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ScienceDirect

Energy Procedia 105 (2017) 1022 – 1028

Energy Procedia

The 8th International Conference on Applied Energy – ICAE2016

Recommended revisions of Norwegian emission factors for wood stoves

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Abstract

In this paper we present recommended revisions of emission factors for Norwegian wood stoves. Emission factors exist for a number of emissions to air, and vary in a wide range between individual studies depending on the technology, operating condition and fuel studied. This is a challenge when authorities need to decide on emission factors for inclusion in national emission inventories. In these inventories, emission factors need to be representative on a national level and include firing habits and technology in use. Herein lies a considerable challenge, resulting in large uncertainties for a number of the emission factors. In addition, value chain analysis is becoming increasingly common to assess the influence of the different elements in the value chain on different impact factors or stressors. For the wood stove value chain, the conversion element, i.e. the combustion process and the resulting emissions, is most important for most of the impact factors. It is essential for the outcome of such analyses that the best available emission factors are used to be able to assess the current impact of these as well as the improvement potential. Hence, it becomes increasingly important to select or derive representative emission factors, at a sufficient detailing level. In this work, recommended emission factors for wood stoves to be used in Norwegian value chain analysis are proposed.

Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.

Keywords: Wood logs, Combustion, Wood stoves, Emission factors, Emission inventories, Value chain analysis

1. Introduction

Specific knowledge regarding both air and water anthropogenic pollutant emissions as well as emissions affecting the climate, from all the various sources that surround us are important for authorities and other decision taking organs when gathering and reporting national inventories and deciding future strategies for emission reduction both on national and international levels. Nowadays authorities tend to focus much of their efforts towards emissions contributing to global warming as well as emissions that are health threatening to human beings.

Despite technology improvements resulting in a steady reduction in pollutant emissions over the last years, air pollution is still responsible for almost half-a-million early deaths in Europe every year [1] as well as having a negative effect on the ecosystem and flora. Transportation, industry and power plants, agriculture, households and waste handling are all important sources of emissions in Europe. Emissions of the main air pollutants in Europe have

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Peer-review under responsibility of the scientific committee of the 8th International Conference on Applied Energy.
doi:10.1016/j.egypro.2017.03.447

decreased in recent decades resulting in better air quality. Despite this, certain sectors have not been able to decrease their emissions, but rather seen an increase for some pollutants, mainly due to increased activity in these sectors. Fine particulate matter emissions from coal and biomass combustion in dwellings and from commercial and institutional buildings have increased in the EU by approximately 9% and 11%, respectively, between 2003 and 2012 [2]. Such sources are now among the highest emitters of particles in the EU. On the other side, the last IPCC Assessment report highlighted the importance of bioenergy as a mitigation measure to limit global warming, mainly due to its CO_2 neutrality.

In Norway, direct utilization of heat using wood stoves is the largest bioenergy value chain. Although bioenergy is a renewable energy source and part of the solution to decelerate global warming, it has potential for local air pollution. Using value chain analysis implementing the best available emission factors related to different stove technologies, to study these tradeoffs is important for a better understanding. Improvements in wood stove technology will influence the emission profile, but technology improvements have monetary costs. Micro- to small-scale residential solid biomass combustion (stoves, boilers) has long traditions in the Nordic region. The 2014 total Nordic residential heat production from solid biomass (logs, pellets, chips) in these installations was approximately 50 TWh with a Norwegian consumption of 8 TWh, or 44 % of the total gross inland bioenergy consumption.

A number of emission studies from wood stoves have been performed in Europe, however, they mainly reflect the local/regional characteristics and are not applicable for countries with other individualities. Wood heating characteristics in Europe differs a lot from country to country. Both heating patterns and technologies in use vary due to differences such as climate, type of building, access to resources, type of basic heating and firing traditions. Further, several emission measurement methods are in use due to the lack of one common method in Europe, leading to major differences in reported emission factors [3]. The most common technology in Norway for biomass space heating is wood stoves with an average heat output of 6-8 kW [4]. Wood stoves in Norway are mainly fired with reduced air inlet openings giving reduced heat output [5], resulting in more unfavourable combustion conditions and higher emissions. The European guidebook "EMEP/EEA air pollutant emission inventory guidebook 2013" contains emission factors for wood stoves. A closer look at the references reveals that data are based on non-representative studies, e.g. in Portugal on a fireplace insert with a high nominal heat output of 14 kW, significantly higher than what is normally used in Norway. The test batch was almost 3 times the size what is usual in Norway [5]. Different types of wood were tested, which are typical for Portugal and resulting in PM emissions varying from 6.7 to 16.3 g/kg, showing the influence of the wood type [6]. The influence of the test batch size on emissions is shown by Schön et al. [7]. Hence, the data from Portugal is little representative for Norway.

