THE FINNISH ENVIRONMENT 46 | 2006

ENVIRONMENTAL PROTECTION

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Helsinki 2006
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SYKE

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Finnish Environment Institute
Research Programme for Global Change

Page layout: Ritva Koskinen
Cover photo: SYKEkuva, Erno Forsström

The publication is also available in the Internet:
http://www.environment.fi/publications

Edita Prima Ltd, Helsinki 2006

ISBN 952-11-2413-X (pbk.)
ISBN 952-11-2414-8 (PDF)
ISSN 1238-7312 (print)
ISSN 1796-1637 (online)

ACKNOWLEDGEMENTS

The emissions and cost tool of this study, the Finnish Regional Emission Scenario (FRES) model, has mainly been developed in two projects aiming at national integrated assessment modelling of PM in Finland. The authors gratefully acknowledge the financial support from the Ministry of the Environment and the KOPRA project in the technological programme "FINE Particles - Technology, Environment and Health 2002-2005" of the National Technology Agency of Finland (Tekes). We thank Mikael Ohlström and the PIHI-KHK project of VTT for the collaboration in the efficiency and cost estimates of power plant control technologies. All the members of the KOPRA project group are acknowledged. Ernst Henriksen from Applied Plasma Physics ASA and Martti Aho from VTT are acknowledged for the collaboration in the cost and performance estimates of small-scale ESP technology.

CONTENTS

1 Introduction

Fine particulate matter ($PM_{2.5}$) in the atmosphere have been estimated to cause 350 000 and 270 000 premature deaths in Europe annually in 2000 and 2020, respectively (EC 2005). Atmospheric PM is the result of direct particle emissions (primary PM) and chemical reactions that convert gaseous substances to particulate form in the atmosphere (secondary PM). In Finland the concentrations are dominated by long range transported secondary PM (Karppinen et al. 2005, Ojanen et al. 1998). However, primary PM may be locally more important, especially in urban areas. Furthermore, primary combustion based PM might be more harmful to human health than secondary particles (Tuomisto et al. submitted a).

Currently in force European agreements on reduction of air emissions have not considered PM but other pollutants (SO_2, NO_x, NH_3, NMVOC) contributing to acidification, euthropication, and formation of ozone. Recently, however, European Commissions Thematic Strategy prepared under Clean Air for Europe (CAFE) programme (EC 2005) includes PM in the analysis framework and proposes national PM emission targets for 2020. Furthermore, the UNECE LRTAP is planning to include PM in the revision of the Gothenburg Protocol. The RAINS model developed at IIASA has been used in the scenario analysis within the CAFE programme and it is envisaged to use it for the forthcoming revision of the Protocol. The integrated assessment model (IAM) RAINS contains the cost efficiency estimates of emission control measures in order to perform effects-oriented cost optimization at a European scale. However, it has been shown that more detailed national studies are important in order to take country-specific circumstances better into account, both in emission (Karvosenoja and Johansson 2003a) and cost efficiency estimates (Karvosenoja and Johansson 2003b). Such information might include e.g., the structure of combustion installations, operating hours, parameters influencing emission factors, fuel prices, and constraints on implementation of certain measures within a given planning (analysis) horizon.

Such national analysis was performed with the Finnish Regional Emission Scenario (FRES) model (Karvosenoja and Johansson 2003c). FRES is the emission tool of the national IAM system of air pollution that has been developed to cover PM in the KOPRA project ("An integrated model for evaluating the emissions, atmospheric dispersion and risks caused by ambient air fine particulate matter") including, in addition to FRES, the modelling of atmospheric transport, chemistry and aerosol processes, and population exposure and health risk modelling (www.fmi.fi/research_air/air_47.html). The objective of KOPRA is to assess the national reduction possibilities of PM health effects. The focus is especially on the assessment of primary PM at fine spatial resolution, at 5 × 5 km^2 and 1 × 1km^2 grid (Tuomisto et al. submitted b).

This study has been carried out as a part of the KOPRA project. The aim of this report is to explore PM emission reduction potentials and costs in Finland in the most important stationary emission sectors, i.e. power plants and industrial combustion, industrial processes and domestic wood combustion. Two primary $PM_{2.5}$ emission scenarios for 2020 were calculated with the FRES model. “Baseline” assumes PM control technology utilization complying with current legislation. Additional reduction potential was estimated in “Reduction” scenario, which assumes more ambitious, technically and economically feasible emission reduction measures. Furthermore, emission reduction costs were calculated for both scenarios. Emission uncertainties are qualitatively discussed.

The emissions sources that were not studied in this report are traffic and miscellaneous PM sources. The emission levels of traffic sources, i.e. vehicular and off-road traffic and machinery, are defined by the EURO emission standards of the EU and the age structure of vehicle fleet. The other miscellaneous primary PM sources include e.g. food preparation, tobacco smoking and fugitive dust induced by traffic, material handling and agricultural activities.

2 PM emissions in Finnish Climate Strategy

Future PM emissions with energy and activity pathways of national Climate Strategy (Ministry of Trade and Industry 2001) have been explored using the FRES model (Karvosenoja and Johansson 2003a). Table 1 presents $PM_{2.5}$ emissions in 2010 and 2020 with the three studied activity scenarios that have been compiled using energy system model EFOM-ENV of the Technical Research Centre of Finland (e.g. Lehtilä and Tuhkanen 1999). "Business-as-usual" scenario assumes the future development of energy production system without restrictions by greenhouse gas (GHG) abatement. The other two scenarios, "Kyoto-gas" and "Kyoto-nuclear", assume GHG emission reduction in order to achieve the EU burden sharing agreement for Finland, *e.g.*, more emphasis on energy saving and fuel switching to low carbon content fuels in centralized heat and power production. "Kyoto-gas" includes a strong shift from coal to natural gas and biomass without new nuclear power capacity. "Kyoto-nuclear" allows the introduction of a new 1400 MW_e nuclear reactor, with more moderate shift from coal to biomass and gas. The studies concluded that future primary energy choices in large energy production units will not have remarkable effect on primary PM emissions.

In this report additional emission reduction potentials and costs in 2020 were studied with one activity pathway. Because Finland has ratified the Kyoto agreement and a decision has been made to start up a new nuclear power station before 2010, "Kyoto-nuclear" was considered as the most realistic pathway. Table 1 shows PM emissions in "Kyoto-nuclear" pathway with "Baseline" scenario assumptions, i.e. emission reduction utilization complying with current legislation. The "Reduction" scenario which includes maximum economically and technically feasible emission reduction measures in "Kyoto-nuclear" pathway is presented in Chapter 4.3. The emission scenarios are being used in a regional integrated assessment modeling project KOPRA (www.fmi.fi/research_air/air_47.html).

Table 1. Finnish primary $PM_{2.5}$ emissions (Gg a^{-1}) in 2000, and 2010 and 2020 with the three activity scenarios of the Finnish Climate Strategy: "Business-as-usual" (BAU), "Kyoto-gas" (KG) and "Kyoto-nuclear" (KN) (Karvosenoja et al. 2003)

	2000	**2010**			**2020**		
		BAU	**KG**	**KN**	**BAU**	**KG**	**KN**
Power plants and industrial combustion	3.4	4.1	4.0	3.6	4.0	3.7	3.7
Industrial processes	5.8	5.4	5.4	5.4	5.8	5.8	5.8
Domestic combustion	13.2	12.7	12.4	12.6	11.1	10.5	11.3
Traffic sources[1]	7.6	3.9	3.9	3.9	1.9	1.9	1.9
Other emission sources[2]	5.9	7.4	7.3	7.3	7.4	7.4	7.4
Total	**35.9**	**33.4**	**33.0**	**32.8**	**30.3**	**29.4**	**30.2**

[1]) incl. exhaust emissions only
[2]) incl. miscellaneous anthropogenic PM sources, e.g. food preparation, tobacco smoking and fugitive dust induced by traffic, material handling and agricultural activities.

3 The emission reduction of primary particles

There is a long tradition of controlling PM emissions from large scale combustion and some of the best options can reduce more than 99% of PM. For small combustion sources, however, the abatement possibilities have so far been more limited. The following chapters and Table 2 present the most important fuel combustion and industry related sectors and typical currently used emission reduction technologies in Finland with their emission factors as assumed in the FRES model.

