IMPROVED PM EMISSIONS INVENTORY FOR RESIDENTIAL WOOD COMBUSTION

J. B. Illerup & M. Nielsen
National Environmental Research Institute, Frederiksborgvej 399, P.O. Box 358, DK-4000 Roskilde Denmark. E-mail: jbi@dmu.dk

Introduction
In many countries residential wood combustion is an important source to particulate matter (PM) emissions and this paper focuses on how to improve the fine particulate matter (PM_{2.5}) emission inventory for the residential wood combustion sector.

Parties to the Long-Range Transboundary Air Pollution (LRTAP) Convention are obliged to report sectoral PM emissions. These national submitted emission data are used for different purposes by several international organisations, e.g. for modelling purposes of various kind. However, current emissions inventories on PM are quite uncertain because national official statistics concerning wooden fuels used in residential combustion often are too aggregated to estimate technology dependent PM emissions. In order to improve the reliability of total emissions and be able to suggest possible reduction measures it is necessary to estimate the national composition of equipment and technology used for wood combustion and the corresponding emission factors.

The present estimation method is exemplified by estimation of activity data and emission factors for Danish conditions. For Denmark the revised PM_{2.5} emission estimates result in considerably – almost five times – higher PM_{2.5} emissions compared to the latest officially reported PM emissions.

Background
At the beginning of 2002 the first Danish emission inventory of particulate matter (PM) was prepared for the year 2000 (Nielsen et al., 2003). The emission inventory was part of the Danish emission inventories reported under the UN-ECE Long-Range Transboundary Air Pollution (LRTAP) Convention. The inventory included total suspended particles (TSP), PM_{10} and PM_{2.5} and was considered to be a provisional version based on activity data and emission factors presently available. The inventory was based on total wood consumption data for the residential sector reported by the Danish Energy Authority and an emission factor of 150 g TSP/GJ recommended in the Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance (CEPMEIP, 2002). A literature survey by Nielsen et al. (2003) showed a wide variation in the reported PM emission factors. The range was from about 100 to 2000 g/GJ and the accuracy of the provisional inventory for residential wood combustion was therefore considered to be low. The TSP, PM_{10} and PM_{2.5} emissions for wood combustion in residential plants in the year 2002 was estimated to be 2214 tonnes, 2111 tonnes and 1993 tonnes (Illerup et al., 2004).

The TNO institute in the Netherlands has calculated a European emission inventory within the CEPMEIP project and provided default emission factors in the reporting guidelines prepared jointly with EMEP and IIASA. TNO gives default TSP emission factors in the interval 150 to 300 g/GJ. In the calculations of the PM emissions for Denmark, TNO used the TSP emission factor 150 mg/MJ for combustion of wood, whether it was combusted in e.g. an institutional boiler or a residential stove. The TSP emission factor 300 mg/MJ was only used for countries where the general emission level is expected to be high.

The improvement of the Danish PM emission inventory was initiated through the work in the ‘Nordic network for emissions of primary particulate matter, measures and their costs’. The
The purpose of the network was to compare and harmonise the data regarding PM$_{2.5}$ emissions and cost-efficient measures in the residential wood combustion sector in the Nordic countries (Sternhufvud et al., 2004).

**Methodology**

In order to improve the PM emission inventory it is necessary to have information about the types of technologies used for wood burning in a given country. From knowledge of the numbers of stoves/boilers and the corresponding emissions factors the PM emission estimate can be improved. In the present method wood consumption rates for the various types of stoves/boilers are estimated from aggregated information on wood consumption in households given in official energy statistics.

