

Cost-effective reduction of fine primary particulate matter emissions in Finland

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2007 Environ. Res. Lett. 2 044002

(<http://iopscience.iop.org/1748-9326/2/4/044002>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 147.125.65.186

This content was downloaded on 29/02/2016 at 09:48

Please note that [terms and conditions apply](#).

Cost-effective reduction of fine primary particulate matter emissions in Finland

Niko Karvosenoja^{1,4}, Zbigniew Klimont², Antti Tohka¹ and Matti Johansson³

¹ Finnish Environment Institute (SYKE), PO Box 140, FIN-00251 Helsinki, Finland

² International Institute for Applied Systems Analysis (IIASA), A-2361 Laxenburg, Austria

³ United Nations Economic Commission for Europe (UNECE), Palais des Nations, CH-1211 Geneva 10, Switzerland

E-mail: niko.karvosenoja@ymparisto.fi

Received 20 June 2007

Accepted for publication 8 November 2007

Published 27 November 2007

Online at stacks.iop.org/ERL/2/044002

Abstract

Policies to reduce adverse health impacts of fine particulate matter (PM_{2.5}) require information on costs of abatement and associated costs. This paper explores the potential for cost-efficient control of anthropogenic primary PM_{2.5} emissions in Finland. Based on a Kyoto-compliant energy projection, two emission control scenarios for 2020 were developed. 'Baseline' assumes implementation of PM controls in compliance with existing legislation. 'Reduction' assumes ambitious further reductions. Emissions for 2020 were estimated at 26 and 18.6 Gg a⁻¹ for 'Baseline' and 'Reduction', respectively. The largest abatement potential, 3.0 Gg a⁻¹, was calculated for power plants and industrial combustion. The largest potential with marginal costs below 5000 € Mg(PM_{2.5})⁻¹ was for domestic wood combustion, 1.7 Gg a⁻¹. For traffic the potential was estimated at 1.0 Gg a⁻¹, but was associated with high costs. The results from this paper are used in the policy-driven national integrated assessment modeling that explores cost-efficient reductions of the health impacts of PM.

Keywords: emission, fine particles, emission reduction, cost-efficiency, Finland

1. Introduction

Atmospheric fine particulate matter (PM_{2.5}) has been estimated to cause 350 000 and 270 000 premature deaths in Europe in 2000 and 2020, respectively (EC 2005). PM results from both direct emissions (primary PM) and chemical reactions of gaseous precursors (secondary PM). European policies on emission reductions do not directly consider PM. However, they include sulfur dioxide (SO₂), nitrogen oxides (NO_x), ammonia (NH₃), and non-methane volatile organic compounds (NMVOC), contributing to acidification, eutrophication, and formation of ozone and secondary PM. Recent proposals by the European Commission under the Clean Air for Europe (CAFE) program (EC 2005) include proposals for national PM emission ceilings for 2020. The United Nations Economic Commission for Europe (UNECE) Convention on Long-range

Transboundary Air Pollution (LRTAP) evaluates PM in the review of the 1999 Gothenburg Protocol (UNECE 1999, 2007).

The RAINS model developed at the International Institute for Applied Systems Analysis (IIASA) (e.g. Schöpp *et al* 1999) was used in CAFE (Amann *et al* 2004) and would be employed in the possible revision of the Gothenburg Protocol. The integrated assessment model (IAM) RAINS includes cost-efficiency estimates for emission control measures, allowing for effects-targeted cost optimization at European scale. More detailed national studies are important to describe country-specific circumstances on emissions (Karvosenoja and Johansson 2003a) and costs (Karvosenoja and Johansson 2003b). They include, *inter alia*, fine sectoral resolution, description of large point sources, additional abatement options, detailed vintage and constraints on implementing measures within the planning period.

Such national analyses were performed with the Finnish regional emission scenario (FRES) model (Karvosenoja and

⁴ Author to whom any correspondence should be addressed.

Johansson 2003c). It is part of the national IAM used in a national project KOPRA on PM (www.environment.fi/syke/pm-modeling). KOPRA aimed to assess health impacts due to various emission sources and reductions at different spatial resolutions, $10 \times 10 \text{ km}^2$ and $1 \times 1 \text{ km}^2$. This paper focuses on anthropogenic primary $\text{PM}_{2.5}$ emissions and related abatement potential and costs in Finland, largely based on results of the KOPRA project. The four most important emission sectors are covered: power plants and industrial combustion; industrial processes; domestic wood combustion; and traffic.

2. Methods and materials

Primary $\text{PM}_{2.5}$ emissions and control costs were calculated with the FRES model. Calculation of emissions and costs is presented in more detail in Karvosenoja *et al* (2006).

