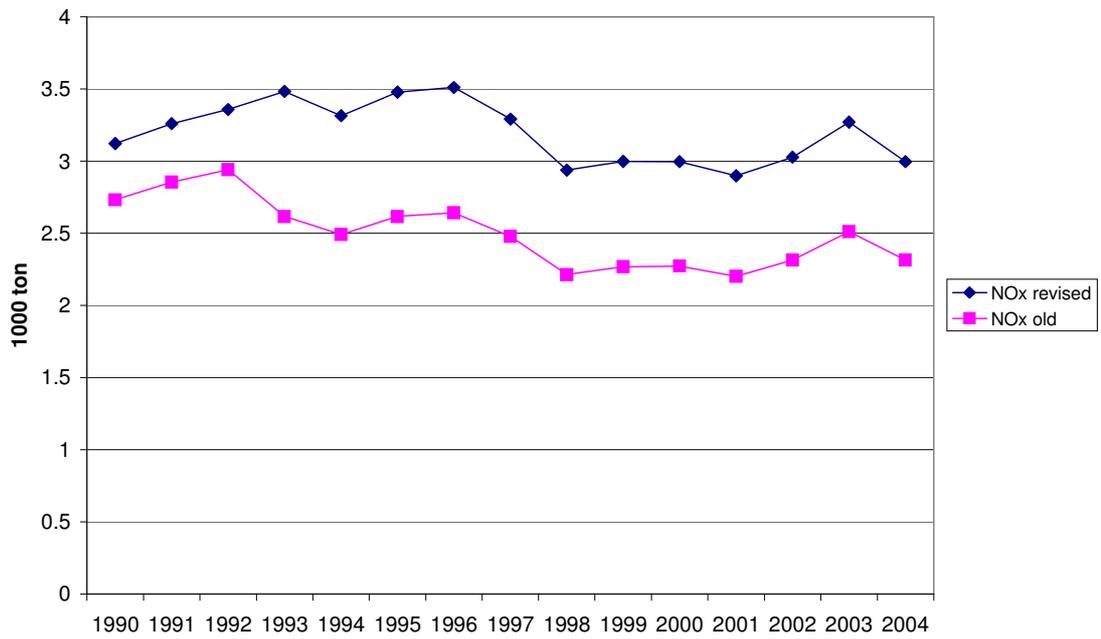


Figure 3. Recalculated NO_x emission 1990-2004 for wood combustion in the residential sector; total NO_x emissions (1000 ton) before revision and NO_x emissions (1000 ton) after revision.

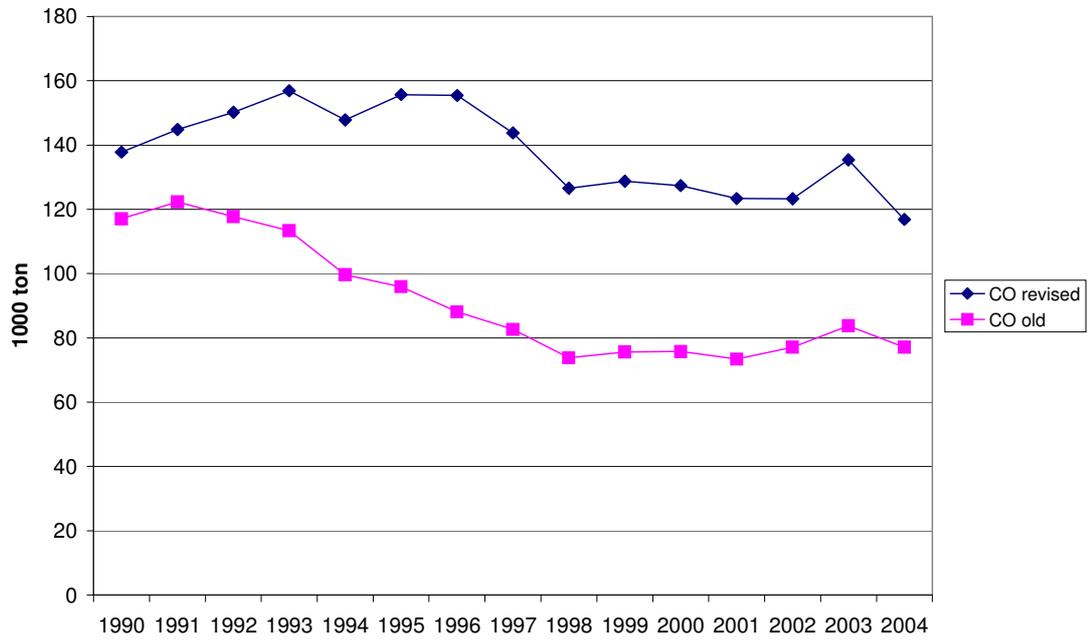


Figure 4. Recalculated CO emissions 1990-2004 for wood combustion in the residential sector; total CO emissions (1000 ton) before revision and CO emissions (1000 ton) after revision.