**Activity data**

The total use of wooden fuel in Denmark is presented in Figure 1 for different categories of wood fuel. Wood fuel that has not been traded (private woodcutting) is considered to account for a considerable part of the total consumption of wood fuel in the residential sector. The total consumption is estimated to be 3 times the traded wood fuel (Nielsen & Evald, 2000). The factor 3 is determined from three independent questionnaires where the origin of wood fuel used in residential combustion was examined. The data on consumption of wood fuel in the residential sector from the energy statistics are thus uncertain but is the best estimate that can currently be given. The Danish energy statistics distinguishes between wood chips, firewood (wood logs), wood pellets, and wood waste. The dominant wood type used in the domestic sector is firewood and about 20% of the wood are pellets mostly used in small boilers with automatic fuel feeding systems.

![Figure 1. Wooden fuel consumption in TJ/year of wood chips, firewood, wood pellets and wood waste in different sectors in Denmark in 2002.](http://www.ds.dk/2117)

The Danish Technological Institute (Nikolaisen, 2002) has ultimo 2001 estimated that there are about 300 000 stoves in Denmark and 90 000 small-scale boilers using wood. There are about 65 000 conventional boilers (old firewood boilers) and 25 000 modern boilers. For the modern boilers about 20 000 are pellet boilers and 5 000 new firewood boilers with accumulator tanks. Information on wooden fuel used in Denmark can be seen in Nikolaisen et al. (1998).

Since 2004 it has been possible for Danish wood burning stoves to obtain the Nordic certification mark the ‘Swan’ ([http://www.ds.dk/2117](http://www.ds.dk/2117)). The emission limit value for these stoves is 10 g/kg (640 mg/MJ) as an average of one measurement at nominal load and 2 measurements at low load. Danish Standards Association (Christensen, 2004) has estimated that about one third of the stoves sold in Denmark in 2004 will meet this value. All stoves in Denmark are conventional and they are in this work classified as old or new stoves. It is assumed that 10% of the 300 000 stoves in 2000 was new stoves and new stoves replace
10,000 old stoves each of the following year. The Danish Association of Fireplaces and Stove Producers (DAPO) (Ågård, 2004) have stated that about 30,000 stoves are sold per year.

Pellet boilers are the only combustion appliance using wood pellets and the number of pellet boilers are therefore estimated from the amount of wood pellets given in the energy statistics and assumptions on the heat capacity of the boilers and the heating value of wood pellets. The development of the number of pellet boilers therefore reflects the trend in wood pellet use.

In order to be able to distribute the wood consumption on various types of stoves and boilers average wood consumption rate per year has to be estimated for each type of combustion appliances. The Danish Technology Institute (Winther, 2004) has estimated the consumption rates for each type of technology listed in Table 1. This table also shows the number of stoves/boilers and the total wood combustion. The lower heating values of wood at Danish conditions are 6.2 GJ/m³ firewood and 17.6 GJ/ton wood pellets (Winther, 2004).

Table 1. Yearly residential wood consumption by stoves/boilers and number of stoves/boilers in 2002.

<table>
<thead>
<tr>
<th>Combustion rate</th>
<th>Number of units</th>
<th>Total wood combustion/year (TJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old stoves</td>
<td>4.5 m³/year/stove</td>
<td>250,000</td>
</tr>
<tr>
<td>New stoves</td>
<td>4.5 m³/year/stove</td>
<td>50,000</td>
</tr>
<tr>
<td>Old boilers</td>
<td>6 m³/year/boiler</td>
<td>65,000</td>
</tr>
<tr>
<td>Pellets boilers</td>
<td>10 tonnes/year/boiler</td>
<td>19,256</td>
</tr>
<tr>
<td>Boilers with accumulation tanks</td>
<td>30 m³/year/boiler</td>
<td>5,000</td>
</tr>
</tbody>
</table>

The presented figures on the fuel consumption are of necessity a simplification of reality, but estimated at best available knowledge.