The main goal of this work was to collect and evaluate in-house and literature data to either confirm the existing emission factors or suggest revised emission factors for wood stoves, reflecting the so-called Norwegian firing pattern. The emission factors were separated into several selected levels necessary to establish a sufficient breakdown for the planned life cycle analysis (LCA), as shown in Table 1. A real need for revising individual emission factors can significantly change their relative contribution to the different environmental and health impact factors and the relative importance of these factors. Additionally, wood stove efficiencies have been evaluated, to asses if there is a need for adjusting the current efficiencies used.

Table 1: Categories where emission factors needs to be established in order to achieve a sufficient break down for the LCA analysis

Stage I (treated in this paper)	A. Old combustion technology < 1998 A.1 8 kW average nominal heat output A.2 4 kW part load heat output B. Current combustion technology (2014) ≥ 1998 B.1 8 kW average nominal heat output B.2 4 kW part load heat output
Stage II (future work)	C. New combustion technology ≥ 2015 C.1 2-4 kW average nominal heat output C.2 1-2 kW part load heat output D. New combustion technology, light heat storage ≥ 2015 D.1 1-4 kW average nominal heat output E. Pellet/multifuel combustion technology E.1 1-4 kW average nominal heat output

2. Current emission factors for Norwegian wood stoves

Today Norway is requested to report emissions to UNECE for the pollutants restricted by CLRTAP. The emission factor used for e.g. particle emissions from wood log combustion in the Statistics Norway (SSB) and the Norwegian Environment Agency (Miljødirektoratet) emission model before 2001 [8] was 10 g/kg dry wood. At that time, one did not distinguish between wood stoves and open fireplaces, nor between traditional and clean-burning technologies. Following the introduction of the Norwegian standard requirements for particle emissions in 1998, new figures were introduced in 2001. All 2001 emission factors related to wood log combustion are shown in Table 2. For stoves, it is distinguished between open fireplace and enclosed stove/fireplace with old or new (clean-burning) technology. The figures for enclosed stove/fireplace with old or new technology are documented by SSB and are partly based on measurements and expert judgments from SINTEF. Emission factors for fuel wood are based on data for different stove technologies and wood species. Stoves made in 1998 and later have significantly improved combustion and reduced emissions. The factors are weighted based on information from national surveys of the amount of wood burned in stoves with the different technologies. According to the IPCC guidelines, the CO_2 emissions from wood (biomass) firing are not included in the national total in the Norwegian emission inventory.

Table 2: Emission factors SSB/Miljødirektoratet recommended for fuel wood in the national emission inventory from year 2001, on left, and later revised or added emission factors, on right. dry matter basis [9]

	Open	Enclosed wood stove/fireplace		
	fireplace	Older than 1998	Newer, from 1998	Unit
PM_{10}	17.3	40	6.2	g/kg
CO	126.3	150	50.5	g/kg
SO_2	0.2	0.2	0.2	g/kg
NO_X	1.3	0.97	0.97	g/kg
N_2O	0.032	0.032	0.032	g/kg
CH_4	5.3	5.3	5.3	g/kg
NMVOC	7	7	7	g/kg
Cd	0.1	0.1	0.1	g/ton
PAH-total	17.4	52	0.0226	g/ton
PAH-6 (OSPAR)	6.1	8.1	0.045	g/ton
PAH-4 (LRTAP)	3	2.7	0.025	g/ton