2.1. Emission calculation

FRES combines a top-down approach for area emission sources with a detailed bottom-up calculation for large energy production and industrial point sources. Area and point sources (i.e. plants with boilers $>50 \text{ MW}_{\text{th}}$ or plants with emissions $>20 \text{ Mg a}^{-1}$ of PM, SO_2 or NO_x) are summed:

$$\text{EM}_t = \sum_{j,k,m} (1 - \eta_{j,k,m}) X_{j,k,m,t} A_{j,k,t}^a \text{EF}_{j,k} + \sum_l (1 - \eta_{j,k,m}) A_{l,t}^p \text{EF}_l \quad (1)$$

where j is fuel, k is the sector, l is the plant, m is the control technology, t is time, η and X are removal efficiency and implementation rate of control technology m , A^a and A^p are area and point source activity data (the annual activity rate of a point source is calculated from the capacity and annual operating hours of the plant) and EF is the unabated emission factor (before emission control devices).

More details on the data sources have been documented in Karvosenoja *et al* (2006) for stationary sources and in Klimont *et al* (2002) for transport sources. Information about the spatial distribution of emissions used in the KOPRA project is presented in Karvosenoja *et al* (2005a).

2.2. Cost calculation

Abatement costs comprise investment and operation-related costs of control equipment. The total annual cost for each technology is the sum of annualized investments (I^{an}) over the lifetime of the equipment (see tables 2 and 3), fixed operation and maintenance (OM^{fix}) and variable operation and maintenance (OM^{var}) costs. The unit costs of abatement (c) (related to one unit of reduced pollutant) are:

$$c = \frac{\frac{I^{\text{an}} + \text{OM}^{\text{fix}}}{P} + \text{OM}^{\text{var}}}{\text{EF}\eta} \quad (2)$$

where P is a plant factor (annual operating hours at full load for stationary sources and fuel consumption per vehicle for mobile sources).

Eventually, in order to rank options, marginal costs of abatement (mc_m) are calculated for each control technique m , i.e. additional costs for the considered measure m are related to the additional abatement of that measure (compared to the abatement of the less effective option $m - 1$):

$$mc_m = \frac{c_m \eta_m - c_{m-1} \eta_{m-1}}{\eta_m - \eta_{m-1}}. \quad (3)$$

More detailed discussion and all respective formulae with full indexing are available from Klimont *et al* (2002).

2.3. Emission control technologies

There is a long tradition of controlling PM emissions from large-scale combustion and processes, and some of the best options, such as electrostatic precipitators (ESPs) or fabric filters, can reduce more than 99% of PM, although the efficiency for fine PM is slightly lower than for the coarse fraction, especially for ESPs (e.g. McElroy *et al* 1982). For smaller boilers that are not covered in the European Union's Large Combustion Plants directive (EC 2001), less efficient technologies, e.g. multicyclones, are often used, or the emissions are released to the air uncontrolled. Efficient technologies to control these smaller boilers, however, are available and include, similarly to larger installations, ESPs and fabric filters that have been successfully applied in some countries (e.g. Nussbaumer 2007).

The domestic sector includes small heating and hot water boilers, stoves and fireplaces. These devices are often a source of high emissions, especially when burning wood in manually fed log boilers and stoves. Inadequate operating practices of boilers and stoves, e.g. a boiler used without a heat storage tank, and poor fuel quality leads to further decline in combustion efficiency and consequently higher emissions (Johansson *et al* 2004, Nussbaumer 2003, Sternhufvud *et al* 2004). Emission reductions can be primarily achieved by installation of heat storage tanks for wood log boilers, replacement of the old stove or boiler with a state of the art installation (e.g. Johansson *et al* 2004) as well as information campaigns on good combustion practices. Lowest emission levels can be achieved by installing a small-scale ESP that has been recently developed and tested independently in Norway and Switzerland (Johansson *et al* 2005, APP 2005, Henriksen 2004, Schmatloch and Rauch 2005).

Traffic sources, specifically diesel engines which are responsible for the bulk of the PM emissions, have not been subject to stringent PM standards and it is only recently that traps and filters are being considered and becoming part of the legislation. Control measures include changes in fuel parameters (e.g. sulfur or aromatics content, fuel density), engine design, flue gas post-combustion treatment (e.g. traps, catalysts), and improved inspection and maintenance (e.g. in-use compliance testing, on-board diagnostic). More detailed review can be found in Klimont *et al* (2002), for example. European legislation defines so-called EURO standards (e.g. EU Directives 98/69/EC for diesel cars and LDT; 88/77/EC for heavy duty trucks and busses; 98/68/EC for off road equipment;

Table 1. Range of PM_{2.5} emission factors for typical technologies applied in Finland and included in the FRES model (Karvosenoja and Johansson 2003c) and average emission rates for the selected categories in the year 2000 (in mg MJ⁻¹).

