THE POTENTIAL AND COSTS OF THE CONTROL OF PARTICULATE MATTER IN EUROPE

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Abstract. Primary particulate matter is emitted directly into the atmosphere from various anthropogenic and natural sources such as power plants (combustion of fossil fuels) or forest fires. Secondary particles are formed by transformation of SO_2, NO_x, NH_3, and VOC in the atmosphere. They both contribute to ambient particulate matter concentrations, which may have adverse effects on human health. Health hazards are caused by small particulate size, high number of especially fine (< 2.5 µm) and ultra-fine (< 0.1 µm) particles and/or their chemical composition. As part of an integrated assessment model developed at IIASA, a module on primary particulate matter (PM) emissions has been added to the existing SO_2, NO_x, NH_3 and VOC sections. The module considers so far primary emissions of total suspended particles (TSP), PM_{10} and $PM_{2.5}$ from aggregated stationary and mobile sources. A primary PM emission database has been established. Country specific emission factors for stationary sources have been calculated within the module using the ash content of solid fuels.

Key words: primary particulate matter, stationary sources, mobile sources, emission factors, abatement measures.

1 Introduction

There is growing concern relating to the health effects of fine particles. Recent studies have demonstrated consistent associations between concentrations of fine particulate matter (PM) and adverse effects on human health (respiratory symptoms, morbidity and mortality) at concentrations commonly encountered in Europe and North America. Airborne suspended particulate matter can be either primary of secondary in nature. Primary particles are emitted directly into the atmosphere either by natural or anthropogenic processes whereas secondary particles are formed in the atmosphere from oxidation and subsequent reactions of sulfur dioxide, nitrogen oxides, ammonia and volatile organic compounds.

Strategies for controlling particle concentrations in the ambient air have to account for these different origins of particles and address the control potentials of the various sources in a systematic way. However, striking a balance of control measures to be taken for different pollutants in different economic sectors in different countries is a demanding task, and a large body of information must be taken into account.

Integrated assessment models were used in the past to identify least-cost strategies to control multiple precursor emissions leading to acidification, eutrophication and ground-level ozone in Europe (Amann *et al.*, 1999). This paper presents a first attempt to extend one of the existing integrated assessment models, i.e., the Regional Air Pollution Information and Simulation (RAINS) model developed at the International Institute for Applied Systems Analysis (IIASA), to incorporate aspects relevant for the control of fine particulate matter.

2 The Concept for an Integrated Assessment Model for Fine Particulate Matter

During the last years the RAINS model was used in a practical policy context to address cost-effective emission control strategies in a multi-pollutant/multi-effect framework. For this purpose, the RAINS model includes now the control of SO_2, NO_x, VOC and NH_3 emissions as precursors for acidification, eutrophication and ground-level ozone. Air pollution by particles can be regarded as an extension of the 'multi-pollutant/multi-effect' concept (Table 1). The search for cost-effective solutions to control ambient levels of fine particles should therefore balance emission controls over the sources of primary emissions as well as over the precursors of secondary aerosols.

TABLE 1:
Air quality management as a multi-pollutant, multi-effect problem

	SO_2	NO_x	NH_3	VOC	Primary PM emissions
Acidification	√	√	√		
Eutrophication		√	√		
Ground-level ozone		√		√	
Health damage due to fine particles	√	√	√	√	√
	via secondary aerosols				

As a further sophistication, one could consider a policy objective for fine particles together with targets for acidification, eutrophication and ground-level ozone, and thereby search for least-cost solutions to simultaneously accommodate for all four environmental fields.

The conceptual extension of the present structure of the RAINS model is illustrated in Figure 1, where the additional elements required for the analysis of fine particulate matter are highlighted.