Table 2. Typical emission reduction technologies and $PM_{2.5}$ emission factors in the studied sectors in Finland (Karvosenoja and Johansson 2003c)

Sector	**Technology**	**Emission factors (mg MJ^{-1})**
Power plants and industrial boilers		
Solid fuel boilers >50MW_{th}	2-3 stage ESP	1-10
Solid fuel boilers <50MW_{th}	1 stage ESP / Multicyclone	2-100
Heavy fuel oil (HFO) boilers	Multicyclone / Unabated	10-50
Other liquid and gaseous fuel boilers	Unabated	0.1-3
Industrial processes		
Black liquor recovery boilers	2-3 stage ESP + NaOH scrubber	5-50
Other processes	Fabric filter / ESP / scrubbers / unabated	–[a]
Domestic combustion		
Light fuel oil	Unabated	1-10
Wood logs	Unabated	100-1000
Wood pellets and chips	Unabated	30-60

a) The unit of industrial process emission factors are mg($PM_{2.5}$) per mass of different end-products or raw materials, and therefore they are not commensurable between different processes

3.1

Power plants and industrial combustion

Solid fuel combustion in pulverized fuel (PF), fluidized bed (FB) or modern grate boilers is efficient, and the fraction of combustible material in fly ash is small. Owing to often high ash content of solid fuels the flue gas contains significant amounts of particulate matter that has to be removed with end-of-pipe equipment. The most typical devices in large plants are electrostatic precipitators (ESPs) that can be used to high PM concentrations with low pressure drop. Removal efficiencies are high, up to 99.9% for coarse particles, but lower, around 96%, for fine particles at a size range of about 0.1-3.0 μm (e.g. McElroy et al. 1982, Ylätalo and Hautanen 1998).

Fabric filters are more equally efficient for all particle sizes with removal efficiencies up to 99.7 - 99.9% (Ohlström et al. 2005). Fabric filters are competitive in investment, but retain higher pressure loss and maintenance need than ESPs. Furthermore, high moisture content or temperature of flue gases might restrict applicability.

Cyclones and multi-cyclones can be found in small solid fuel and heavy fuel oil fired plants. Removal efficiencies are relatively high for coarse particles, but decrease sharply for fine particles (Flagan and Seinfeld 1988).

Centralized power and heat production in Finland is mainly based on PF combustion of coal, FB co-combustion of wood and peat, and natural gas combustion in combined cycle turbines (CCGT). Liquid fuels are mainly used in small peak capacity boilers and as start-up fuels in large plants. Particle emissions from power plants and industrial boilers are currently relatively efficiently controlled, and the Large Combustion Plants Directive, LCPD (EC 2001) of the European Union is not bringing significant new PM reduction requirements to Finnish plants (Karvosenoja and Johansson 2003a). All solid fuel plants larger than 50 MW_{th} thermal capacity are equipped with ESPs. In addition, coal power plants use flue gas desulphurization (FGD) which further reduce PM emissions. There are relatively many small (<50 MW_{th}) district heating and industrial solid fuel boilers in Finland that are not covered with the LCPD, although national environmental permits are required also for these plants. However, PM emission limits for small plants are not so strict. Especially solid fuel boilers with capacity less than 5 MW_{th} and heavy fuel oil (HFO) boilers are often equipped only with cyclones, and emission factors can be relatively high (see Table 2).

3.2

Industrial processes

Industrial activities cause PM emissions in combustion and production processes. The emissions are formed from fuels, as well as raw and process materials. The emissions that originate in production processes predominately from raw and process materials were considered process emissions in this study. Combustion processes that are predominately performed in order to produce energy for production processes were treated as industrial combustion in the previous section. The division for combustion and industrial processes is not always unambiguous. For example, black liquor combustion in recovery boilers is primarily carried out for process chemical regeneration as a part of paper pulp process, but it also produces energy for the process. Black liquor combustion was treated as industrial process in this study.

Emission reduction technologies in industrial processes are in principal similar than what are used in energy production sector. However, particle composition vary more, which might restrict the applicability of some reduction measures. Furthermore, part of the process emissions might be fugitive, i.e. they are released from non-sealed process environments directly or through a ventilation system to the atmosphere. These emissions can often not be easily directed to stack pipelines, and therefore emission reduction is not as straightforward and efficient as for stack emissions. Fugitive emissions can typically be abated by various good practice methods, such as simple sealings or collecting ventilation hoods.

In Finland, the most important industrial sectors in terms of PM emissions are pulp and paper and metal industries. The level of PM emission reduction is more variable between different plants than in energy production. Most of the large processes are efficiently controlled. However, some individual processes have considerable additional emission reduction potential. Industrial process emissions are regulated plant-by-plant basis by national environmental permits that are granted making use of the information of the criteria of Best Available Techniques (BATs) as defined in the Integrated Pollution Prevention and Control (IPPC) directive of the EU (EC 1996). Sector-specific BATs are defined in national BAT Reference Documents, BREFs (e.g. Nuortimo 2002, Riekkola-Vanhanen 1999a,b).

3.3

Domestic combustion

Domestic combustion refers to house heating in residential and recreational buildings with small boilers or stoves typically below 100 kW_{th} thermal capacity. In Finland the most common domestic heating fuels are wood and light fuel oil (LFO), with 41.0 and 33.0 PJ in 2004, respectively (Statistics Finland 2005). PM emissions from LFO use are relatively low, typically below 2 mg MJ^{-1} in well functioning domestic boiler (Tissari et al. 2005). In this study emission reduction potential from LFO use was estimated to be negligible.

Wood is used as both primary and supplementary heating fuel mainly in detached residential houses. Primary heating use takes place mainly in central heating boilers. The most commonly used is over-fire type batch-burning log boiler. Over-fire boilers have natural draught air supply from below the batch through a grate, and combustion takes place on and directly on top of the batch in a combustion chamber. The structure is simpler, investment costs lower and emissions typically higher than in under-fire type boilers that are more common in Sweden and Central Europe. Operation in low boiler loads means restriction of combustion air supply and causes low efficiency and high emissions. Especially the lack of accumulator tank in boiler system leads to need for partial load operation in times with low heat demand. Emission measurements for log boilers without accumulator have been carried out in Sweden (Johansson et al. 2005). Total suspended particle (TSP) emission factors were between 350 and 2200 mg MJ^{-1}, with the average 900 mg MJ^{-1}. The majority of particle mass in domestic wood combustion emissions are in the size range from 0.1 to 1 µm, and $PM_{2.5}$ particles contribute to more than 90% of TSP (Boman 2005). Roughly one third of log boilers in Finland are used without accumulators (pers. comm. S. Tuomi, Finnish Work Efficiency Institute, 28.8.2003).

Automatic feed wood chip and pellet boilers are at the moment less common than log boilers. Wood chip boilers are used mainly in rural areas. Pellet combustion have quickly been gaining popularity in recent years, but it is still of minor importance in Finland. Continuous combustion process in automatically fed boilers is easier and more flexible to control than batch-wise, and PM emissions are lower, typically below 40 and 60 mg(TSP) MJ^{-1} for pellet and wood chip boilers, respectively (Tissari et al. 2005). Especially pellet boilers can be used with low emissions also without accumulators (Johansson 2002).

In addition to central heating boilers, wood is combusted in different types of stoves and masonry heaters. Stove and masonry heaters as a primary heating form is less common than central heating. Instead, supplementary wood heating in electricity and oil heated houses has been very common from the 1980s. In 2000 approximately 50% of all residential detached houses that were heated with other media than wood had supplementary wood heater installed, the share being around 80% in houses built after the 1980s (Sevola et al. 2003). In addition, stoves and masonry heaters are widely used in recreational buildings.

Potential emission reduction measures for domestic wood combustion have been explored in a Nordic study (Sternhufvud et al. 2004, Karvosenoja et al. 2004) and in a number of other studies where a more general review was presented. For the Nordic countries, fuel switch from log to pellet boiler was identified as the most potential current technology to reduce emissions. Efficiencies range from 50% to more than

90%, depending on the emission level of replaced log boiler. Based on a case study, the cost efficiency was estimated to 2800-9200 € Mg($PM_{2.5}$)$^{-1}$ for manual log boiler used without accumulator tank in Finland.

A technology that was not studied by Sternhufvud et al. (2004) is ESP applicable to small-scale combustion units. They have lately been under development by several manufacturers, e.g. Applied Plasma Physics (APP) ASA, Norway (Berntsen 2004, Henriksen 2004) and MiniPab, Switzerland (Schmatloch 2005), but they have not entered the markets yet. The emission reduction potential and cost estimates of this study were based on the introduction of the APP ESP that has been developed and tested in an EU CRAFT project CleanAir (Haaland 2003). Field and laboratory test results (Johansson et al. 2005) suggest it to be potential reduction option with efficiencies around 85-95% for particles larger than 0.04 μm and reasonable reduction costs.