Sector	Technology	Range	Average
<i>Power plants and industrial boilers</i>			
Solid fuel boilers >50 MW _{th}	2–3-stage ESP/ESP + FGD scrubber	1–10	4.1
Solid fuel boilers < 50 MW _{th}	1-stage ESP/multicyclone	2–100	30
Heavy fuel oil (HFO) boilers	Multicyclone/unabated	10–50	31
Other liquid and gaseous fuel boilers	Unabated	0.1–3	0.2
<i>Industrial processes</i>			
Black liquor recovery boilers	2–3-stage ESP + NaOH scrubber	5–50	19
Other processes	Fabric filter/ESP/scrubbers/unabated	— ^a	— ^a
<i>Domestic wood combustion</i>			
Pellet/wood chip boilers	Unabated	30/50	—
Log boilers with/without heat storage tank	Unabated	80/700	—
Iron stoves	Unabated	700	—
Other stoves and ovens	Unabated	140	—
Open fireplaces	Unabated	800	—
<i>Traffic land-based sources</i>			
Gasoline: passenger cars, vans, motorcycles	EURO4-0	1.1–6.0	4.5
Gasoline: 2-stroke machinery, snowmobiles	Stage 2-0	70–350	315
Diesel: passenger cars, vans	EURO 4-0	15–110	77
Diesel: trucks, busses, other heavy-duty	EURO 5-0	2.3–58	31
Diesel: machinery	CAGE 4-0	2.4–140	87

^a The units of industrial process emission factors are mg per mass of different end-products or raw materials, and therefore they are not commensurable between different processes.

^b Average domestic wood combustion emission factor over different combustion appliances.

Table 2. PM_{2.5} removal efficiencies, investments and calculated unit costs for stationary sources

Sector	Technology	Removal efficiency (%)	Investment (€ kW _{th} ⁻¹)	Unit cost (€ Mg ⁻¹)
<i>Power plants and industrial combustion</i>				
Coal power plants 560–1300 MW _{th}	2–3-stage ESP + wet FGD	99	6.2 ^{a,b}	380–480 ^{a,b}
Peat and fuelwood power plants and industrial boilers, 50–600 MW _{th}	2–3-stage ESP	96	13 ^b	350–5200
	Fabric filter	99.7	14 ^b	370–5800
	Multicyclone (<5 MW _{th})	50	7.8 ^b	420–2600
Solid fuel power plants and industrial boilers 0–50 MW _{th}	1 stage ESP (5–50/<5 MW _{th})	93	14 ^b /85 ^b	260–2300/220–13 000
	Fabric filter (5–50 MW _{th})	99.7	18 ^b	330–2900
	Multicyclone (5–50/<5 MW _{th})	50	4.6 ^b /6.4 ^b	4700/6500
Heavy fuel oil power plants and industrial boilers, 0–50 MW _{th}	1-stage ESP (5–50 MW _{th})	93	14 ^b	7400
<i>Industrial processes</i>				
Black liquor ind. recovery boilers, 50–600 MW _{th}	2–3-stage ESP + NaOH scrubber	99	10 ^{a,b}	18–85 ^{a,b}
Other industrial processes	ESP/ESP + scrubber/fabric filter	96/99/99.7	—	17–1500 ^c
<i>Domestic wood combustion</i>				
	Small ESP	80/85/90/95 ^d	20	420/3700/7000/15 000

^a The costs of ESP only. The costs of FGD are allocated to sulfur reduction, although it also enhances PM reduction.

^b Based on Finnish cost data (documented in Karvosenoja *et al* 2006).

^c Based on the RAINS model data (Klimont *et al* 2002).

^d Removal efficiencies in pellet boilers/wood chip boilers/log boilers with heat storage tank/log boilers without heat storage tank (Johansson *et al* 2005, Schmatloch and Rauch 2005, Henriksen 2006).

2000/25/EC for agricultural and forestry machinery), which require implementation of a combination of measures listed above.

Table 1 presents, for key source sectors, the ranges of PM_{2.5} emission factors for emission reduction technologies present in Finland and the average emission factors for the year 2000 as assumed in the FRES model. The emission controls considered in the analyzed scenarios, their removal efficiencies, investment costs and resulting unit costs per reduced Mg of PM_{2.5} are shown in tables 2 and 3.

3. Scenario assumptions

The FRES model has been used to estimate future PM emissions for several activity pathways of the national climate strategy (Hildén *et al* 2005). For this study, the ‘Kyoto nuclear’ activity path was selected as a basis for PM abatement scenarios due to its consistency with the current energy policy and expected compliance with the Kyoto Protocol, ratified by Finland.

Two PM abatement scenarios, ‘Baseline’ and ‘Reduction’, were developed. The ‘Baseline’ scenario fulfills the require-

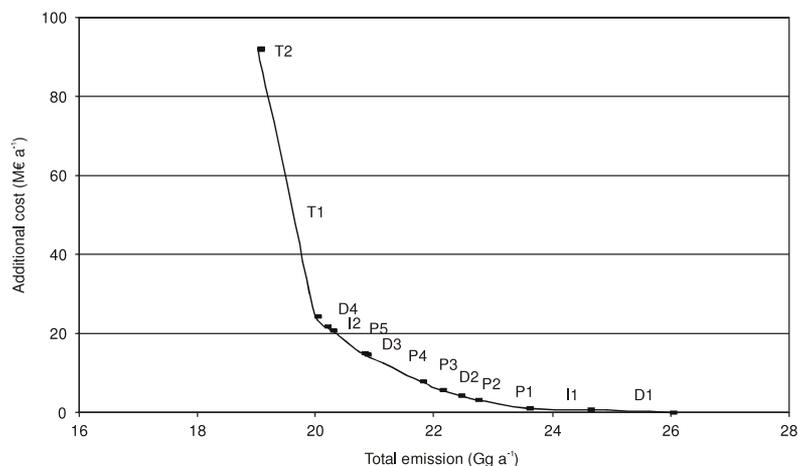


Figure 1. Cost curve for Finnish primary PM_{2.5} emissions for 2020 displaying reductions and related costs (explanations for segments in table 4).

