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Interim Report **IR-02-076**

Modelling Particulate Emissions in Europe

A Framework to Estimate Reduction Potential and Control Costs

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Contents

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Abstract

This paper presents the extension of the Regional Air Pollution Information and Simulation (RAINS) model that addresses present and future emissions of fine particulates in Europe, the potential for controlling these emissions and the costs of such emission reductions. Together with the existing modules dealing with the emissions of the precursor emissions of secondary aerosols such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC), this extension enables the comparison of the potentials and costs for controlling primary emissions of fine particles with those of secondary aerosols and to find cost-minimal approaches for reducing ambient levels of particulate matter.

The emissions of particulate matter (PM) in the RAINS model are calculated for three different size classes: the fine fraction ($PM_{2.5}$), the coarse fraction (PM_{10} - $PM_{2..5}$) and large particles (PM_>10 µm). Summed up, these three fractions represent total suspended particles (TSP).

Fine particles are emitted from a large number of sources with large differences in their technical and economic properties. The methodology distinguishes 392 source categories for stationary energy combustion, industrial processes, mobile sources and agriculture. For each of these sectors, the study explores the applicable options for reducing PM emissions, their efficiency and their costs.

Emissions characteristics of the individual sectors are strongly determined by country-specific conditions. The methodology estimates emission control costs of standard technologies under the specific conditions characteristic for the various European countries. Based on the assumption of the general availability of control technologies with equal technical properties and costs, a number of country-specific circumstances (level of technological advancement, installation size distribution, labor costs, etc.) are used to estimate the costs for the actual operation of pollution control equipment.

For the individual source sectors, emissions are estimated based on statistical information on economic activity and emission factors that reflect hypothetical emissions if no control measures were applied. These emission factors were taken from the literature and were, to the maximum possible extent, adapted to the country-specific conditions. Actual emissions are calculated taking into account the application of emission control measures in a given sector, for which also costs are estimated.

The methodology was implemented for all European countries, covering the period from 1990 to 2010. At an aggregated level, estimates for past years (1990, 1995) correspond well with other national and international inventories. However, discrepancies are found for some detailed results for individual sectors and activities, and more work will be necessary to clarify them.

This preliminary implementation suggests for Europe a 50 percent decline of primary emissions of fine particles between 1990 and 1995, mainly due to the economic restructuring in central and eastern European countries. The recently tightened regulations on large combustion plants and mobile sources will further reduce PM emissions, so that for 2010 European PM emissions

are expected to be 60 percent below the level of 1990. However, less improvement is expected for the health-relevant fraction of fine particles ($PM_{2.5}$).

It needs to be emphasized that these preliminary estimates are still associated with considerable uncertainties, and more work, involving national experts, will be necessary to obtain a verified and generally accepted European data base to estimate the potential for further reductions of fine particles in Europe.

The present implementation (version 2.00) of the RAINS PM module on the Internet (http://www.iiasa.ac.at/rains/Rains-online.html) provides free access to the input data and results to facilitate interaction with national experts.

Modelling Particulate Emissions in Europe
A Framework to Estimate Reduction Potential and Control Costs

1 Introduction

There is growing concern related to the health effects of fine particles. Recent studies have demonstrated a consistent association between the concentrations of fine particulate matter (PM) in the air and adverse effects on human health (respiratory symptoms, morbidity and mortality) for concentrations commonly encountered in Europe and North America.

Airborne suspended particulate matter can be either primary or secondary in nature. Primary particles (PM) are emitted directly into the atmosphere by natural and/or anthropogenic processes whereas secondary particles are predominantly man-made in origin and are formed in the atmosphere from the oxidation and subsequent reactions of sulfur dioxide, nitrogen oxides, ammonia and volatile organic compounds.

Strategies for controlling particle concentrations in ambient air have to take into account their different origins and address the control potentials for the various sources in a targeted way. However, to strike a balance among control measures for various pollutants in different economic sectors in several countries is a demanding task, and a large body of information needs to be considered.

Integrated assessment models have been used in the past to identify least-cost strategies that can control multiple precursor emissions leading to acidification, eutrophication and ground-level ozone (Amann and Lutz, 2000). Johansson *et al*. (2000) have presented an initial attempt to extend the existing framework of the RAINS [**R**egional **A**ir Pollution **In**formation and **S**imulation, developed at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria] model to address control strategies for fine particulate matter.