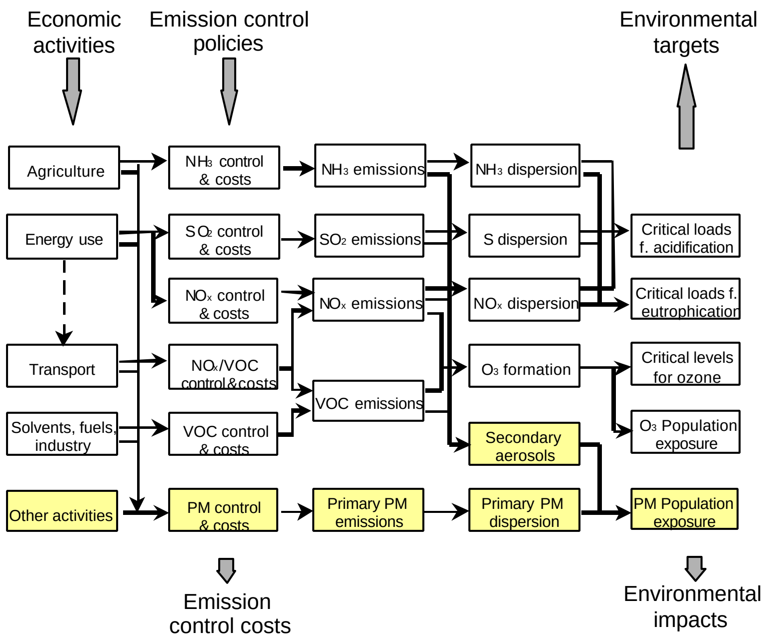

Figure 1: Conceptual extension of the present structure of the RAINS model. The additional elements required for the analysis of fine particulate matter are highlighted.

2 An Inventory of Primary PM Emissions in Europe

To include PM assessment into the RAINS integrated assessment model, an inventory of primary PM emissions in Europe was developed, covering all relevant source categories in Europe and estimating emission rates based on statistical information about activity levels in the various European countries. The approach takes into account country- and source-specific emission factors as well as information on the degree of control applied in a certain year and source category. As far as possible, the inventory relies on the databases already used within the RAINS model to calculate SO_2, NO_x, NH_3 and VOC emissions. This ensures internal consistency with the estimates made for these other pollutants. Additional statistical information has been collected to describe emissions from non-combustion related sources. The analysis covers the 43 countries in Europe and includes 1990 and 1995 as historical years.

In a first step, the inventory calculates based on the statistical data emissions of **total suspended matter** (TSP) using source- and country-specific emission factors. For solid fuels emission factors have been computed by applying a mass balance approach, using country-specific information on ash content, heat values and the fraction of ash retained in the boiler. For emissions from liquid fuels, industrial processes, agricultural sources and material handling emission factors from the literature were used (Berdowski *et al.,* 1996; Visschedijk *et al.*, 1997; Airborne Particle Expert Group, 1999; CBS, 1998).

In a second step, **emissions of fine particulates** (for three size fractions: $PM_{2.5}$, 'coarse', i.e., PM_{10}-$PM_{2.5}$, and >PM10) are calculated from the TSP estimates by using typical size profiles available in the literature (e.g., Ahuja *et al.,* 1989; Houck *et al.*, 1990).

The inventory first determines the hypothetical amount of 'unabated' emissions, i.e., ignoring any emission controls in place. Actual emissions for 1990 and 1995 are then estimated based on information on the type and the current application of measures to control the various emission sources in each country. Such a quantification of the effects of emission control technologies is an essential basis for calculating emission control costs.

3 Options to Control Primary PM Emissions

The large number of technologies available for controlling TSP and PM emissions was grouped into a limited set of emission control options with characteristic technical and economic efficiencies. For stationary combustion and industrial sources, the analysis distinguishes cyclones, fabric filters and electrostatic precipitators (ESP) with two, three and four fields, respectively. For light- and heavy-duty diesel vehicles, four packages (combination of fuel- and engine-technologies measures) are considered (EURO-I to EURO-IV). Emissions from livestock farming (animal houses) can be controlled through filters. At the moment, no control possibilities are considered for the large variety of diffuse sources (material handling, surface erosion, etc.).

For estimating actual PM emissions for a given year it is essential to capture the type and the extent of emission controls that were in place in a given country. For the initial assessment of the 1990 situation it has been assumed that all power plants in Western Europe were equipped with ESP with three or four fields with an average removal efficiency of 97.5 percent for PM_{10} and 96.5 percent for $PM_{2.5}$. For industrial sources less efficient emission controls were applied (two-field ESP with an average efficiency of 95.0 percent for PM_{10} and 94.0 percent for $PM_{2.5}$). There is evidence that the emission controls prevailing in central and eastern European were less efficient. Thus, for these countries two-field ESP controls have been assumed for electricity generation and the least efficient control option (cyclones) for parts of the industry. Emissions from small domestic sources were essentially uncontrolled. For mobile sources, the EURO-I/II standards regulated PM emissions from diesel vehicles in Western Europe, while no specifications were in force for gasoline engines and traffic-related non-exhaust emissions (road abrasion, tyre wear, etc.).