Table 3. PM_{2.5} removal efficiencies, investments and calculated unit costs for transport^a.

Sector	Technology	Removal efficiency (%)	Investment (€ vehicle ⁻¹)	Unit cost (€ Mg ⁻¹)
Passenger cars, vans, motorcycles, gasoline	EURO 3	82	301	320 000
	EURO 4	82	342	320 000
Passenger cars, vans, diesel	EURO 3	85.9	355	13 000
	EURO 4	92.9	536	18 000
Heavy duty trucks and busses, diesel	EURO 4	97	7590	55 000
	EURO 5	97.05	7341	57 000
Off-road, diesel	CAGE 1	20	185	4100 ^b /2700 ^c
	CAGE 2	50	1520	16 000 ^b /9000 ^c
	CAGE 3	85	2450	25 000 ^b /14 000 ^c
	CAGE 4	97	6950	54 000 ^b /30 000 ^c
Off-road, 2-stroke engines	Stage 2	70	116	9100

^a Based on the RAINS model data (Klimont *et al* 2002).

^b Costs for agricultural machinery.

^c Costs for construction machinery.

ments of current national and international legislation (e.g. EC 2001, 1996, EURO standards). The ‘Reduction’ scenario assumes implementation of the best technically and economically feasible reduction measures for the selected sectors. Technical constraints and cost-efficiencies of control options were analyzed to assess their feasibility. The technologies assumed in the ‘Reduction’ scenario include, for example, installation of fabric filters to replace ESPs in large solid fuel power plants and industrial processes, use of small-scale ESPs in domestic biomass boilers and full implementation of EURO levels for on- and off-road traffic sources. At the time of calculation, only insufficient information was available about EURO 6 for heavy-duty trucks and 5 and 6 for light-duty vehicles and therefore they were not included. Although, as discussed earlier, promotion of good combustion practices, e.g. retrofitting of wood log boilers with a heat storage tank, can result in significant reductions of emissions, there are limitations, e.g. lack of space, and therefore such an option is not directly taken into account in this analysis, i.e. in the ‘Reduction’ scenario. However, both scenarios assume that about 20% of currently operating wood log boilers will be replaced with pellet boilers by

2020. The main assumptions are summarized in table 4 while more details are presented in Karvosenoja *et al* (2006).

4. Results and discussion

Total Finnish PM_{2.5} emissions in 2020 are estimated at 26.0 Gg a⁻¹ in the ‘Baseline’ and 18.6 Gg a⁻¹ in the ‘Reduction’ scenario. The four studied sectors represent 71% and 60% of the total emissions in the ‘Baseline’ and ‘Reduction’ scenarios, respectively. The largest contribution to emissions, 7.1 Gg a⁻¹ in ‘Baseline’, originates from domestic wood combustion. The largest possible reduction, about 3.0 Gg a⁻¹, is estimated for power plants and industrial combustion. Detailed results are presented in table 4 where measures are ordered by increasing marginal cost within a given sector. The cost-efficiencies of emission reduction beyond ‘Baseline’ are illustrated on a cost curve (figure 1). Figure 2 presents the estimated abatement potential for sectoral and total emissions, grouping measures by marginal cost category.

Table 4. PM_{2.5} emissions and reduction costs in the ‘Baseline’ (B) and ‘Reduction’ (R) abatement scenarios.