	Open	Enclosed wood stove/fireplace		
	fireplace	Older than 1998	Newer, from 1998	Unit
TSP	17.3	22.7	13.4	g/kg
TSP large cities	17.3	17.4	12.2	g/kg
PM_{10}	17	22.2	13.1	g/kg
PM_{10} large cities	17	17.1	12	g/kg
$PM_{2.5}$	16.4	21.6	12.7	g/kg
$PM_{2.5}$ large cities	16.4	16.5	11.6	g/kg
NH_3	0.066	0.066	0.066	g/kg
Pb	0.05	0.05	0.05	g/ton
Hg	0.010244	0.010244	0.010244	g/ton
As	0.159	0.159	0.159	g/ton
Cr	0.152	0.152	0.152	g/ton
Cu	0.354	0.354	0.354	g/ton
Dioxins	5.9	5.9	5.9	µg/ton

In 2013, Norwegian emission factors for particulate emissions from wood stove firing, as TSP, PM_{10}, $PM_{2.5}$, EC and OC, were revised or added based on experiments performed by SINTEF in the BLACKOut project [4]. The revised or added factors as per the emission inventory 2013 are also given in Table 2. Particulate emissions are now specified as TSP, PM_{10} and $PM_{2.5}$ and categorized based on an assumption that stoves are used differently in large cities compared to the rest of the country. Only TSP was measured during the campaign and commonly used factors have been applied to derive PM_{10} and $PM_{2.5}$ from TSP. Additionally, factors for NH_3, Pb, Hg, As, Cr and Cu were introduced in the 2013 emission inventory, or earlier, but after 2001.

3. Recommended emission factors for Norwegian wood stoves

In this work, recommended emission factors were elaborated as representative values from experimental activities performed on various stoves by SINTEF dating back several decades. Illustrations of some of the stoves tested are shown in Fig. 1. In addition the other current emission factors were evaluated, and new ones were suggested where better values than the existing ones used were found based on literature data or wood composition analyses (as max values based on element concentration in the wood), and comparison with emission factors for wood pellets and even charcoal were made. As some of the emission factors in use are actually used for rather different fuels, applications and hence operating conditions, the accuracy of these can be suspected to be highly questionable.

Fig. 1. Some selected stoves tested at SINTEF over the last decades.

Table 3 shows the recommended emission factors for enclosed wood stoves/fireplaces, for old and new technology, and for both part load and nominal load operation of these.

Table 3: Recommended emission factors for fuel wood, dry matter basis

	Enclosed wood stove/fireplace				
	Older than 1998		Newer, from 1998		
	Part load	Nominal load	Part load	Nominal load	Unit
TSP	35.1	3.8	11.1	2	g/kg
PM_{10}	33.7	3.5	11	2	g/kg
$PM_{2.5}$	30.2	3.5	10.4	1.9	g/kg
CO	126	57.5	103.1	45.2	g/kg
SO_2	0.3306	0.348	0.348	0.348	g/kg
NO_X	0.97	0.97	0.97	0.97	g/kg
N_2O	0.032	0.032	0.032	0.032	g/kg
NH_3	0.066	0	0	0	g/kg
CH_4	20.88	7.35	5.32	0.53	g/kg
NMVOC	31.3	5.54	21.2	1.26	g/kg
Cd	0.160	0.160	0.160	0.160	g/ton
Pb	0.487	0.487	0.487	0.487	g/ton
Hg	0.0025	0.0025	0.0025	0.0025	g/ton
As	0.00036	0.00036	0.00036	0.00036	g/ton
Cr	0.152	0.152	0.152	0.152	g/ton
Cu	0.354	0.354	0.354	0.354	g/ton
Dioxins	14.4	1.65	4.97	0.93	ug/ton
PAH-total	52	52	0.026	0.026	g/ton
PAH-6 (OSPAR)	8.1	8.1	0.045	0.045	g/ton
PAH-4 (LRTAP)	2.7	2.7	0.025	0.025	g/ton
EC	0.96	1.2	0.68	0.59	g/kg
OC	19.18	2.21	5.82	1.41	g/kg
CO_2 birch	1424	1708	1584	1764	g/kg
CO_2 spruce	1444	1728	1604	1784	g/kg

Based on the emission factors given as mass emissions per mass dry fuel, weighted emission factors can be calculated based the amount of wood used in the different wood stove categories. The current weighting procedure involves dividing in old and new technology and using reduced emission factors for large cities, where less part load operation is assumed. The weighted values are then presented in the national emission inventory. As there is a continuous replacement of old stoves with new ones, the weighted emission factors will change from year to year. The proposed revised weighting procedure assumes also a division between old and new stoves, and then these are divided into two categories, part load and nominal load operated. This is believed to be a more realistic division than the assumption of different emission factors for large cities and the rest of the country.