Other measures were found less potential, or their efficiency or costs could not be quantified. Retrofit accumulator tank installation to log boiler would decrease emissions considerably. However, the dimensions of existing heating room restrict the applicability in most cases. Flue gas treatment technologies, such as catalysts and secondary combustion chambers, exist, but they are currently not used in the Nordic countries and information about their applicability, efficiency and costs were poorly available. Some non-technical measures, such as information campaigns on advisable combustion practices, were identified as a potential reduction measure, but their efficiency could not be quantified.

4 Methods and material

4.1

Finnish Regional Emission Scenario (FRES) model

The Finnish Regional Emission Scenario (FRES) model has been developed to work as a part of the integrated assessment model (IAM) system of PM. The IAM system includes, in addition to FRES, the modelling of atmospheric transport, chemistry and aerosol processes, and population exposure and health risk modelling. Emission compounds include primary particles in different size classes (total suspended TSP, inhalable PM_{10}, fine $PM_{2.5}$ and submicron PM_1 particles), and precursor gases of secondary PM (SO_2, NO_x, NH_3 and NMVOCs). In addition, primary PM chemical composition in different sizes, including black and organic carbon and sulphates, are calculated. The description of technical emission control measures and associated costs enables the planning of cost-optimal emission reduction strategies in order to reach predefined health targets. The main features of the emission model are described in the following.

4.1.1

Emission calculation

The basic structure of the FRES model is a combined top-down approach of aggregated area emission source sector description with more detailed bottom-up calculation of large point sources. Large energy production and industrial plants (i.e. plants utilizing boilers with thermal capacity exceeding 50 MW_{th} or plants with emissions >20 Mg(TSP, SO_2 or NO_x) a^{-1}, 250 plants) are described as point sources. Area sources include smaller industrial activities, residential combustion, road traffic, off-road and machinery, as well as various sources associated with NH_3 (agriculture), primary PM (fugitive dust and other non-combustion sources) and NMVOC (solvents use etc.). The top-down feature makes a relatively light model structure possible, while the annual activity rate inputs of the source sectors are described in a relatively aggregated level. Large point sources and their emission control facilities are described in more technical detail, which enables the estimation of emissions more accurately both spatially and in the terms of emission quantities. The following presents $PM_{2.5}$ emission calculation procedure in FRES.

Point source emission EM^p is calculated from annual activity rate A^p, unabated emission factor EF (*i.e.* the emission factor before emission control devices) and the emission removal efficiency η of emission control technologies used in the plant.

$$EM^p{}_{j,k,l,m,t} = (1 - \eta_{j,k,l}) \cdot A^p{}_{j,k,m,t} \cdot EF_m \qquad (1)$$

where t = time, j = fuel, k = sector, l = control technology and m = plant. The annual activity rate of a point source is calculated from the capacity information C of the plant (thermal capacity in the case of fuel combustion, and production capacity in the case of industrial processes) and annual operating hours OH.

$$A^{p}_{j,k,m,t} = C_{m} \cdot OH_{j,k,t} \tag{2}$$

Area source emission EM^{a} from a source sector (*i.e.* sector-fuel type combination) is calculated from annual activity data A^{a}, unabated emission factor and removal efficiencies η of various emission control technologies which can be applied to each source sector with certain utility rates X. The numbers of sectors and fuels are 102 and 10, respectively.

$$EM^{a}_{j,k,l,m,t} = \sum_{l} (1-\eta_{j,k,l}) \cdot X_{j,k,l,t} \cdot A^{a}_{j,k,m,t} \cdot EF_{j,k} \tag{3}$$

The activity rate of an area source sector is calculated from the total activity rate A^{tot} and the point source activity rates of the respective source sector.

$$A^{a}_{j,k,m,t} = A^{tot}_{j,k,t} - \sum_{m} A^{p}_{j,k,m,t} \tag{4}$$

Total emission EM^{tot} in Finland is:

$$EM^{tot}_{j,k,l,m,t} = \sum_{m} EM^{p}_{j,k,l,m,t} + \sum_{j}\sum_{k} EM^{a}_{j,k,l,m,t} \tag{5}$$

The data sources for emission factors and removal efficiencies have been estimated using national and other literature presented in Karvosenoja and Johansson (2003c). Point source specific emission factor and technical data (*e.g.* capacity, age and control technologies in use) are based on the data register on air pollution permits of the Finnish environment administration VAHTI (Korkia-Aho *et al.* 1995) that contains technical, and annual emission and activity information on Finnish industrial and energy production plants.

4.1.2
Cost calculation

Annual emission control costs C^{an} are calculated from investment and other cost information of technical control equipment.

$$C^{an}_{j,k,l} = I^{an}_{j,k,l} + OM^{fix}_{j,k,l} + OM^{var}_{j,k,l}$$

where I^{an} annual investment cost that is calculated by annualizing the investment cost I^{co} with interest rate ir and the technical lifetime of the plant lt.

$$I^{an}_{j,k,l} = \frac{(1-ir)^{lt} \cdot ir}{(1+ir)^{lt} - 1} \cdot I^{co}_{j,k,l}$$

Fixed operation and maintenance costs OM^{fix} are not related to the operation hours of the plant. Variable operation and maintenance costs OM^{var} include typically labour, electricity and ash disposal costs caused by plant operation. Unit costs is annual emission control costs expressed per mass of emission reduced or primary energy consumed annually.

4.2

The efficiency and cost data of emission reduction technologies

The parameters used in cost calculation were estimated based on Finnish and international data sources. Two Finnish cost surveys were used for power plants and industrial combustion sector. For other sectors there were less Finnish cost data available, and mainly data from the RAINS model of IIASA and a Norwegian residential ESP manufacturer were used, instead.

4.2.1

Power plants and industrial combustion

For power plants and industrial combustion sector there were Finnish cost data available. Investment, fixed operation and maintenance cost and electricity demand data (Tables 3 and 4) were estimated based on a wide but relatively old Finnish cost survey (Lammi et al. 1993), a more recent cost questionary sent to Finnish power plants (Ohlström et al. 2005) and RAINS model data (Klimont et al. 2002). The costs by Lammi et al. (1993) have been inflation corrected to the euros of year 2000. In addition, general data on electricity price (28 € MWh^{-1}) and ash disposal cost (8 € Mg^{-1}) were estimated based on spot prices at the Nord Pool Power Exchange from 06/2003 to 06/2005 and personal contacts to energy producers (A. Valli, Fortum Meri-Pori power plant 30.11.2004, T. Bergman PVO Kristiina power plant 14.12.2004, L. Taipale, Helsinki Energy 16.12.2004), respectively. Interest rate and life time used for the annualization of investments were 4% and 20 a, respectively.

Table 4 presents also calculated unit costs per reduced Mg $PM_{2.5}$ and consumed TJ primary energy. Large deviations in unit costs per reduced emission are mainly caused by variable unabated emission factors, and thus variable amounts of $PM_{2.5}$ reduced, between different plants and fuels. Remarkably high unit costs in HFO boilers are explained by low annual operation hours.

Table 3. PM control technology options and technology-specific parameters in power plants and industrial combustion sectors used in this study

Technology	**Electricity demand ($kWh\ GJ^{-1}$)**	**Fixed o&m (% of investment a^{-1})**	**$PM_{2.5}$ removal efficiency (%)**
Fabric filter	0.2	1.0	99.7
2-3 stage ESP + scrubber	0.14	0.5	99
2-3 stage ESP	0.14	0.5	96
1 stage ESP (plants below $50MW_{th}$)	0.11	0.5	93
Multicyclone	0.15	0.5	50

Table 4. Investment and calculated unit costs in sector – control technology combinations considered in this study in power plants and industrial combustion sectors

Sector	**Technology**	**Investment (€ kW_{th}^{-1})**	**Unit cost (€ $Mg(PM_{2.5})^{-1}$)**	**Unit cost (€ TJ^{-1})**
Coal power plants 560-1300MW_{th}	2-3 stage ESP (+wet FGD)	6.2[a]	384-485 [a]	58-66 [a]
Peat and wood power plants and ind. boilers 50-600MW_{th}	2-3 stage ESP Fabric filter	13 14	349-5230 367-5840	65-101 76-110
Solid fuel power plants and ind. boilers 5-50MW_{th}	1 stage ESP Fabric filter	14 18	257-2310 327-2940	86-88 117-119
Solid fuel power plants and ind. boilers <5MW_{th}	Multicyclone 1 stage ESP	7.8 85	416-2600 2180-12700	48-52 468-472
HFO power plants and ind. boilers, 5-50MW_{th}	Multicyclone 1 stage ESP	4.6 14	4660 7440	104 310
HFO power plants and ind. boilers, <5MW_{th}	Multicyclone	6.4	6480	145
Black liquor ind. recovery boilers 50-600MWth	2-3 stage ESP (+NaOH scrubber)	10[a]	18-85[a]	37-118[a]

a) The costs of ESP only. The costs of FGD were allocated to sulphur reduction, although it enhances also PM reduction.

