FINE PARTICULATE MATTER EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION AND REDUCTION POTENTIAL IN THE NORDIC COUNTRIES

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ABSTRACT

Residential wood combustion is relatively common in the Nordic countries, and it has been considered a potential way to reduce greenhouse gas emissions. However, other emissions, *e.g.* fine particulate matter (PM2.5), may be considerable. Current emission inventories comprise relatively coarse and simplified estimates for the residential sector. In this study, current heterogeneous PM2.5 emission estimates from residential wood combustion in the Nordic countries were harmonised. Volumes of wood use and originally very different default emission factors specific to combustion technologies were reassessed for each country, and the total PM2.5 emissions were calculated. Potential emission reduction measures were explored. A case study on the fuel switch from logs to pellets was carried out to quantify reduction potentials and their cost-effectiveness. The PM2.5 emissions from the residential sector in 2000 in this study were 13, 8, 40 and 20 kton (52, 26, 69 and 42% of total PM2.5 emissions) in Denmark, Finland, Norway and Sweden, respectively. Fuel switch to pellets was found to have a large emission reduction potential of 18 kton(PM2.5)/a in the Nordic countries, with a cost-efficiency of 3000-16000 euro/ton reduced PM2.5. This study founded a basis for a detailed and harmonised estimate of residential wood combustion emissions using all available measurement data from the Nordic countries. The improved emission estimates will be used to evaluate the background material in the expected revisions of air pollution agreements in Europe.

INTRODUCTION

Concern about climate change and the extinction of fossil energy resources have increased the pressure for renewable energy utilization, *e.g.* wood combustion. Wood is the most important indigenous fuel-based energy source in the Nordic countries. Total wood fuel use in the year 2000 was 24, 127, 50 and 157 PJ in Denmark, Finland, Norway and Sweden, respectively. Because of northern location, heating season of residential houses is relatively long, and heating by wood combustion is common in all the Nordic countries. Wood was used in the residential sector 12, 39, 23 and 41 PJ in Denmark, Finland, Norway and Sweden, respectively.

Residential wood combustion takes place in different kinds of stoves, ovens, fireplaces and small boilers. Some of these appliances are mechanically relatively simple, and the characteristics of combustion process control are inadequate. In addition, since logs are often chopped and dried by the user, fuel quality (*e.g.* moisture content) might be unequal, and the burning habits also affect the emissions. Resulting incomplete combustion leads to low efficiency and high emissions of hydrocarbon and soot particles. On the other hand, many types of modern equipment are more sophisticated, and PM emissions are low. Pellet combustion, for example, entails high efficiency and low emissions.

Air pollutant emissions have been estimated in national inventories submitted to UNECE. PM2.5 emissions from residential wood combustion in 2000 contributed to 1600, 15000, 38500 and 17500 tons, or 12, 40, 69 and 39% of country total emissions in Denmark, Finland, Norway and Sweden, respectively. The emissions for the whole residential sector are calculated using one wood use volume and national average emission factor value. The average emission factors used in the inventories vary widely between the countries (135, 384, 1932 and 520 mg(PM2.5)/MJ in Denmark, Finland, Norway and Sweden, respectively). The basis for the selection of emission factors vary as well: in Sweden and Norway the emission factors are based on national measurements [1,2], in Finland they are loosely based on relatively old measurements [3], and in Denmark on European default emission factor [4].

The first objective of this study was to estimate the residential wood use volumes and PM emission factors of different types of wood combustion equipment in the Nordic countries in a harmonized way. Secondly, the potential for emission reductions in the residential sector was explored, and a case study on one potential reduction measure, *i.e.* fuel switch from logs to pellets, was carried out.

METHODOLOGY AND MATERIAL

This study was carried out in a Nordic project with representatives from Denmark, Finland, Norway and Sweden. The purpose of the study was to compare and harmonise the data regarding PM2.5 emissions in the residential wood combustion sector, and estimate cost-efficient emission reduction measures.

Literature information on the prevalence of different wood combustion appliances was scarce [5,6,7,8]. Classification of appliances was made taken into account data availability and differences in emission characteristics. Wood use volumes in different appliances were mainly estimated based on national expert estimates (*e.g.* S. Tuomi, Finnish Work Efficiency Institute, 2003; M. Schöllin, Statistics Sweden, 2003; G. Haakonson, Statistics Norway, 2003). The emission factors were estimated using all available Nordic measurement data [1,2,3,9] and expert estimates by the measurers. Emission factors for each combustion appliance class were assumed country-independent.