Taking the emission inventory 2013 as the reference, weighted emission factors have been calculated based on the current method and the proposed revised method and are presented in Table 4. The weighting according to the current method is for the emission inventory 2013 based on the following division between old and new stoves and fireplaces, **47.4**, **48.3** and **4.3** %, and wood used in large cities and the rest of the country, **6.3** and **93.7** %. The weighting according to the proposed revised method is based on the same division between old and new stoves, and the following division between wood used at part load and nominal load for the two categories, **65/35** and **70/30** %.

In our work, also efficiencies were evaluated for old and new stove technologies, and it was found that the current efficiency used for old technologies, i.e. **50** %, is too low. In fact, it was found that the efficiency of old stoves is quite close to those of new stoves, **67** and **65** % at part load and nominal load. The current used efficiency of new stoves, i.e. **70** %, is in line with what was found in this work, **72** and **69** % at part load and nominal load. When comparing emission levels per unit of utilized energy, this makes a big difference, also in LCA analysis presenting impacts based on energy units.

Table 4: Current and recommended weighted emission factors for fuel wood, dry matter basis, and comparison with other fuels and technologies

	stoves	stoves	stoves	stoves	boilers	boilers	boilers	boilers	stoves	stoves	
	Fuel wood	**Fuel wood**									
	Current	**Recommended**	**Wood pellets**	**Charcoal**	**Wood waste**	**Black liquor**	**Wood pellets**	**Wood briquettes**	**Coal**	**Coke**	**Unit**
TSP	17.78	16.23	1.1	2.4	**2.69**	0	**2.69**	**2.69**	4.2	2.85	g/kg
PM_{10}	17.43	15.70	1.1	2.4	**2.52**	0	**2.52**	**2.52**	2.8	1.71	g/kg
$PM_{2.5}$	16.89	14.38	1.1	2.4	**2.52**	0	**2.52**	**2.52**	0.86	0.86	g/kg
CO	101.2	95.2	2.6	100	**15**	0	**15**	**15**	3	3	g/kg
SO_2	0.2	0.34	-	-	**0.37**	**0.37**	-	-	20	18	g/kg
NO_X	0.986	0.98	1.1	1.4	**0.9**	**0.9**	**1.3**	**1.3**	3	3	g/kg
N_2O	0.032	0.032	0.032	**0.04**	**0.07**	**0.07**	**0.07**	**0.07**	**0.04**	0.04	g/kg
NH_3	0.066	0.023	0.066	-	0	0	0	0	0	0	g/kg
CH_4	5.3	9.76	5.3	**8.4**	**0.25**	**0.25**	**0.25**	**0.25**	**8.4**	8.4	g/kg
NMVOC	7	18.22	6.501	10	**1.3**	-	**1.3**	**1.3**	1.1	0.6	g/kg
Cd	**0.1**	0.158	-	-	**0.1**	**0.1**	-	-	0.15	0.15	g/ton
Pb	**0.05**	0.468	-	-	**0.05**	**0.05**	-	-	2.5	2.5	g/ton
Hg	**0.010244**	0.0028	-	-	**0.010244**	**0.010244**	-	-	0.3	0.3	g/ton
As	**0.159**	0.00716	-	-	**0.159**	**0.159**	-	-	1.2	1.2	g/ton
Cr	**0.152**	0.152	-	-	**0.152**	**0.152**	-	-	0.9	0.9	g/ton
Cu	**0.354**	0.354	-	-	**0.354**	**0.354**	-	-	1.2	1.2	g/ton
Dioxins	5.9	6.78	5.9	**10**	**1**	**1**	**1**	**1**	**10**	10	μg/ton
PAH-total	25.41	25.41	38.8	**39.9**	**0.18**	**0.18**	**0.16**	**0.16**	**39.9**	27.8	g/ton
PAH-6 (OSPAR)	4.13	4.12	6.8	**18**	**0.061**	**0.061**	**0.061**	**0.061**	**18**	13.4	g/ton
PAH-4 (LRTAP)	1.42	1.42	2.5	**2.6**	**0.016**	**0.016**	**0.016**	**0.016**	**2.6**	0.4	g/ton