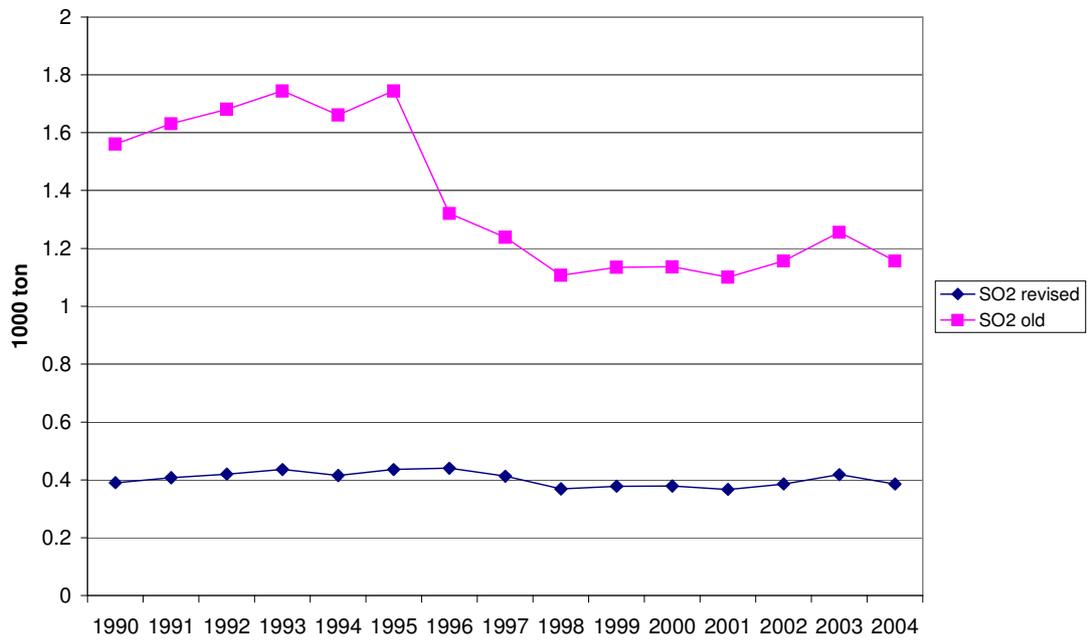


Figure 5. Recalculated SO₂ emissions 1990-2004 for wood combustion in the residential sector; total SO₂ emissions (1000 ton) before revision and SO₂ emissions (1000 ton) after revision.