Potential PM emission reduction measures were explored based on literature and expert estimates. Quantitative calculation on emission reduction potential and costs was carried out for fuel switch from log boilers without accumulator system to modern low-emission pellet boilers. Heating costs, PM2.5 emissions and unit costs for emission reduction were calculated for a typical single-family household comparing an old log boiler without investment cost, and a new pellet boiler including amortization of investment (4% interest rate, 20a pay-back time). Calculation parameters were estimated based on literature [10] and expert estimates. The basis for the emission and case study calculations are presented in more detail in Sternhufvud *et al.* (2004) [11].

RESULTS AND DISCUSSION

Technology-dependent wood use and emissions

Wood use quantities and PM2.5 emission factors were estimated for different kinds of combustion appliances, and PM2.5 emissions were calculated (Table 1). Wood use vary strongly between the countries. Combustion in log boilers is most common in Denmark, Finland and Sweden. The use of accumulator tanks is prevailing only in Finland. In Norway nearly all wood is combusted in iron stoves. Other types of stoves and ovens are common in Finland and Sweden.

Emission factors vary between different appliances, from 20 mg(PM2.5)/MJ of pellet stoves to 2000 mg(PM2.5)/MJ of conventional iron stoves. The emissions vary strongly between the countries. Calculated national average emission factors based on activity/technology use pattern and technology dependent emission factors were 1100, 200, 1800 and 500 mg(PM2.5)/MJ in Denmark, Finland, Norway and Sweden, respectively.

The emissions calculated in this study differed substantially for Denmark and Finland when compared to official inventory numbers, in which the emission factors used are not based on reliable national measurements. For Sweden and Norway the officially used emission factors are based on national measurements, and the emissions of this study are in the same order of magnitude. This indicates that the emission factors used in inventories may be incorrect for Denmark and Finland. Due to the scarcity of Nordic emission measurements of different types of appliances, the emission factors were harmonized by applying from single measurement study results to the whole combustion appliance class in all four Nordic countries. However, this is also a source of uncertainty when country-specific emissions are assessed. For instance, the high emission factor of conventional iron stoves was derived from Norwegian stove measurements [2], and therefore justifiably explains the high emissions in Norway. However, the use of the estimate with Danish iron stoves should be evaluated.

Table 1. Energy consumption, PM2.5 emission factors and emissions in residential wood combustion appliances in the Nordic countries in 2000.

	Wood use [TJ/a]				Em. factor [mg/MJ]	Emission [tons(PM2.5)/a]			
Country	*Denmark*	*Finland*	*Norway*	*Sweden*	*All*	*Denmark*	*Finland*	*Norway*	*Sweden*
Conventional manually fed boilers without accumulator tank	6 100	2 700	1 200	17 000	700	4 300	1 900	840	11 900
Conventional manually fed boilers with accumulator tank	470	5 400		3 500	80	38	430		280
Pellet boilers	1 100	100		1 800	30	32	3		54
Automatically fed boilers other than pellet		1 400			80		110		
Other low em. (*e.g.* certified) log boilers				1000	30				30
Conventional iron stoves	4 300	1 100	19 100	1 800	2 000	8 600	2 200	38 200	3 600
Modern iron stoves			1 500		300			450	
Masonry heaters and stoves		8 000		4 300	100		800		430
Masonry ovens		5 900			100		590		
Kitchen range/stoves		5 300		8 000[a]	100		530		800 [a]
Sauna stoves		8 600			100		860		
Pellet stoves				400	20				8
Open fireplaces		600	860	3 400	800		480	690	2 700
Total	**11 900**	**39 100**	**22 700**	**41 200**		**12 900**	**7 900**	**40 200**	**19 800**
Emission derived from official UNECE inventory						1 600	15 000	38 500[b]	17 500

a) Sum of kitchen stoves and masonry ovens.
b) Residential combustion of all fuels

Emission reduction measures

Technical PM emission reduction measures and political instruments promoting the reductions were explored. From political instruments, subsidies for low-emission installations and combustion appliance standardisation systems are used in the Nordic countries to some extent. However, there is little evidence on their effects on emissions. Since the way how the wood is combusted has a substantial effect on emissions, information campaigns on advisable combustion practises was identified as a potential reduction measure.

Technical emission reduction measures (Table 2) involve investments by the user. They are more suitable on central heating boiler systems than on small stoves. Largest potential was identified on manually fed log boilers that are used without heat accumulator. Log boilers that are not equipped with accumulator tank are often used with partial loads, which results in intermittent combustion and high emissions. Retrofit installation of accumulator tank has been found to have substantial effect on emissions [12]. However, space available for tank installation in heating room probably restricts applicability in many cases. Fuel switch to pellets, either by replacing old boiler with a pellet boiler or installing only pellet burner to existing log boiler, is less space demanding and therefore applicable in most cases. For new installations, possible advisable political instruments could be the compulsory use of accumulator tank use with log boilers, or promotion of pellet boiler installations.