When comparing the weighted emission factors calculated based on the current and proposed revised method, as well as critically evaluating the accuracy of the emission factors, the following conclusions and recommendations can be given:

1) For TSP, PM_{10}, $PM_{2.5}$ and CO slightly lower weighted emission factors are recommended based on experiments. 2) For SO_2 a higher emission factor is suggested based on fuel composition analysis. 3) For NOx and N_2O, no change in the emission factors are recommended. 4) For NH_3, a much lower value is recommended, as NH_3 is expected to be emitted only at part load operation of old stoves. 5) For CH_4 and NMVOC, higher emission factors are recommended based on experiments. 6) For the heavy metals, changes have been recommended, based on fuel composition analysis, for Cd, Pb, Hg, and As, while no change has been recommended for Cr and Cu. 7) For dioxins a slightly higher value has been recommended, and significant differentiation between the four categories of old and new technology, operated at part load or nominal load. 8) For PAH, no changes have been recommended, due to no new experimental data available.

When comparing the current emission factors with those of other relevant fuels and technologies, the following main observations can be made:

1) Identical emission factors have been set in many cases for different fuels and even for different technologies (stoves, boilers). 2) Wood waste used in boilers has frequently identical emission factors with wood pellets and briquettes used in boilers. 3) Fuel wood heavy metal emission factors are identical to those of waste wood and black liquor. 4) Charcoal and coal emission factors are identical for several compounds. 5) Dioxin levels in boilers are very low compared to stoves, which support the differentiation of dioxin emission factors between the four recommended stove categories. 6) Wood pellets and wood briquettes have significantly higher NOx emission levels

than waste wood and fuel wood, which is hard to defend. 7) N_2O emission factors for boilers are significantly higher than for stoves, which is hard to defend.

Hence, further work should focus on increasing the accuracy and representativeness of several of the emission factors used for fuel wood, however, prioritizing those emissions that are most important for LCA analysis. This is not an easy task, since even though the impact factors/stressors relatively easily can be calculated, the relative importance of these will in practice be different. LCA analysis work for the wood stove value chain, using the recommended emission factors, would identify the most critical compounds emitted with respect to the relevant impact factors or stressor. Hence, this work and further LCA analysis could aid authorities with respect to further efforts of establishing a more accurate emission inventory for the wood stove value chain. When comparing the emission factors used for all the biomass fuels used in stoves and boilers it becomes quite clear that identical emission factors are used in cases where this is not reasonable. Hence, more realistic emission factors should be sought for inclusion in future emission inventories and LCA analysis of the corresponding biomass value chains.

4. Conclusions

In this work, the review of current emission factors used for fuel wood in the Norwegian national emission inventory combined with new knowledge derived through experiments and fuel composition analysis has revealed a real need of updating some of the emission factors, while others have basically been confirmed. When comparing emission factors used for biomass fuels in stoves and boilers, and even with coal and coke in stoves, it becomes clear that there is an extensive use of identical emission factors for different fuels as well as different technologies. This approach is hard to defend, and more realistic emission factors should be sought.

The approach used in this work to derive weighted emissions factors, to be used in the Norwegian national emission inventory, is believed to be more realistic than the current one used, since it differentiates clearly between part load and nominal load operation. This approach could be extended in the future to include downscaled wood stoves for energy efficient buildings.

Acknowledgements

The authors acknowledge the financial support from CenBio - Bioenergy Innovation Centre, which is one of Norway's Centers for Environment-friendly Energy Research (FME) co-funded by the Research Council of Norway.

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Biography

Morten Seljeskog, born in 1964 – holds a Doctor of Engineering (Dr.ing) from the Norwegian University of Science and Technology defended in 2002 on the topic of shock tubes and cold plasma experiments. He is currently employed, since 1998, as a researcher at SINTEF Energy Research working on industry-oriented projects towards both develop-ment/use of simulation tools as well as prototype equipment for thermal conversion of gaseous, liquid and solid fuels. Since 2009 he is project leader for the EUFP7 DECARBit project, 48 months - 15.5 million €, with a total of 16 European industrial and research partners, funded by EU FP7.