Sub-category acronym	Sub-category	Technology	Emission (Gg a ⁻¹)	Emission reduction cost (M€ a ⁻¹)	Marginal cost (€ Mg ⁻¹)
Power plants (PP) and industrial combustion (IN)					
P1, P2	Solid fuel PP and IN 5–600 MW _{th}	B: ESP R: Fabric filter	1.26 0.10	20.5 23.4	2200–3300
P3, P5	Heavy oil PP and IN 1–50 MW _{th}	B: Unabated/multicyclone R: Multicyclone/ESP	1.24 0.40	5.5 17.9	6500–11 000
P4	Solid fuel PP and IN 1–5 MW _{th}	B: Multicyclone R: ESP	1.1 0.15	2.7 9.5	6 900
	Coal PP300–1300 MW _{th}	B: ESP + wet FGD	0.07	2.8	—
	Other liquid and gas PP and IN	B: Unabated	0.02	—	—
Industrial processes					
I1, I2	Paper pulp lime kilns	B: ESP R: Fabric filter	0.42 0.03	na ^a na ^a	na ^a
	Other processes with reduction potential	B: ESP/unabated R: Fabric filter	1.17 0.02	4.8 6.8	600–13 000
	Black liquor recovery boilers 50–600 MW _{th}	B: ESP + NaOH scrubber	3.0	8.9	—
	Other processes, no reduction potential	B: Fabric filter, ESP + scrubber, Fugitive sources	0.63	6.2	—
	Small processes ^b	Not studied ^b	0.58	Not studied ^b	—
Domestic wood combustion					
D1, D2	Manual feed log boilers	B: — R: ESP	1.8 0.12	— 2.2	420–3700
D3, D4	Automatic feed wood chip and pellet boilers	B: — R: ESP	0.26 0.05	— 2.8	7000–15 000
	Stoves, ovens and fireplaces	B: —	5.0	—	—
Traffic sources					
T1	Diesel machinery	B: Unabated—CAGE 4 R: CAGE 4	1.0 0.07	99 167	70 000
T2	On-road 4-stroke vehicles	B: EURO 3–4/5 R: EURO 4/5	0.69 0.70	58 59	78 000
	Snowmobiles, machinery, 2-stroke	B: Stage 2	0.16	4.2	—
	Total	B: R:	26.0 18.6	474 522	

^a No cost data available.

^b Emission reduction potential from processes with emissions below 20 Mg a⁻¹ was not studied.

Nearly half of the emissions in the power plant and industrial combustion sector originate from installations smaller than 5 MW_{th}, i.e. solid fuel boilers equipped with multicyclones and uncontrolled heavy fuel oil boilers. Although, they use only about 4% of total fuel in this sector, about 40% of total reduction in the ‘Reduction’ scenario is achieved in these small installations (P3, P4 in table 4). However, a comparable reduction could be achieved moving towards fabric filters in larger solid fuel boilers (P1, P2) and at a 50% lower marginal cost. These options appear cost-effective for overall reduction of PM emissions in Finland as they can be found in the lower part of the cost curve (figure 1).

The largest source of PM from industrial processes is black liquor recovery. Very high PM_{2.5} concentrations in flue gas make reductions technically challenging (Mikkanen *et al* 1999). However, installation of fabric filters and

consequently further emission reduction is not technically feasible. Additional reductions could be achieved in paper pulp lime kilns and the ‘other processes’ category. Relatively low marginal costs were estimated for oil refineries and glass wool and fibre production processes (I1), largely due to a very low level of emission control in the ‘Baseline’. For the metal industry (I2), where the reduction potential is associated with upgrading from ESP to fabric filters, the marginal costs are rather high. For paper pulp lime kilns the costs of further abatement could not be evaluated. Cost and reduction potential estimates for this sector entail considerable uncertainties.

The highest emission reductions with marginal costs below 5000 € Mg⁻¹ could be achieved in the domestic sector introducing small ESP for wood log boilers, i.e. 1.7 Gg a⁻¹ (D1, D2). Further reduction of 0.21 Gg a⁻¹ could be achieved

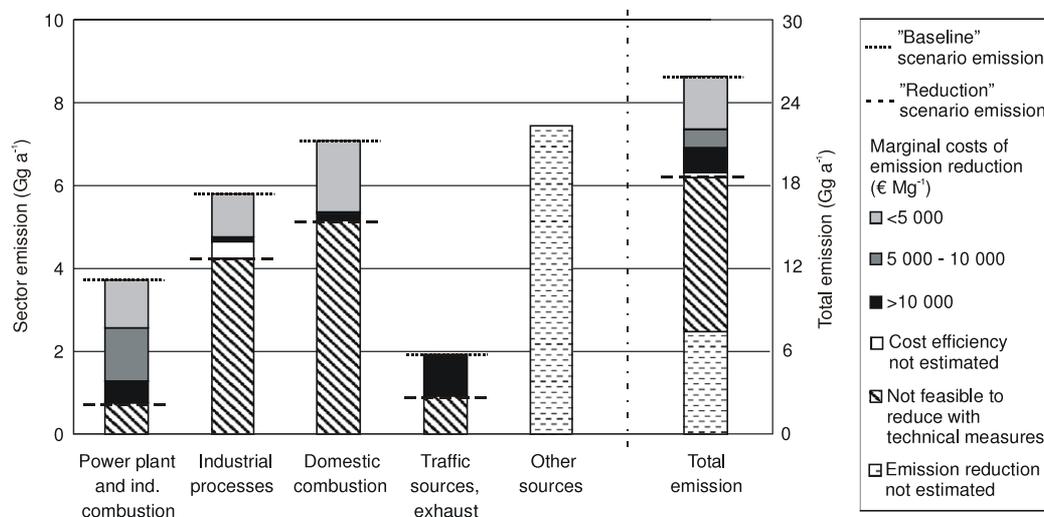


Figure 2. PM_{2.5} emissions and related cost-efficiencies for reductions in the ‘Baseline’ and ‘Reduction’ control scenarios in Finland in 2020. The left-hand axis and the first five columns refer to sectoral emissions and the right-hand axis refers to the total emission column.

with ESPs in automatic wood chip and pellet boilers at a higher marginal cost (D3, D4).