4 Primary PM Emissions in Europe in 1990 and 1995

Using the databases on economic activities available in the RAINS model, the additionally collected information, the emission factors determined as described above and the information on emission controls in the various European countries, TSP and PM emissions for Europe have been estimated for the years 1990 and 1995. The initial results, which do not include emissions from natural sources and exclude re-suspension, suggest that for all of Europe about two thirds of PM_{10} emissions originate from stationary fuel combustion, 25 percent from industrial processes and about eight percent from traffic (Tab. 2). A similar picture emerges for $PM_{2.5}$, although with a somewhat higher share of traffic-related emissions.

TABLE 2
Estimate of European primary PM_{10} and PM2.5 emissions in 1990, in kilotons

	EU-15			Non-EU countries		
	TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
Power plants	649	501	240	3209	2193	770
Industry						
- Combustion	511	330	131	660	423	171
- Production processes	761	485	314	2707	1596	1067
Domestic	1431	1055	744	3784	2301	1091
Exhaust emissions:						
- Heavy duty trucks	119	114	103	111	108	96
- Light duty vehicles	279	261	227	59	54	45
- Off-road	52	50	46	58	49	40
- Shipping	15	15	14	4	4	4
Road non-exhaust .	286	57	20	134	26	8
Material handling	162	45	2	37	24	0
Agriculture	63	30	11	70	34	13
SUM	4328	2943	1852	10833	6812	3304

5 Projections of Future PM Emissions

A scenario was run to project PM_{10} and $PM_{2.5}$ emissions to the year 2010. The estimates are based on the national economic , energy and transport scenarios used by the RAINS model for the recent calculations for the UN ECE Protocol negotiations and for the analyses on emission ceilings conducted for the European Commission (Amann *et al.*, 1999). For the projection it has been assumed that in Western Europe the emission controls for power plants, industrial boilers and for process emissions that were in force in 1990 will not change until 2010. For Eastern European countries emission controls will gradually achieve the typical 'western' efficiencies. Emissions from domestic sources will remain uncontrolled. The EU decision about the EURO-III/IV standards will affect exhaust emissions from diesel vehicles, but no changes are foreseen for emission rates from gasoline exhaust and from traffic-related non-exhaust sources.

TABLE 3
European PM10 and PM2.5 emissions projected for 2010. Percentage changes refer to 1990.

	EU-15			Non-EU countries		
	TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
Power plants	227	212	155	1239	964	437
Industry						
- Combustion	22	21	17	92	73	43
- Production processes	300	202	144	747	502	337
Domestic	644	605	573	2343	1539	884
Exhaust emissions:						
- Heavy duty trucks	24	23	21	97	93	84
- Light duty vehicles	81	79	69	30	29	25
- Off-road	37	36	33	31	29	27
- Shipping	16	16	16	7	7	6
Road non-exhaust .	440	88	31	153	30	10
Material handling	132	55	12	100	55	12
SUM	1922	1337	1071	4838	3323	1867

According to the projection, total European TSP emissions will decline by 55 percent during the period 1990 to 2010, PM_{10} emissions by 52 percent and $PM_{2.5}$ emissions by 43 percent (Tab. 3). While stringent legislation for diesel vehicles adopted in the European Union will cut exhaust PM emissions from traffic, non-exhaust emissions, for which no control is assumed, would grow proportionally with total mileage by 56 percent.

Conclusions

The preliminary analysis suggests that stationary combustion processes contributed the major share to anthropogenic emissions of fine particulate matter in Europe. It is estimated that the continued economic restructuring process in central and eastern Europe, the ongoing decline in the use of solid fuels in western Europe and the introduction of stringent emission controls for vehicles in the EU will lead to a decline in PM emissions.

The approach selected for the construction of the emission inventory will enable a systematic assessment of the future potential for controlling PM emissions in the various economic sectors in the European countries and will allow estimating emission control costs in a comparable manner. This information will be crucial for the design of cost-effective PM emission control strategies, that will have to balance measures between the sources of primary particle emissions and the precursors leading to secondary aerosols.

An on-line version of the PM module of the RAINS model and all its databases is accessible on the Internet at http://www.iiasa.ac.at/~rains.

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