4.2.2

Industrial processes

Industrial processes were divided into four categories in this study: (1) small or adequately controlled, (2) black liquor recovery boilers, (3) other paper pulp processes than black liquor combustion, (4) metal industry processes and (5) other processes. The processes with emission below 20 $Mg(PM_{2.5})$ a^{-1} in 2020 were considered to have such minor contribution that they were classified small or already adequately efficiently controlled. Emission reduction potential and costs were estimated only for the processes with emissions higher than 20 $Mg(PM_{2.5})$ a^{-1} (categories 2-5).

For black liquor combustion in recovery boilers there were Finnish emission reduction investment cost data available (Ohlström et al. 2005, Table 4). Furthermore, there were detailed thermal capacity information of recovery boilers available. The costs were calculated with the same parameters of removal efficiency, fixed operation and maintenance cost, electricity demand and price, and ash disposal cost than for power plants and industrial combustion.

For the other processes than black liquor combustion (categories 3-5) there were no national cost data available. Instead, reduction costs were calculated based mainly on the parameters of the RAINS model (Klimont et al. 2002). The same removal efficiencies and electricity and ash disposal prices than for power plants and industrial combustion were used.

4.2.3

Domestic combustion

The reduction technology in the domestic sector considered in this study was small-scale ESP model developed and tested in an EU CRAFT project CleanAir (Berntsen 2004, Henriksen 2004). Technical and cost information were estimated based on laboratory and field test results (Johansson et al. 2005) and other information from the manufacturer. The removal efficiencies were estimated higher for higher concentrations of particles (pers. comm. E. Henriksen, Applied Plasma Physics ASA, Norway, 14.2.2006).

The field tests for the ESP has been carried out on a wood stove with PM emission factors of 42-44 mg(TSP) MJ^{-1} when operated without ESP. The emission levels achieved after the ESP have been 5-6 mg(TSP) MJ^{-1}. The emission factors with ESP utilization of this study, however, were estimated higher compared to the test results, in order to reflect the possible degradation of removal efficiencies over time in actual use. Other parameters used in cost calculations were as follows (Berntsen 2004, pers. comm. E. Henriksen, Applied Plasma Physics ASA, Norway, 14.2.2006):

- Investment cost 400 € per appliance
- Electricity demand for the time of operation 120W
- Fixed operation and maintenance cost (1% of the investment a^{-1})

The same electricity price (28 € MWh^{-1}), ash disposal cost (8 € Mg^{-1}), technical lifetime (20a) and interest rate (4%) than for power plants sector were used.

Table 5. Unabated emission factors, ESP reduction efficiencies, resulting emission factors after the ESP and calculated unit costs in different domestic wood boiler types (20 kW thermal peak output and 1200 h a^{-1} annual peak operation hours).

Boiler type	**Em.factor without ESP (mg MJ^{-1})**	**ESP removal eff. (%)**	**Em.factor after the ESP (mg MJ^{-1})**	**Unit cost (€ $Mg(PM_{2.5})^{-1}$)**	**Unit cost (€ PJ^{-1})**
Manual feed log boiler with accumulator tank	100	90	10	3700	333
Manual feed log boiler without acc. tank	800	95	40	419	318
Automatic feed wood chip boiler	60	85	9	6960	355
Automatic feed pellet boiler	30	80	6	15300	368

4.3

Scenario assumptions

Future activity data of this study were based on "Kyoto-nuclear" 2020 energy and activity pathway of national Climate Strategy (Ministry of Trade and Industry 2001).

4.3.1

Power plants and industrial combustion

The annual operation hours of point sources, the start-up of new plants, as well as the close-down of old plants were estimated based on information from Climate Strategy and energy producers, and authors' expert estimates. Control technology utilization in new and existing capacities in the "Baseline" scenario was estimated based on currently used reduction measures from the VAHTI database (Korkia-Aho *et al.* 1995) and legislative requirements of LCPD (EC 2001) for plants larger than 50 MWth and national BREF document for smaller plants (Jalovaara et al. 2005).

For the "Reduction" scenario the utilization of fabric filters was assumed the prevailing technology in all capacities where it was estimated to be technically and economically feasible. The cases where fabric filters were not assumed to be used were:

- Coal power plants that use combined ESP and wet FGD with very low emission factors 1 – 3 mg($PM_{2.5}$) MJ^{-1}. Furthermore, their contribution to total country emission were estimated to be negligible (0.2%).
- Fabric filters were not considered economically feasible for small solid fuel energy plants below 5 MW_{th} (Jalovaara et al. 2003). Assumed technology was 1-stage ESP.
- HFO boilers are used mainly as peak or reserve capacity with low annual operating hours below 1000 h a^{-1}. Economically feasible emission reduction technologies were assumed to be 1-stage ESP and multicyclone for 5-50 and below 5 MW_{th} size ranges, respectively.

4.3.2

Industrial processes

For black liquor recovery boilers control technology information from the VAHTI database was used. For industrial processes other than black liquor boilers, however, the information about emission control use in VAHTI was relatively limited. Instead, the estimates on the current use of control technologies and planned reduction investments of this study were based on a survey including direct contacts to the plants and literature review of environmental reports and permits (Tohka and Karvosenoja in press). The survey covered all 23 industrial plants considered in this study, and reliable information was obtained for 19 plants. Furthermore, BAT requirements documented in national BREF reports (Nuortimo 2002, Riekkola-Vanhanen 1999a,b) were used to estimate the adequacy of current and planned reduction technologies in 2020.

- Also for industrial processes fabric filters was assumed the technology to be utilized in the "Reduction" scenario. The exceptions were the following cases:
- Black liquor recovery boilers that use combined ESP and wet NaOH scrubber. Technical feasibility with wet Na content flue gases was estimated to limit the use of fabric filters (pers. comm. J. Kosonen, Stora Enso Imatra Mills 9.11.2005).
- Blast furnaces where flue gas composition after ESP and wet scrubber limit the technical feasibility of fabric filters.
- A steel industry smelter where a vast majority of emissions were fugitive. The emissions are controlled with various good operation practice methods (pers. comm. M. Gottberg Fundia Wire Koverhar 15.12.2004 and 5.12.2005).

4.3.4

Domestic combustion

On domestic combustion, total wood use estimate in 2020 were based on Climate Strategy data. Appliance specific activities has been estimated for the year 2000 in Karvosenoja et al. (submitted). The estimate for 2020 was based on the prevalence of appliances in houses of different age in current housing stock and authors' expert estimate on the development of new installations and outgoing appliance stock. The emission reduction potential estimates of this study concentrated on the combustion of wood logs, chips and pellets in residential houses. The main assumptions from 2000 to 2020 were:

- Strong increase in pellet use (from 0.1 to 6.8 PJ a^{-1}) in both new installations and existing wood and oil boilers. The increase takes especially place during the 2010s.
- Manual feed log boilers, that is the most common boiler technology at the moment, maintains its position in the 2000s, but is to some extent replaced by pellet technology during the 2010s (20% decrease from 2000). The share of boiler use without accumulator tank was assumed to remain one third of total manually feed boiler use.
- Automatic feed wood chip boilers remain an important heat source in rural estates. Their use, however, decrease 20% because of the decline in the number of agricultural farms and increase in pellet use in 2010s.
- The installation of supplementary masonry heaters to electricity and oil heated residential buildings will remain popular. Combustion in masonry heaters increases 47% from 2000. Modern heater technology with advanced grate and air supply systems and low emissions become prevalent.

- The installation of other stoves, ovens and fireplaces is currently less common than of masonry heaters. Their share continue to decrease, leading to 20% decrease in their wood use.