Installation of ESPs on stoves and ovens has not been included in this study, although we estimated they are responsible for nearly 70% of emissions from the residential sector. They are typically used for supplementary heating, operating typically for only 100–300 h a⁻¹, and installation of ESPs is not very cost-efficient; marginal cost was estimated at 30 000 to over 50 000 € Mg⁻¹. Their emissions are strongly dependent on operating practice and fuel properties. Further emission reductions would be possible, though difficult to quantify, by, for example, information campaigns on good combustion practices or programs stimulating the accelerated replacement of old stoves and ovens with modern technologies.

Owing to the introduction of strict emission standards for the transport sector, its exhaust emissions are estimated to decline significantly by 2020. The largest remaining sources will be diesel off-road machinery, where also the largest reduction potential was identified in the ‘Reduction’ scenario, i.e. about 1.0 Gg a⁻¹; however, the costs are relatively high (T1).

This study does not include estimates of reduction potential for non-combustion, non-industrial primary PM emissions (referred to as ‘Other sources’ in figure 2). They contribute about 7.4 Gg a⁻¹ and include non-exhaust emissions from traffic, product handling, agriculture, construction activities, fuel extraction, meat preparation, tobacco smoking and fireworks. The largest contribution (1.8 Gg a⁻¹) comes from non-exhaust traffic sources. Very few data exist about abatement options for these sources.

Although emission reduction of precursors of the secondary particles (SO₂, NO_x, NH₃, NMVOC) are not discussed in this paper, some of the control technologies included in the analyzed scenarios do reduce these emissions, e.g. controls in the transport sector and renewal of combustion devices in the domestic sector. The predominant share of the

background PM_{2.5} concentrations in Finland consist of long-range transport secondary particles (Karppinen *et al* 2004), and the exceedances of the EU 24 h air quality limit values for PM₁₀ that occur in major cities are mainly associated with the primary emissions of PM.

5. Discussion of emission and cost uncertainties

Karvosenoja and Johansson (2003a) have compared FRES base year 2000 emissions with other national and international emission inventories. The largest differences were detected in the domestic wood combustion sector. In a global inventory of carbonaceous aerosol emissions Bond *et al* (2004) estimated that this sector is also the major contributor to uncertainty in Europe, and key factors determining high uncertainty are emission factors. Table 1 illustrates the variation in the average PM_{2.5} emission factors in this study for different combustion technologies used in devices in the domestic sector. However, the measurements of emission factors for specific combustion installations show great variability, even within the same type of device (e.g. Johansson *et al* 2004, Kupiainen and Klimont 2007, Bond *et al* 2004). Obviously, the choice of average emission factor will have an impact on total emissions from this sector. Additionally, for log boilers, the results are sensitive to the assumptions about the performance of the reduction technology. Consequently, assumptions about the performance of the reduction technology contribute to the uncertainty of the results. The small-scale ESP we include in this study has not been commercialized yet but has been tested in the laboratory and in real-life conditions, achieving removal efficiencies around 86% and ESP outlet concentrations of 4 mg MJ⁻¹ (Johansson *et al* 2005). Measurements with another ESP device suggest reduction efficiencies of 80–90% for variety of stoves and a pellet boiler (Schmatloch and Rauch 2005). We assumed such efficiencies for ESP installed in devices with similar unabated emissions, i.e. pellet, wood chip and heat storage tank log boilers (table 2). Ernst Henriksen, a

member of the ESP development team at APP (Applied Plasma Physics ASA, Norway) suggested that the use of ESP with higher inlet PM concentrations would result in higher removal efficiencies (Henriksen 2006), therefore the ESP efficiency for a high-emission wood log boiler without a heat storage tank was assumed to be 95%. However, test information on combustion with high PM emission factors or for long-term operation was not available. Therefore, the presented results on the reduction potential and costs of the small-scale ESP should be seen as preliminary.

Most significant uncertainties in the 'Reduction' scenario estimates for power and industrial plants are related to the removal efficiency assumed for fabric filters. Measurements at Finnish plants suggest that the removal efficiency of fabric filters for PM_{2.5} in normal use is approximately 99.9% but malfunctions or other bypass situations decrease the average efficiency in actual operation to about 99.7% (Ohlström *et al* 2005). However, the effects of malfunctions on actual emission levels have not been widely studied, and they might result in lower reduction efficiencies than those assumed in this study. On the other hand, even assuming a real-life reduction efficiency of only 99%, would result in a change of the abatement potential in power plant sector by about 0.2 Gg a⁻¹. This represents less than 5% of the total reduction potential estimated in this study (table 4).

For industrial processes, emission estimates included in this study were based mainly on direct contacts with enterprises (Tohka and Karvosenoja 2006). However, for several processes it was not possible to discriminate between fugitive and stack emissions. This increases the uncertainty of the reduction potential for this source since a fraction of fugitive losses might actually be calculated as stack emissions in such a case, leading to overestimation of the emission reduction potential.