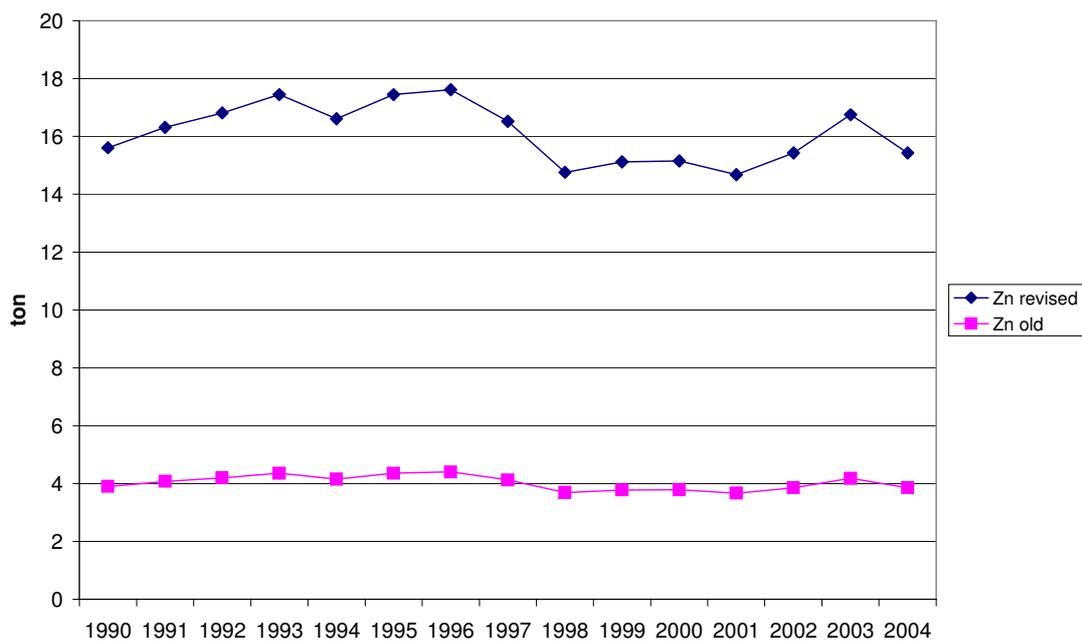


Figure 6. Recalculated Zn emissions 1990-2004 for wood combustion in the residential sector; total Zn emissions (ton) before revision and Zn emissions (ton) after revision.

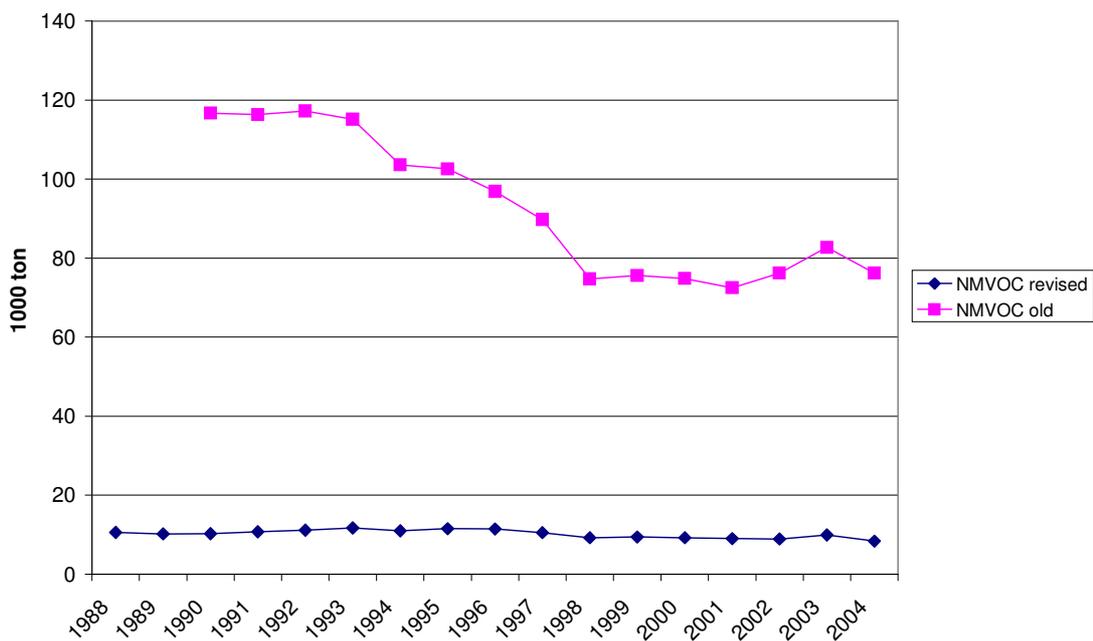


Figure 7. Recalculated NMVOC emissions 1988-2004 for wood combustion in the residential sector; total NMVOC emissions (1000 ton) before revision and NMVOC emissions (1000 ton) after revision.

5 Discussion

In this study data from several recent measurements as well as disaggregation of emissions factors by technology and fuel has lead to quite large differences between previously used values and the revised emission factors presented. In particular the new emission factors for NMVOC and particles are much lower whereas the new emission factors for CO and dioxin are higher. The explanation for this is that these new emission factors are based on data from more measurements. Recently there have been several studies carried out in Sweden on in-field measurements of emissions from wood log boilers and stoves. A lot of new data of emissions from wood combustion and new knowledge about firing behaviour has been obtained. To decrease the uncertainty of emission factors it is important that the result is based on many measurements, especially in-field measurements as they take into account factors such as the complete combustion process, consisting of combustion unit, flue pipe, chimney and the habitual practice of the operators (e.g. maintenance, storage of fuels). Due to these factors, in field measurements of emissions generally show higher values than measurements under laboratory conditions.

Modern wood boilers with storage tank, modern wood stoves as well as units for continuous burning of wood chips and wood pellets showed the lowest values for the pollutants of incomplete combustion. However, there are significant variations in emission factors for specific combustion appliances and operation conditions. Two recent Swedish studies (Johansson, 2006, Paulrud, 2006) have also shown that the differences in level of emissions from new and old burning equipment (stoves and boilers) and the importance of start-ups is less than was thought earlier.

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