In the “Baseline” scenario there were no emission control technology use assumed. Small ESP utilization was assumed in the “Reduction” scenario for the total heating boiler capacity. Stoves and masonry heaters were used for supplementary heating typically only 100 - 300 h a^{-1} operation, which would make ESP use economically infeasible.

5 Scenario emissions and reduction costs in 2020

5.1

Power plants and industrial combustion

Largest emissions in “Baseline” were caused by small solid fuel boilers that are equipped only with multicyclones (Table 7). Emissions from plants below 5 MW$_{th}$ contributed to 46% of total PM$_{2.5}$ from solid fuel plants, although their respective share of total activity was only 3.5%. Also HFO combustion caused relatively high emissions because of the lack of efficient emission controls.

In the “Reduction” scenario emissions were relatively low in all the sectors. The use of fabric filters in solid fuel combustion plants brought considerable additional reductions with marginal costs below 5000 € Mg^{-1}. ESP use in smaller than 5MW$_{th}$ solid fuel plants reduced emissions efficiently with slightly higher marginal costs. The highest emissions in the “Reduction” scenario were caused by small HFO plants below 5 MW$_{th}$ where the use of control measures that requires high investments, such as ESPs or fabric filters, were estimated to be economically infeasible because of low annual operation hours. The marginal cost for ESP use in medium-size HFO plants 5-50 MW$_{th}$ were high because of the same fact.

Table 7. PM$_{2.5}$ emission calculation and emission reduction costs in power plants and industrial combustion in the “Baseline” (B) and “Reduction” (R) scenarios. Average marginal costs were calculated for the emission reductions in the “Reduction” scenario that were incremental to “Baseline” controls.

2020	**Total activity (PJ a^{-1})**	**Unabated em. factor (mg MJ^{-1})**	**Technology; Utilization of total activity; removal efficiency**	**PM$_{2.5}$ emission (Gg a^{-1})**	**Emission red. cost (M€ a^{-1})**	**Average marginal cost (€ Mg^{-1})**
Coal power plants 300-1300MW$_{th}$	47.1	120-180[a]	B&R: ESP+wet FGD; 100%; 99%	0.07	2.8	–
Peat and wood power plants and ind. boilers 50-600MW$_{th}$	208	13-300[a]	B: 2-3 stage ESP; 100%; 96% R: Fabric filter; 100%; 99.7%	0.95 0.09	16.7 18.6	2200
Solid fuel power plants and ind. boilers 5-50MW$_{th}$	43.6	40-360[b]	B: 1 stage ESP; 100%; 93% R: Fabric filter; 100%; 99.7%	0.31 0.01	3.8 4.8	3300
Solid fuel power plants and ind. boilers <5MW$_{th}$	11.0	40-230[b]	B: Multicyclone; 100%; 50% R: 1 stage ESP; 100%; 93%	1.1 0.15	2.7 9.5	6900
Heavy fuel oil (HFO) power plants and ind. boilers, 5-50MW$_{th}$	27.0	45[b]	B: Multicyclone; 100%; 50% R: 1 stage ESP; 100%; 93%	0.60 0.08	2.8 8.4	10700
HFO power plants and ind. boilers, <5MW$_{th}$	14.2	45[b]	B: Unabated; 100%; – R: Multicyclone; 100%; 50%	0.64 0.32	– 2.1	6500
Other liquid and gaseous fuel power plants and ind. boilers, all sizes	296	0.1-2.9[a,b]	B&R: Unabated; 100%; –	0.02	–	–
TOTAL	**646**		**B:** **R:**	**3.7** **0.77**	**28.8** **46.1**	**5900**

a) boiler specific emission factors
b) fuel and combustion technology specific emission factors

5.2

Industrial processes

In general, the level of PM control in industrial process sector in Finland is relatively high (Table 8). The highest process emissions were caused by black liquor combustion because of very high flue gas fine PM concentrations that make PM reduction technically challenging (Mikkanen et al. 1999) and extensive activity level, 163 PJ a^{-1} in 2020. Further reduction by fabric filters were estimated technically infeasible. Considerable additional reductions could be achieved in paper pulp lime kilns and other processes, mainly in oil refineries and glass wool and fibre production.

Marginal costs for additional emission reductions were relatively low for "Other processes" category where there were mainly no emission controls in use in the "Baseline" situation, and high for metal industry where the potential concerned change from ESP to fabric filters. However, the emission reduction cost estimates of this study that were based on the RAINS model data should be considered indicative only.

Table 8. PM$_{2.5}$ emissions and emission reduction costs in industrial processes in the "Baseline" (B) and "Reduction" (R) scenarios. Average marginal costs were calculated for the emission reductions in the "Reduction" scenario that were incremental to "Baseline" controls.

2020	**Number of processes**	**Technology; Utilization of total activity; removal efficiency**	**PM$_{2.5}$ emission (Gg a^{-1})**	**Emission red. cost (M€ a^{-1})**	**Average marginal cost (€ Mg^{-1})**
Black liquor recovery boilers 50-600MW$_{th}$	24	B&R: ESP+NaOH scrubber; 100%; 99%	3.0	8.9	-
Paper pulp lime kilns	6	B: 2-3 stage ESP R: Fabric filter	0.42 0.03	–[a] –[a]	–[a] –[a]
Metal industry	B: 4 2 2 1	B: Fabric filter ESP + scrubber 2-3 stage ESP Fugitive, controlled with good practice methods	0.16 0.37 0.12 0.04	3.7 2.2 4.3 –	
	R: 6 2 1	R: Fabric filter ESP + scrubber Fugitive, controlled with good practice methods	0.17 0.37 0.04	9.4 2.2 –	12500
Other processes	B: 1 1 6	B: Fabric filter 2-3 stage ESP Unabated	0.06 0.17 0.88	0.33 0.51 –	
	R: 8	R: Fabric filter	0.07	1.4	600
Small or adequately controlled processes	56	not studied	0.58	not studied	
TOTAL	**103**	**B:** **R:**	**5.8** **4.3**	**20.0** **21.9**	 **1700**

a) cost data not available (not included in RAINS)

5.3

Domestic combustion

Total domestic combustion "Baseline" emission in 2020 was 11.3 Gg($PM_{2.5}$) a^{-1}, of which 11.1 Gg a^{-1} originated from wood combustion, and 0.2 Gg a^{-1} from oil combustion. The majority of emissions originate in wood combustion in stoves, ovens, masonry heaters and open fireplaces, 8.7 Gg a^{-1}, of which 6.5 Gg a^{-1} was caused by the use in residential and 2.2 Gg a^{-1} in recreational buildings. The central heating of residential buildings by wood boilers corresponded to 2.4 Gg a^{-1}.

In the "Reduction" scenario no technical emission controls were assumed applicable to any of the stoves and ovens categories that are typically used for supplementary heating only occasionally. Wood boilers, instead, are used as primary heating devices which makes the investment for small-scale ESP economically more feasible. Marginal costs per Mg($PM_{2.5}$) reduced vary between different boiler technologies because of different unabated emission factors. Cost-efficiency is better for high-emitting manual log boilers. Country-level emission reduction potential is considerable, 2.0 and 0.22 Gg a^{-1} for manual and automatic boilers, respectively.

Table 9. $PM_{2.5}$ emissions and emission reduction costs in domestic combustion in the "Baseline" (B) and "Reduction" (R) scenarios. Marginal costs equal to the unit costs calculated for residential ESP in the "Reduction" scenario.

2020	**Activity (PJ a^{-1})**	**Unabated em. factor (mg MJ^{-1})**	**Control tech.; util rate; red. eff.**	**$PM_{2.5}$ emission (Gg a^{-1})**	**Emission red. cost (M€ a^{-1})**	**Marginal cost (€ Mg^{-1})**
Manual feed log boilers with accumulator tank	4.4	100	B: – R: ESP; 100%; 90%	0.44 0.04	– 1.5	3700
Manual feed log boilers without accumulator tank	2.1	800	B: – R: ESP; 100%; 95%	1.7 0.08	0.67 –	420
Automatic feed wood chip boilers	1.2	60	B: – R: ESP; 100%; 85%	0.07 0.01	– 0.42	7000
Automatic feed pellet boilers	6.8	30	B: – R: ESP; 100%; 80%	0.20 0.04	– 2.4	15300
Modern masonry heaters	6.0	100	B&R: –	0.60	–	
Iron stoves and open fireplaces	1.6	1000	B&R: –	1.6	–	
Other stoves and ovens[1]	21.7	300	B&R: –	6.5	–	
Oil combustion	26.4	7	B&R: –	0.2	–	
Domestic combustion TOTAL	**70.1**		**B:** **R:**	**11.3** **9.1**	**–** **5.0**	**2300**

1) incl. conventional masonry heaters, masonry ovens, kitchen ranges and sauna stoves

6 Discussion on scenario results

The summary of incremental emission reduction potentials and cost-efficiency in three studied sectors is presented in Figure 1.