The objective of this paper is to present a methodology for estimating primary PM emissions in Europe and the costs involved in reducing primary PM emissions from the various sources in European countries. The remainder of this introductory section reviews the context in which the emission and cost estimates should serve. Section 2 introduces the methodology for estimating emissions and explores the appropriate level of aggregation for a Europe-wide analysis. Section 3 reviews the available literature sources for the individual source categories and outlines how emission factors were derived for the RAINS model. Cost calculations are the subject of Section 4. Provisional results from the analysis are presented in Section 5, and conclusions are drawn in Section 6. Annex I provides a glossary of frequently used terms.

1.1 An Integrated Assessment Model for Fine Particulate Matter

Over the last few years, the RAINS model has been used to address cost-effective emission control strategies in a multi-pollutant/multi-effect framework. For this purpose, the RAINS model now includes the control of SO_2, NO_x, VOC and NH_3 emissions as precursors for acidification, eutrophication and ground-level ozone.

For fine particulate matter (PM) there is evidence that several emission sources contribute via various pathways to the concentrations in ambient air. While a certain fraction of fine particles found in the ambient air originates directly from the emissions of those substances (the “primary particles”), a second fraction is formed through secondary processes in the atmosphere from precursor emissions, involving SO_2, NO_x, VOC and NH_3.

Consequently, the search for cost-effective solutions to control the ambient levels of fine particles should balance emission controls over the sources of primary emissions as well as over the precursors of secondary aerosols. Thus, the control problem can be seen as an extension of the “multi-pollutant/multi-effect” concept applied for acidification, eutrophication and ground-level ozone (Table 1.1).

Table 1.1: 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	√	√	√

Further, a more sophisticated assessment framework could be used for more than just balancing measures for the five pollutants to control fine particles. Such a framework could consider the possible policy objectives for fine particles together with targets for acidification, eutrophication and ground-level ozone, and thereby search for least-cost solutions to address all four environmental problems simultaneously.

The present implementation of the RAINS model contains modules to describe emissions and emission control costs for the first four pollutants. The atmospheric dispersion models employed by RAINS also include the processes leading to the formation of secondary aerosols. Additional modules are necessary to capture primary emissions, control potential and control costs for fine particles, the dispersion of fine particles in the atmosphere and the formation of secondary aerosols from the “conventional" precursor emissions. A module has been developed to assess the health impacts resulting from a certain emission control strategy.

The conceptual extension of the present structure of the RAINS model is illustrated in Figure 1.1, where the additional elements required for the analysis of fine particulate matter are highlighted (Johansson *et al.*, 2000).