Uncertainties in control costs for industrial combustion sources are related to the aggregation of plant-specific data, e.g. depending on size, production and operation profile, lifetime, etc, when developing model sector parameterization. The data used in this study were collected directly from Finnish plants rather than from the literature or international data sets. For industrial processes and transport, however, local factors could have been accounted for only to a limited extent as the primary cost data originate from international sources and therefore cost estimates for these sectors carry higher uncertainties.

6. Conclusions

The total Finnish emissions of PM_{2.5} in 2020 in the 'Baseline' scenario are estimated at 26.0 Gg a⁻¹. The introduction of additional measures in the 'Reduction' scenario results in a decrease in emissions by 7.4 Gg a⁻¹, i.e. 29% of the total emissions. The largest abatement potential was identified for stationary industrial and domestic combustion sources and about half of it could be achieved at a cost below 5000 € Mg⁻¹. Reduction potential was also identified for a few industrial processes; however, reduction and cost-efficiency estimates bear high uncertainty and could be only partly quantified.

Tailpipe emissions from transport sources are already subject to stringent legislation included in the 'Baseline' and any further reduction will be very expensive.

The uncertainties in the emission estimates and reduction potential are strongly linked to the estimates of emission factors and assumptions about penetration rates and performance of control technology. The study highlights this aspect specifically for the domestic sector that contributes nearly 30% of the total PM_{2.5} emissions in Finland. There is only limited experience with some of the low-emission technology in this sector and the assumptions made in this study about the applicability of ESPs for wood boilers and the exclusion of stoves and ovens from the reduction analysis have important implications for the result. Although the application of ESPs to intermittently operated stoves and ovens is technically possible, we estimated that it would be associated with very high reduction costs. Analysis of the potential for accelerated replacement of old and polluting devices in this sector is of vital importance but could not have been performed owing to lack of data.

The IAM project KOPRA has introduced new information on the health impacts of different emission sources in Finland. The results emphasize the importance of low-altitude emission sources, especially traffic and domestic combustion (Karvosenoja *et al* 2005b, Tuomisto *et al* 2007). The results of this study will be integrated with this project to allow for state of the art assessment of the cost-efficiency of emission reduction measures to reduce health impacts due to PM.

Acknowledgments

The authors acknowledge financial support from the Ministry of the Environment and the KOPRA project in the technological program 'FINE Particles-Technology, Environment and Health 2002–2005' of the National Technology Agency of Finland (Tekes). All project group members are acknowledged.

References

- Amann M, Bertok I, Cofala J, Gyarfas F, Heyes C, Klimont Z, Schöpp W and Winiwarter W 2004 Baseline scenarios for the clean air for Europe (CAFE) programme *Final Report for the European Commission* [http://www.iiasa.ac.at/rains/CAFE_files/Cafe-Lot1_FINAL\(Oct\).pdf](http://www.iiasa.ac.at/rains/CAFE_files/Cafe-Lot1_FINAL(Oct).pdf) IIASA, October 2004
- APP (Applied Plasma Physics ASA) 2005 Development of residential ESP <http://www.app.no/Development/ResidentialESP/tabid/72/Default.aspx>
- Bond T C, Streets D G, Yarber K F, Nelson S M, Woo J-H and Klimont Z 2004 A technology-based global inventory of black and organic carbon emissions from combustion *J. Geophys. Res.* **109** D14203
- EC (European Commission) 1996 Directive 96/61/EC of 24 September 1996 concerning integrated pollution prevention and control *Official J. European Communities* L 257 10/10/1996
- EC (European Commission) 2001 Directive 2001/80/EC of the European Parliament and of the Council on the limitation of emissions of certain pollutants into the air from large combustion plants *Official J. European Communities* L 309/1
- EC (European Commission) 2005 Thematic strategy on air pollution *Communication from the Commission to the Council and the European Parliament (Brussels, 21.9.2005 COM(2005))*
- Henriksen E 2004 Industrial validation *Report EVK4-CT-2001-30005 CLEANAIR—Task 4.2, EU CRAFT Project 'CLEANAIR'* European Commission, DG Research, Brussels, Belgium