![Figure 2. Total wood consumption in the residential sector, 2000-2003.](image)

**Emission factors**

PM emission factors are often quite uncertain because it is difficult to estimate standard emission factors from measurements since the emissions from stoves and domestic boilers very much depend on the combustion conditions and technologies. As part of the Nordic project ‘Particulate matter emissions and abatement options in the residential wood burning in the Nordic countries’ (Sternhufvud et al., 2004) technology dependent emission factors based on measurements and investigations in the Nordic countries was compared. From this comparison harmonised PM emission factors were assigned for all relevant technologies for the four Nordic countries. These emission factors are used as a basis for estimation of the Danish technology dependence emission factors given in Table 2.
Table 2. PM emission factors used for the Danish improved PM emission inventory (g/GJ).

<table>
<thead>
<tr>
<th></th>
<th>TSP</th>
<th>PM_{10}</th>
<th>PM_{2.5}</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old stoves</td>
<td>1 100</td>
<td>1 045</td>
<td>990</td>
<td>a</td>
</tr>
<tr>
<td>New stoves</td>
<td>640</td>
<td>608</td>
<td>576</td>
<td>b</td>
</tr>
<tr>
<td>Old boilers</td>
<td>900</td>
<td>855</td>
<td>810</td>
<td>c</td>
</tr>
<tr>
<td>Pellets boilers</td>
<td>95</td>
<td>90</td>
<td>86</td>
<td>c</td>
</tr>
<tr>
<td>Boilers with accumulation tanks</td>
<td>95</td>
<td>90</td>
<td>86</td>
<td>c</td>
</tr>
</tbody>
</table>


The PM\textsubscript{2.5} emission factor for old stoves are based on Norwegian measurements on various types of stoves and assumption on the wood load (Haakonsen & Kvingedal, 2001). The Norwegian measurements have shown that emissions of particles strongly depend on the wood load (kg wood/hour) (Haakonsen and Kvingedal, 2001). Figure 3 shows the emission of PM for various combustion technologies as a function of average wood consumption. It shows that the PM emission increases dramatically when the consumption rate of wood decreases. It also shows that the emissions are significantly lower for stoves tested in laboratory and for catalytic stoves. In Denmark a typical load is about 2 kg wood/hour or about 1.7 kg dry wood/hour (Winther, 2004; Christensen, 2004). From figure 3 it is seen that the corresponding TSP emission factor is about 20 kg/tonnes wood for old conventional stoves or 1100 g/GJ assuming a lower heating value of 19 GJ/tonnes of dry wood (Christensen, 2004). This is a considerably higher emission factor than the emission factor of 150 – 300 g/GJ recommended by TNO (CEPMEIP, 2002) and used in the former official Danish PM emission inventory.

The emission factor for new stoves is assumed to equal the emission limit value of 10 g/kg for Swan certified stoves. This is about the same value as Norwegian stove producers have stated for new Norwegian stoves (Karlsvik, 2004).

The emission factors of 20 g/kg and 10 g/kg are supported by measurements carried out by the U.S. Environmental Protection Agency (US EPA 1996; Correll et al., 1997) where emission factors for old and new stoves are reported to be about 22 g/kg and 10 g/kg respectively. Not yet published results of emission measurements on wood burning stoves in a Danish residential area carried out by the National Environmental Research Institute of Denmark during the winter 2004 show a large variation in the emission level and indicate an average emission factor equivalent to the emission factor used in the improved PM estimates.
Figure 3. PM emission of 6 wood fired stoves. Dependency of wood consumption rate. A: catalytic stove, B-D: old stoves, E: open fireplace (Haakonsen and Kvingedal, 2001).

The emission factors for boilers are based on Swedish measurements on conventional and modern boilers carried out by Johansson et al. (2003). PM emissions from boilers equipped with accumulator tank are lower than if an accumulator tank system is not installed, since the existence of an accumulator tank permits more efficient firing.

The PM$_{10}$ and PM$_{2.5}$ emission factors are estimated as 95% and 90% of the TSP emission (CEPMEIP, 2002) and the factors in Table 2 are used in the calculations of the emission estimates given below.

From the emission factors in Table 2 and the yearly wood consumption rates in figure 2 implied emissions factors for residential wood combustion in Denmark are estimated (Table 3).