Table 2. Most important identified technical emission reduction measures.

Measure	Reduction efficiency	Description	Current status and comments
Installation of accumulator tank	70%[12]	Installation on boilers that do not have accumulator tank at present. Use of log boiler without accumulator often results in high emissions.	Large potential. Heating room dimensions might restrict applicability in retrofit installations.
Fuel switch from logs to pellets	50-90%[13]	Installation of pellet boiler (or pellet burner to existing log boiler). Pellet boilers typically have lower emissions and better heat production efficiency than log boilers.	Large potential. Pellets are relatively common in Sweden, and increasing strongly in Finland.
Catalyst for wood burner	30%[14]	Catalytic burners are equipped with a honeycomb device coated with catalyst material that enhances the combustion of unburned compounds.	Not in use in the Nordic countries. Installations in the USA.
Secondary combustion chamber	30%[14]	Flue gases with unburned hydrocarbons are directed into a secondary chamber where they are mixed with fresh preheated air and after-burned.	Not in use in the Nordic countries. Installations in the USA.

Case study

Fuel switch to pellets, which was considered as the most potential technical emission reduction measure, was studied quantitatively in a case study (Table 3). Heat production costs in log and pellet boilers vary from country to country, mainly because of variability in fuel prices. Especially log prices vary widely. Furthermore, the prices are difficult to quantify when the logs are self-collected from own forest.

PM2.5 emissions decrease substantially due to fuel switch. The emission reduction potential, if all the log boilers that are not equipped with accumulator tanks are replaced, is roughly 18000 tons/a in the Nordic countries, varying from less than 1000 tons/a in Norway to more than 10000 tons/a in Sweden.

Unit costs of emission reduction vary from 5000 euro/ton(PM2.5) to 16000 euro/ton, depending mainly on assumptions on fuel prices. The unit costs are high when compared to *e.g.* electrostatic precipitator (ESP) retrofit installation in small (3 MW) district heat solid fuel boilers, where unit cost is typically around 300-500 euro/ton(TSP) [15]. On the other hand, the marginal cost for particle filter retrofitting on heavy duty vehicles was estimated to be 70000 euro/ton(PM10) in a Danish study [16].

It should be taken into account that the case study corresponds to a situation where an old functioning wood boiler is replaced, and the investment cost is calculated only for the pellet boiler

Table 3. Main calculation parameters and results of the case study.

Main common parameters	**Old log boiler**		**New pellet boiler**	
Net heat production efficiency [%]	65		83	
Fuel calorific heating value [MJ/kg]	15		17	
Emission factor [mg/MJ(PM2.5)]	700		30	
Main country-specific parameters	**Denmark**	**Finland**	**Norway**	**Sweden**
Log fuel price [euro/ton]*	91 40	76 33	158 63	69 27
Pellet fuel price [euro/ton]	210	125	226	185
Price of a pellet boiler, incl. installation [euro]	6 900	7 000	7 100	7 540
Results	**Denmark**	**Finland**	**Norway**	**Sweden**
Heat production cost, old log boiler [euro/MWh]*	62 43	49 33	89 54	47 31
Heat production cost, new pellet boiler [euro/MWh]	103	67	112	85
Unit cost for $PM_{2.5}$ abatement, log -> pellet [euro/ton(PM2.5)]*	11 100 16 100	5 000 9 200	6 300 15 600	10 200 14 300
PM emission red. at country-level [kton(PM2.5)/a]	4.1	1.8	0.8	11.5
PM emission reduction cost at country-level [Meuro/a]*	46 66	9 17	5 13	117 165

* The prices and costs are for chopped logs which have been purchased (top) contra self collected (bottom).

CONCLUSIONS

Residential wood combustion is an important source for fine particle emissions in all the Nordic countries. This study provides new insight for the sector which is not well studied. The harmonization of activity and emission factor data across a group of countries indicated that emissions can vary largely between the countries and burning appliances, and that emission inventories may need revising due to the large effects of absolute PM emission values from the studied sector. The case of fuel switch demonstrated the possibility to quantify with reasonable accuracy the cost-efficiency of a control measure, to provide background information for potential abatement policies.

The study indicated the difficulties in planning emission abatement policies to residential wood combustion sector. Compared to technical controls of *e.g.* large combustion plants, the turnover time for domestic heating systems is slow, and the technical solutions are few and relatively costly. In addition, due to elusive parameters, such as wood volume used, fuel quality and burning habits, emission factors can vary with orders of magnitude for single sources. Even the robustness of regionally or country-averaged relative emission changes due to control option scenarios may be difficult to assess.

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