The highest emission reductions with marginal costs below 5000 € Mg^{-1} could be achieved by the introduction of ESPs in residential log boilers, 2.0 $Gg(PM_{2.5})\ a^{-1}$. Marginal costs are lower for the cases when boiler is operated without accumulator because of higher unabated emission factors and thus bigger amounts of PM reduced. Further reduction of 0.22 Gg a^{-1} could be achieved with ESPs in automatic wood chip and pellet boilers. However, the marginal costs would be higher because of relatively low unabated emission factors. The cost and reduction potential estimates depend strongly on the assumptions of unabated emission factors and the performance of the ESP. These assumptions are uncertain and therefore should be considered indicative only (see discussion in the next chapter).

In industrial-scale combustion relatively cost-efficient reductions would be possible in solid fuel boilers by the utilization of fabric filter technologies. The emission of 1.2 Gg a^{-1} could be reduced with marginal costs below 5000 € Mg^{-1} in boilers larger than 5 MW_{th}. Less cost-efficient reductions of 1.8 Gg a^{-1} are achievable in smaller solid fuel and heavy fuel oil boilers by ESP technology.

Reduction potential in industrial processes was more moderate occurring in few individual plants. Marginal costs were estimated relatively low for the majority of the potential. However, both cost and reduction potential estimates entail considerable uncertainties (see discussion in the next chapter).

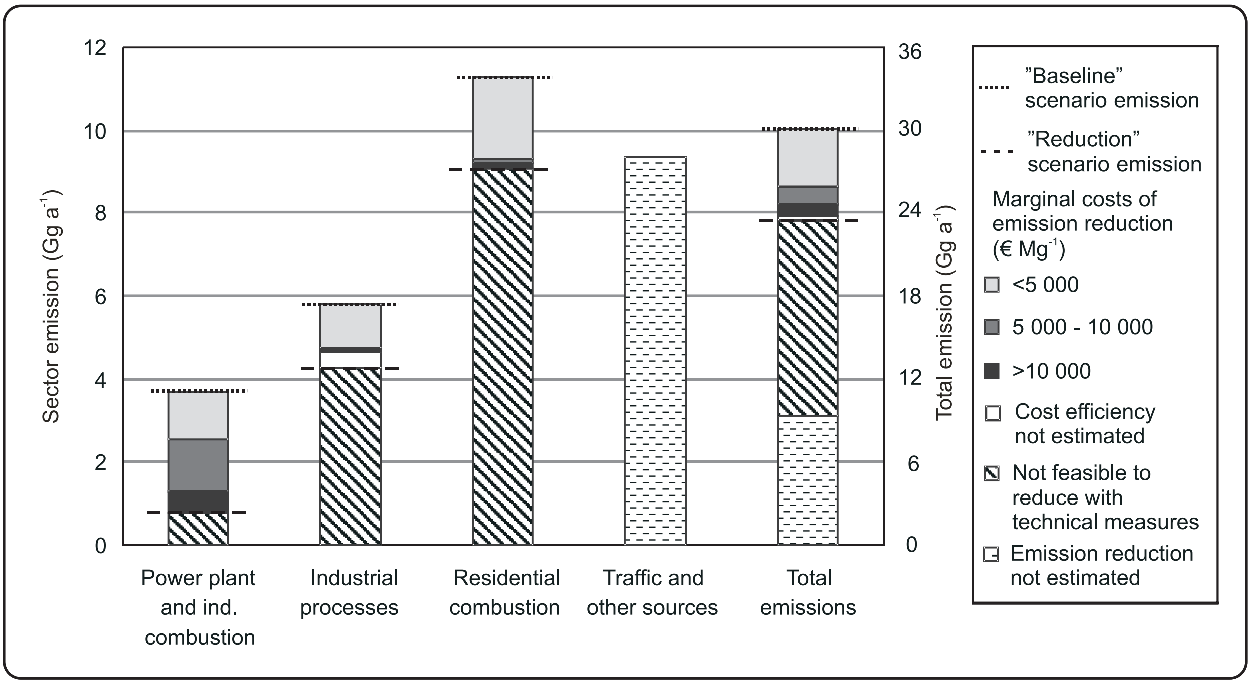

Figure 1. Total Finnish $PM_{2.5}$ emissions (right-hand axis and bar) and the emissions by sectors (left-hand axis and four bars) in Baseline and Reduction scenarios and cost-efficiency of emission reductions in 2020.

7 Emission and cost uncertainty discussion

Uncertainties in different parts of the FRES emission and cost calculation can be identified, i.e. in activity levels, emission factors, reduction efficiencies, the assumptions on control technology utilization and cost parameters. In the following the most important sources of uncertainty of this study were identified and qualitatively discussed.

7.1

Domestic combustion

Karvosenoja and Johansson (2003a) have compared FRES base year 2000 emissions with other national and international emission inventories. The largest differences were detected in residential wood combustion sector because of remarkable uncertainties in emission factors. The uncertainties are mainly caused by highly variable emission characteristics in batch-wise combustion that are affected by many factors, e.g. technically variable combustion appliances, non-uniform fuel qualities and the substantial effect of user's combustion practices. Karvosenoja et al. (submitted) present uncertainty analysis for Finnish year 2000 domestic wood combustion emissions. The limits of 95% confidence interval for $PM_{2.5}$ emission factors were estimated 54% down, 88% up of the mean value. The calculated total domestic wood combustion uncertainty was 29% down, 37% up, with most important parameters being the emission factors.

The emission factors of various residential wood combustion equipment used in this study were estimated by the authors and other Nordic experts (Sternhufvud et al. 2004) based mainly on Finnish (Tissari et al. 2005) and Swedish (Johansson et al. 2005) measurements. Recent measurements by Tissari et al. (2005) suggest, however, that the emission factors of masonry heaters, masonry ovens and sauna stoves would mainly be below 200 mg MJ^{-1}, compared to 300 mg MJ^{-1} used in this study. The resulting overestimation in 2020 emissions of this study would be around 3-4 Gg a^{-1}.

The emission factors of manual log boilers operated without water accumulator tanks are highly variable. Johansson et al. (2005) reported emission factors between 350 and 2200 mg(TSP) MJ^{-1}. The variability causes uncertainty, in addition to emission estimate, also to unit cost calculated per mass of emission reduced. Furthermore, the ESP has not been tested in operation with such high emission factors. Therefore the unit cost of residential ESP in log boilers without accumulator should be considered indicative only.

In addition to emission factors, another remarkable source of uncertainty of domestic wood combustion is future activity assumptions on the use of different combustion equipment. The highest uncertainties on "Baseline" emissions were caused by the assumptions on log boiler use without accumulators. Based on the fact that there are no legislation that would restrict log boiler use without accumulators, it was assumed that their relative fraction remains the same as currently, i.e. one third of the total log boiler use. The full implementation of accumulator tanks by 2020 would lead to 1.5 Gg a^{-1} lower emissions than estimated in this study.

The "Reduction" scenario emissions for the domestic sector were based on the use of small-scale ESP in wood boilers. The technology has been tested both in laboratory (Berntsen 2004) and on field (Johansson et al. 2005), but it is not commercially available at the moment. The field tests did not cover combustion situations with emission factors higher than 50 mg(TSP) MJ^{-1}. Therefore, the lack of wide actual operation experiences causes uncertainty in the estimation of ESP reduction efficiencies, technical feasibility and costs. In order to reflect possible efficiency degradation in actual operation, the reduction efficiency values used in this study were lower than what have been obtained in the tests.

7.2

Power plants, industrial combustion and industrial processes

For power and industrial plants emission uncertainties were assessed lower than for residential combustion. Point source specific emission factors that were utilized for large combustion plants >50MW_{th} and industrial processes reflect the variable emission and technical characteristics of individual plants. A statistical analysis on Finnish large combustion plants by Sarelin (2003) showed that the limits of 95% confidence interval in the annual average PM emission factors of individual plants in 1995-2001 were mainly between ±20 and ±30%.