Table 3. Implied emissions factors for residential wood combustion in Denmark (g/GJ).

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSP</td>
<td>807</td>
<td>743</td>
<td>720</td>
<td>715</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>767</td>
<td>706</td>
<td>684</td>
<td>679</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>726</td>
<td>669</td>
<td>648</td>
<td>643</td>
</tr>
</tbody>
</table>

**Improved PM emission estimate**

Table 4 and Figure 4 shows the improved PM$_{2.5}$ emission estimates for the years 2000 to 2003. The graphs in Figure 4 reflects an increasing use of pellet boilers and new stoves, however, old stoves are still the most important PM emission source compared with other wood burning residential plants.

Table 4. Revised PM$_{2.5}$ emission estimates for the years 2000 to 2003 (tonnes).

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old stoves</td>
<td>7 469</td>
<td>7 353</td>
<td>6 706</td>
<td>6 570</td>
</tr>
<tr>
<td>New stoves</td>
<td>483</td>
<td>658</td>
<td>780</td>
<td>956</td>
</tr>
<tr>
<td>Old boilers</td>
<td>1 961</td>
<td>2 005</td>
<td>1 902</td>
<td>1 941</td>
</tr>
<tr>
<td>Pellets boilers</td>
<td>67</td>
<td>102</td>
<td>107</td>
<td>107</td>
</tr>
<tr>
<td>Boilers with accumulation tanks</td>
<td>80</td>
<td>81</td>
<td>77</td>
<td>79</td>
</tr>
<tr>
<td>Total</td>
<td>10 059</td>
<td>10 201</td>
<td>9 573</td>
<td>9 652</td>
</tr>
</tbody>
</table>
Figure 4. Revised PM$_{2.5}$ emission estimates for residential wood combustion in the years 2000 to 2003.

The revised emission estimates result in considerably higher PM$_{2.5}$ emissions, about 9 500 tons in 2002 as compared to the 2 000 tonnes estimated by the method used in the latest official report to UNECE. It appears that combustion of wood is the primary emission source (Figure 5) in spite of the limited consumption of this fuel (Figure 6). Emission of PM$_{2.5}$ from wood burning residential plants makes up a total of 85% of emission from all stationary combustion plants in Denmark.

Figure 5. PM$_{2.5}$ emission from residential plants for 2002 distributed on fuel types (improved inventory)

Figure 6. Fuel consumption in residential plants for 2002 distributed on fuel types

Figure 7 shows the total Danish PM emission for all sources. It is seen that the three largest sources to PM$_{2.5}$ emissions are residential plants (47%), road transport (20%) and other mobile source (17%). However, it should be stressed that the PM emission inventory, especially for residential wood combustion, is quite uncertain due to very limited national knowledge of emissions from wood burning stoves at present.
Conclusions and future work

The work has resulted in a more detailed calculation of fine particulate matter emissions from residential wood burning employing a classification, which is based on the technological differences in burning but a compromise of data availability for activities and emission factors. The classification used in this study is more detailed than in the former official inventories. The allocation to technological sub categories is made by combining information from national investigations (Winther, 2004, Nikolaisen, 2002) and expert judgement. The single default emission factor for the whole sector is replaced with data from other Nordic countries. The improved PM emission inventory will be implemented in the next official Danish inventory, which is going to be submitted February 2005 to the LRTAP Convention.

The improved Danish PM inventory is still quite uncertain and will be revised when new knowledge on emissions from residential wood combustion becomes available.

Furthermore future work will include more detailed technological sub-categorisation, in order to point out technologies with potential low PM emissions. However, the fuel quality and burning techniques may have a greater uncertainty than the burning technology and they are extremely difficult to quantify. Since they affect some technological sub-sectors more strongly than others (e.g. manually fed iron stoves vs. automatically fed pellet boilers), the most uncertain sub-sectors may be pointed out for more assessment work.

References