- Henriksen E 2006 Applied Plasma Physics ASA, Norway, personal communication 14 February
- Hildén M, Karvosenoja N, Kankaanpää S, Ratinen M, Liski J and Hämeikoski K 2005 Environmental assessment of the National strategy for the implementation of the Kyoto protocol *The Finnish Environment 802 (Helsinki, Finland)* www.environment.fi/publications
- Johansson L, Leckner B, Gustavsson L, Cooper D, Tullin C and Potter A 2004 Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets *Atmos. Environ.* **38** 4183–95
- Johansson L, Leckner B, Gustavsson L, Cooper D, Tullin C, Potter A and Berntsen M 2005 Particle emissions from residential bio-fuel boilers and stoves—old and modern techniques *Aerosols in Biomass Combustion (Thermal Biomass Utilization vol 6)* ed I Obernberger and T Brunner pp 145–50 Graz, Austria
- Karppinen A, Härkönen J, Kukkonen J, Aarnio P and Koskentalo T 2004 Statistical model for assessing the portion of fine particulate matter transported regionally and long range to urban air *Scand. J. Work Environ. Health* **30** 47–53
- Karvosenoja N and Johansson M 2003a Primary particulate matter emissions and the Finnish climate strategy *Boreal Environ. Res.* **8** 125–33
- Karvosenoja N and Johansson M 2003b Cost curve analysis for SO₂ and NO_x emission control in Finland *Environ. Sci. Policy* **6** 329–40
- Karvosenoja N and Johansson M 2003c The Finnish Regional Emission Scenario model—a base year calculation *Proc. Air Pollution XI Conf. (Catania)* pp 315–24
- Karvosenoja N, Klimont Z, Tohka A and Johansson M 2006 Fine particle emissions, emission reduction potential and reduction costs in Finland in 2020 *The Finnish Environment 46 (Helsinki)* www.environment.fi/publications
- Karvosenoja N, Porvari P, Raateland A, Kupiainen K and Johansson M 2005a The spatial allocation of air pollutants in Finnish regional emission model *Proc. 3rd Air Quality Management Conf. (Istanbul, Sept. 2005)* pp 571–80
- Karvosenoja N, Porvari P, Raateland A, Tuomisto J T, Tainio M, Johansson M and Kousa A 2005b Emission modeling in the assessment of PM_{2.5} from traffic and residential wood combustion *Proc. 3rd Air Quality Management Conf. (Istanbul, Sept. 2005)* pp 581–90
- Klimont Z, Cofala J, Bertok I, Amann M, Heyes C and Gyarmas F 2002 Modelling particulate emissions in Europe: a framework to estimate reduction potential and control costs *IR-02-076, IIASA* <http://www.iiasa.ac.at/rains/reports/ir-02-076.pdf> Laxenburg, Austria
- Kupiainen K and Klimont Z 2007 Primary emissions of fine carbonaceous particles in Europe *Atmos. Environ.* **41** 2156–70
- McElroy M W, Carr R C, Ensor D S and Markowski G R 1982 Size distributions of fine particles from coal combustion *Science* **215** 13–9
- Mikkanen P, Kauppinen E I, Pyykkönen J, Jokiniemi J, Aurela M, Vakkilainen E K and Janka K 1999 Alkali ash formation in four Finnish industrial recovery boilers *Energy Fuels* **13** 778–95
- Nussbaumer T 2003 Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction *Energy Fuels* **17** 1510–21
- Nussbaumer T 2007 *Feinstaubabscheider: Wirkung und Kosten, Technische Möglichkeiten der Staubabscheidung für automatische Holzfeuerungen, Umwelt Perspektiven, Februar 2007* <http://www.verenum.ch/publikationen.html> (in German)
- Ohlström M, Tsupari E, Lehtilä A and Raunemaa T 2005 Fine particle emissions and their reduction potentials in Finland *VTT Research Notes 2300 (Helsinki, Finland)* <http://www.vtt.fi/inf/pdf/tiedotteet/2005/T2300.pdf> (in Finnish with English abstract)
- Schatmloch V and Rauch S 2005 Design and characterisation of an electrostatic precipitator for small heating appliances *J. Electrostat.* **63** 85–100
- Schöpp W, Amann M, Cofala J, Heyes C and Klimont Z 1999 Integrated assessment of European air pollution emission control strategies *Environ. Modelling Softw.* **14** 1–9
- Sternhufvud C, Karvosenoja N, Illerup J, Kindbom K, Lükewille A, Johansson M and Jensen D 2004 Particulate matter emissions and abatement options in residential wood burning in the Nordic countries *Nordic Council of Ministers, Copenhagen, ANP 2004* p 735 <http://www.norden.org/pub/miljo/miljo/sk/ANP2004735.pdf>
- Tohka A and Karvosenoja N 2006 Fine particle emissions and emission reduction potential in Finnish industrial processes *Reports of Finnish Environment Institute 21 (Helsinki, Finland)* www.environment.fi/publications
- Tuomisto J T, Wilson A, Evans J S and Tainio M 2007 Uncertainty in mortality response to airborne fine particulate matter: combining European air pollution experts *Reliab. Eng. Syst. Saf.* at press [doi:10.1016/j.ress.2007.03.002](https://doi.org/10.1016/j.ress.2007.03.002)
- UNECE 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone done at Gothenburg, Sweden on 30 November 1999 *Handbook for the 1979 Convention on Long-range Transboundary Air Pollution and its Protocols, ECE/EB.AIR/85* Economic Commission for Europe, United Nations, New York and Geneva
- UNECE 2007 Review of the 1999 Gothenburg Protocol *ECE/EB.AIR/WG.5/2007/1* 1 February 2007 Economic Commission for Europe, United Nations, Geneva