For smaller plants <50MW_{th}, in addition to emission factor uncertainties, the assumptions of emission reduction technology utilization have remarkable effect on the "Baseline" emission levels. Since the emissions of small plants are not regulated by the EU or strict national legislation, the assumptions of reduction technology utilization in the "Baseline" scenario were relatively conservative based on current average reduction levels.

The highest uncertainties in the "Reduction" scenario estimates for power and industrial plants are related to the feasibility of emission reduction technologies and very high removal efficiency assumed for fabric filters. According to Finnish measurement studies documented by Ohlström et al. (2005) fabric filter removal efficiency for fine particles in normal use is around 99.9%, but malfunctions or other bypass situations decrease the average efficiency in actual operation to 99.7%. However, the effects of malfunctions on actual emission levels have not been widely studied, and they might result in considerably lower reduction efficiencies than what was assumed in this study. Thus the emissions from industrial and power plants in the "Reduction" scenario might be underestimated.

The technical feasibility of emission reduction technologies could be relatively reliably estimated for the most of the emission sources. The estimates were mainly based on direct contacts with entrepreneurs. However, there are uncertainties related to fugitive industrial process emissions which are not as easily directed to flue gas pipeline and reduction appliances as normal stack emissions. The emissions could not be distinguished between fugitive and stack emissions for all the industrial processes considered in this study because of the lack of information. Therefore, some fraction of fugitive emissions might be calculated as stack point sources in the FRES model, which might result in the overestimation of emission reduction potential. Furthermore, the information about reduction technologies that are currently and thus in "Baseline" in use in industrial processes was not complete. Four of the plants in category "Other processes" that were assumed unabated might have some control equipment installed. Therefore, the reduction potential might be overestimated for these plants, i.e. by 0.4 Gg a^{-1} at the most.

Emission reduction costs for power plants and industrial boilers were estimated based on parameters gathered from Finnish plants. Investment costs per thermal capacity for different boiler types and sizes were assessed to be relatively reliable. Investment costs were responsible for the majority of annual costs for the most of the sectors. For large coal power plants and black liquor recovery boilers, however, ash disposal cost corresponded to up to more than a half of the total annual costs. Ash disposal cost information obtained from energy plants and Finnish Energy Industries varied largely depending on ash utilization possibilities and the required distance of transportation. Furthermore, there were no data available on the ash disposal cost of black liquor combustion. Therefore, emission reduction cost estimates for coal power plants and black liquor combustion are regarded highly uncertain.

For industrial processes the cost information from the RAINS model were used. The investment costs for industrial processes in RAINS are given linearly dependent on activity level (€ Mg(product)$^{-1}$) for all plant sizes. However, in reality the dependency is different for different plant sizes. This leads to considerable uncertainty in industrial process cost calculations.

8 Conclusions

The study gave a view on Finnish primary $PM_{2.5}$ emissions and cost efficient reduction potentials in different emission source sectors in 2020. Emissions were calculated for two scenarios with different assumptions on control technology utilization: (1) "Baseline", i.e. the emissions resulting when control technologies complying legislative requirements were used, and (2) "Reduction", the utilization of technically and economically feasible control technologies. The potential and cost efficiency of emission controls was estimated for stationary combustion and industrial sectors by the means of marginal costs per reduced emission quantities.

The total "Baseline" emissions were 30.2 Gg a^{-1}, of which the studied sectors covered 20.8 Gg a^{-1}. The highest emissions were caused by residential wood combustion and industrial processes, contributing to 37 and 19% of the total emissions, respectively. Total emission reduction potential below "Baseline" emissions was estimated at 6.7 Gg a^{-1}, or 22% of the total emissions. Considerable emission uncertainties were detected, especially in residential wood combustion sector.

Emission reductions were estimated most cost efficient for the utilization of small ESPs in residential wood log boilers and fabric filters in large solid fuel combustion plants. Emission reduction potential was estimated to occur also in few individual industrial processes, however the estimates on cost efficiency were uncertain.

The health effects of primary $PM_{2.5}$ from different emission sources are different, not only in terms of emission quantities, but also of the physical location where the emissions are released in to the atmosphere. The emissions from traffic sources and residential combustion take place from low altitude near the height of human respiration, whereas industrial sources use high stacks which enable more thorough dilution of emissions before they can cause human exposure. Furthermore, the geographical location of emissions in relation to the location of population are substantially different for different sources. For example, traffic emissions that occur mainly in urban areas cause presumably higher population exposure than residential wood combustion that take to large extent place also in less populated areas (Tuomisto et al. submitted b).

The emission estimates of this study calculated with the FRES model are being used in integrated assessment modeling project KOPRA (www.fmi.fi/research_air/air_47.html). The integration of emission, atmospheric and health risk models enables the assessment of negative health effects caused by various emission sources and health benefits gained by emission reductions. One of the main goals of KOPRA is to provide cost efficiency information on the reduction of negative health impacts in the form relevant to policy makers.

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DOCUMENTATION PAGE

Publisher	Finnish Environment Institute (SYKE)	*Date* September 2006
Author(s)	Niko Karvosenoja, Zbigniew Klimont, Antti Tohka and Matti Johansson	
Title of publication	**Fine particle emissions, emission reduction potential and reduction costs in Finland in 2020**	
Publication series and number	The Finnish Environment 46/2006	
Theme of publication	Environmental protection	
Parts of publication/ other project publications	This publication is also available in the Internet www.environment.fi/publications	
Abstract	Fine particulate matter (PM$_{2.5}$) in the atmosphere have been associated with severe human health effects. This report explores future emissions of primary PM$_{2.5}$, their reduction potential and related reduction costs in Finland. One activity pathway of 2020 of the Finnish Climate Strategy was studied with two different PM emission control utilization scenarios: (1) “Baseline” which involves PM control technology utilization complying with current legislation, and (2) “Reduction” which assumes the use of maximum technically and economically feasible emission reduction measures. The studied sectors included stationary combustion and industrial activities. The work was performed using the Finnish Regional Emission Scenario (FRES) model of Finnish environment institute (SYKE). Total emission reduction potential below “Baseline” was estimated at 6.7 Gg(PM$_{2.5}$) a^{-1}, or 22% of the total emissions. The biggest relatively cost-efficient reductions (marginal cost below 5000 € Mg^{-1}) can be achieved by the use of small electrostatic precipitators (ESPs) in domestic wood log boilers, 2.0 Gg a^{-1}. In large-scale combustion installations in power plants and industry the reduction of 1.2 Gg a^{-1} is possible by fabric filter installations instead of ESPs. A comparable reduction with slightly higher costs can be achieved in small (below 5 MW$_{th}$) industrial boilers by the introduction of ESPs. For industrial processes potential occurs in few individual plants. The uncertainties in emission reduction and cost estimates are biggest for domestic combustion and industrial processes. This report presents cost-efficiency estimates of future emission reductions per mass of PM$_{2.5}$ reduced. However, the magnitude of health benefits gained from emission reductions are different for different emission sources, depending on e.g. the altitude of emission release, the emission location in relation to the location of population etc. The results of this study are used in the integrated assessment modeling framework developed in the KOPRA project in order to link the information of emission reductions and costs, atmospheric dispersion and induced health impacts.	
Keywords	fine particles, emissions, control, environmental engineering, costs, modeling, scenarios	
Financier/ commissioner		

ISBN 952-11-2413-X (pbk.)	ISBN 952-11-2414-8 (PDF)	ISSN 1238-7312 (print)	ISSN 1796-1637 (online)
No. of pages 33	*Language* Englich	*Restrictions* Public	*Price (incl. tax 8 %)* 8,50 €

For sale at/ distributor	Edita Publishing Ltd., P.O.Box 800, 00043 Edita Finland, Phone +358 20 450 00 Mail orders: Phone +358 20 450 05, telefax +358 20 450 2380 Internet: www.edita.fi/netmarket
Financier of publication	Finnish Environment Institute, P.O.Box 140, FIN-00251 Helsinki, Finland
Printing place and year	Edita Prima Ltd, Helsinki 2006

KUVAILULEHTI

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<tr><td><i>Tiivistelmä</i></td><td colspan="4">Ilmakehän pienhiukkasten (PM$_{2.5}$) on havaittu aiheuttavan vakavia terveysvaikutuksia. Tässä raportissa arvioidaan tulevaisuuden primääri PM$_{2.5}$ päästöjä, päästövähennyspotentiaaleja ja aiheutuvia kustannuksia Suomessa. Tarkasteltiin Kansallisen ilmastostrategian yhtä vuoden 2020 aktiviteettipolkua (KIO2) käyttäen kahta eri hiukkaspäästöjen vähennysskenaariota: (1) ”Baseline”, jossa vähennysteknologioiden käyttö vastaa lainsäädännön vaatimuksia (nk. ”current legislation”), ja (2) ”Reduction”, jossa oletetaan käytettävän parasta taloudellisesti ja teknisesti käyttökelpoista teknologiaa (nk. ”maximum feasible reduction”). Tutkimus tehtiin Suomen ympäristökeskuksen alueellisella päästöskenaariomallilla (Finnish Regional Emission Scenario, FRES). Tarkastelu kattoi kiinteät polttolähteet sekä teollisuusprosessit.

Tutkittujen sektoreiden päästövähennyspotentiaaliksi arvioitiin 6.7 Gg(PM$_{2.5}$) a^{-1}, joka vastaa 22% Suomen kokonaispäästöistä vuonna 2020. Suurimmat kustannustehokkaat (marginaalikustannus alle 5000 € Mg^{-1}) päästövähennykset voidaan saavuttaa sähkösuodattimilla (ESP) puun pienpolton klapikattiloissa, 2.0 Gg a^{-1}. Voimalaitoksissa ja teollisuuden suurissa polttolaitoksissa jotka normaalisti varustetaan sähkösuodattimilla, päästöjä voidaan edelleen vähentää kuitusuodattimilla. Päästövähennyspotentiaalia löytyy myös pienemmissä teollisuuden kattiloissa, joissa normaalisti käytettäisiin vain multisykloneita. Teollisuusprosessien kohdalla päästövähennykset arvioitiin mahdollisiksi muutamissa yksittäisissä laitoksissa. Arvioiden epävarmuudet ovat suurimmat pienpoltolle ja teollisuusprosesseille.

Tämän raportin arviot koskevat päästövähennysten kustannustehokkuuksia esitettynä vähennettyä PM$_{2.5}$ massapäästöä kohden. Näistä vähennyksistä saavutettavat terveyshyödyt riippuvat kuitenkin monista tekijöistä, mm. päästökorkeuksista ja päästöjen sijainnista suhteessa väestön sijaintiin. Nämä tekijät poikkeavat merkittävästi eri päästösektoreiden välillä. Tämän tutkimuksen tuloksia käytetään osana Tekesin ja ympäristöministeriön rahoittamaa projektia KOPRA, jossa yhdistetään tiedot päästövähennyksistä ja -kustannuksista, hiukkasten leviämisestä ja aiheutuvista terveysvaikutuksista yhtenäiseen mallinnuskehikkoon.</td></tr>
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<tr><td><i>Rahoittaja/ toimeksiantaja</i></td><td colspan="4"></td></tr>
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952-11-2413-X (nid.)</td><td>ISBN
952-11-2414-8 (PDF)</td><td>ISSN
1238-7312 (pain.)</td><td>ISSN
1796-1637 (verkkoj.)</td></tr>
<tr><td><i>Sivuja</i>
33</td><td><i>Kieli</i>
Englanti</td><td><i>Luottamuksellisuus</i>
Julkinen</td><td><i>Hinta (sis.alv 8 %)</i>
8,50 €</td></tr>
<tr><td><i>Julkaisun myynti/ jakaja</i></td><td colspan="4">Edita Publishing Oy, PL 800, 00043 Edita, vaihde 020 450 00
Asiakaspalvelu: puh. 020 450 05, telefax 020 450 2380
Sähköposti: asiakaspalvelu@edita.fi, www.edita.fi/netmarket</td></tr>
<tr><td><i>Julkaisun kustantaja</i></td><td colspan="4">Suomen ympäristökeskus, PL 140, 00251 Helsinki</td></tr>
<tr><td><i>Painopaikka ja -aika</i></td><td colspan="4">Edita Prima Oy, Helsinki 2006</td></tr>
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PRESENTATIONSBLAD

Utgivare	Finlands miljöcentral (SYKE)			*Datum* September 2006
Författare	Niko Karvosenoja, Zbigniew Klimont, Antti Tohka och Matti Johansson			
Publikationens titel	**Fine particle emissions, emission reduction potential and reduction costs in Finland in 2020** (Utsläpp av mikropartiklar, minskningspotential och kostnader i Finland till år 2020)			
Publikationsserie och nummer	Miljön i Finland 46/2006			
Publikationens tema	Miljövård			
Publikationens delar/ andra publikationer inom samma projekt	Publikationen finns tillgänglig också på internet www.environment.fi/publications			
Sammandrag	Atmosfärens mikropartiklar ($PM_{2.5}$) har förknippats med allvarliga hälsoeffekter. Denna rapport uppskattar utsläppen av primär $PM_{2.5}$ i framtiden i Finland, förutsättningarna att minska dem och till vilken kostnad. Den nationella klimatstrategins aktivitetscenario 2020 studerades med hjälp av två olika minskningsstrategier för mikropartiklar: (1) ”Baseline”, där den använda tekniken för minskning motsvarar kraven i lagstiftningen (sk. ”current legislation”), och (2) ”Reduction”, där antagendet är, att den mest ekonomiska och tekniskt mest användbara teknologin används (sk.”maximum feasible reduction”). Undersökningen gjordes med Finlands miljöcentrals regionala modell för utsläppsscenario (Finnish Regional Emission Scenario, FRES). Utredningen omfattade fasta förbränningskällor och industriprocesser. De undersökta sektorernas minskningspotential uppskattades till 6.7 Gg($PM_{2.5}$) a^{-1}, som motsvarar 22 % av Finlands totala utsläpp år 2020. De kostnadseffektivaste minskningarna i utsläppen (marginalkostnad under 5000 € Mg^{-1}) kan uppnås med elektrostatiska filter (ESP) vid förbräning av klabbar i små vedpannor, 2.0 Gg a^{-1}. I kraftverk och i industriernas stora förbränningsstationer, som normalt förses med elekrostatiaska filter, kan utsläppen ytterkigare minskas med fiberfilter. Vidare finns det minskningspotential också i mindre indsutripannor, där man normalt skulle använda endast multicykloner. När det gäller industriprocesser bedömdes utsläppsminskningarna vara möjliga i enstaka anläggninar. Den största osäkerheten gäller förbränning i små partier i hushållen och i industriprocesser. Uppskattningarna i denna rapport gäller utsläppsminskningarnas kostnadseffektivitet per minskad $PM_{2.5}$ massa. Den erhållna hälsonyttan beror dock på många faktorer, bl.a. på utsläppshöjd och utsläppskällans läge i förhållande till var befolkningen finns. Dessa faktorer avviker betydligt mellan olika utsläppssektorer. Resultaten av denna undersökning används som en del i projektet KOPRA, som finansieras av Tekes och miljöministeriet, där uppgifter om utsläppsminskningar och -kostnader, spridning av partiklar och orsakade hälsoeffekter kombineras i en enhetlig modelleringsram.			
Nyckelord	mikropartiklar, utsläpp, minskning, miljöteknologi, kostnader, modellering, scenarier			
Finansiär/ uppdragsgivare				
	ISBN 952-11-2413-X (hft.)	ISBN 952-11-2414-8 (PDF)	ISSN 1238-7312 (print)	ISSN 1796-1637 (online)
	Sidantal 33	*Språk* Engelska	*Offentlighet* Offentlig	*Pris (inneh. moms 8 %)* 8,50 €
Beställningar/ distribution	Edita Publishing Ab, PB 800, FIN-00043 Edita, Finland, växel 020 450 00 Postförsäljningen: Telefon +358 20 450 05, telefax +358 20 450 2380 Internet: www.edita.fi/netmarket			
Förläggare	Finlands miljöcentral, PB 140, 00251 Helsingfors, Finland			
Tryckeri/tryckningsort och -år	Edita Prima Ab, Helsingfors 2006			

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SYKE

Edita Publishing Ltd
P.O. Box 800, 00043 EDITA, Finland
Phone +358 20 450 00
Mail orders: Phone +358 20 450 05
Edita bookshop in Helsinki:
Annankatu 44, phone +358 20 450 2566

ISBN 952-11-2413-X (nid.)

ISBN 952-11-2414-8 (PDF)

ISSN 1238-7312 (pain.)

ISSN 1796-1637 (verkkoj.)

FINE PARTICLE EMISSIONS, EMISSION REDUCTION POTENTIAL AND REDUCTION COSTS IN FINLAND IN 2020

THE FINNISH ENVIRONMENT 46 | 2006