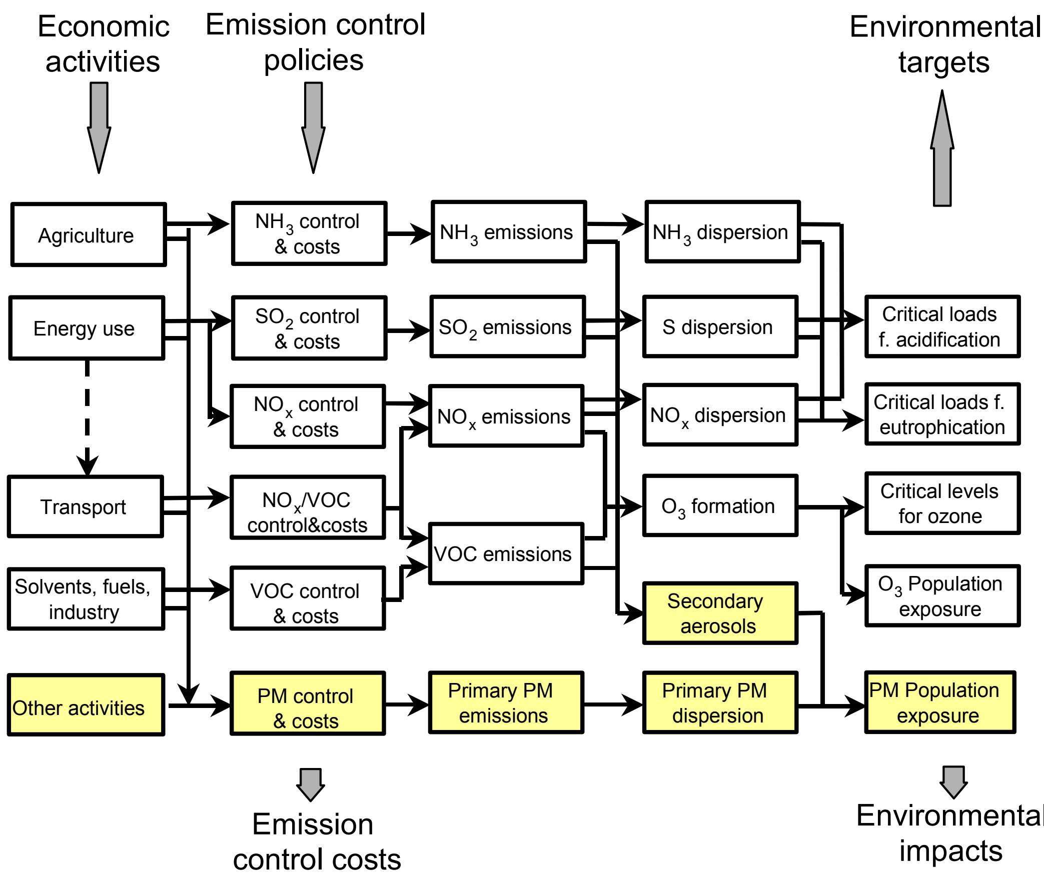

Figure 1.1: Flowchart of the extended RAINS model to address particulate matter.

1.2 The Objectives of an Emission Control Cost Module within the Framework of an Integrated Assessment Model

A central objective of integrated assessment models is to assist in the cost-effective allocation of emission reduction measures across various pollutants, several countries and different economic sectors. Obviously, this task requires consistent information about the costs of emission control at the individual sources, and it is the central objective of this cost module to provide such information.

The optimal allocation of emission control measures between countries is crucially influenced by differences in emission control costs for the individual emission sources. It is therefore of utmost importance to identify systematically the factors leading to differences in emission control costs among countries, economic sectors and pollutants. Such differences are usually caused, *inter alia*, by variations in the composition of the various emission sources, the state of technological development and the extent to which emission control measures are already applied.

In order to capture these differences across Europe in a systematic way, a methodology has been developed to estimate the emissions and emission control costs of standard technologies under the specific conditions characteristic for the various European countries. Given the basic assumption of the general availability of control technologies with equal technical properties and costs, a number of country-specific circumstances (level of technological advancement, installation size distribution, labor costs, etc.) are used to estimate the costs for the actual operation of pollution control equipment.

1.3 Summary of Changes Introduced since the Last Release of the RAINS PM Module

This report documents changes that have been introduced in the RAINS PM module since summer 2001 and, consequently, it is an update and extension of the previous report by Lükewille *et al.*, 2001. This section provides a brief summary of the changes.

New sectors

The RAINS model structure has been modified and a number of new emission categories have been introduced, including several industrial processes, mining, storage and handling of bulk materials, open burning of agricultural and residential waste, construction, and other miscellaneous sources (cigarette smoking, barbeques, etc.). A full list of sectors distinguished in RAINS can be found in Table 2.2, Table 2.4, Table 2.5, and Table 2.6.

Revisions

Several emission categories have been revised, i.e., updates of emission factors, activity data and removal efficiencies, and structure modifications within relevant sectors were carried out.

For stationary combustion sources, significant changes in the assumptions about the size fraction distribution of particulate emissions were introduced, as well as an update of size-fraction specific removal efficiencies. Additionally, emission factors for biomass combustion are no longer estimated on the basis of ash content but are derived instead from the literature. A major structural change was introduced for the residential sector for solid fuel combustion, where, instead of one category, RAINS now distinguishes between fireplaces, stoves, single-family house boilers, and medium size boilers. For the latter two, a distinction between manual and automatic fuel loading installations is made.

Within the industrial processes category, the iron and steel sector has been extended to distinguish between sinter plants, pig iron, open hearth, basic oxygen, and electric arc furnace iron and steel foundries. Additionally, fugitive emissions from the iron and steel industry are modeled separately.

The transport sector structure has been extended: motorbikes are treated separately and there are now separate off-road categories for construction and industry, agriculture, rail, inland navigation, shipping, and other. In addition, emission factors for vehicles with spark ignition engines were updated.

Based on new information available for the agricultural sector, the structure of the sector was modified to include "arable farming" in the list of sub-sectors. New emission factors for livestock housing were introduced and the set of control techniques was updated.

New fuels

Recognizing the fact that alternative fuels might play an important role in the near future, a number of new fuel categories were distinguished including methanol, ethanol, and hydrogen. A full list of fuels can be found in Table 2.3.

New control options

Modifications and extensions of the model sectoral structure required the introduction of new control options. In some cases these are, technically speaking, the same options as in the previous model version, e.g., electrostatic precipitator, fabric filters, etc., but applicable specifically to industrial processes and, therefore, their removal efficiency and cost characteristics might be different. For several sectors where fugitive emissions play an important role, options to control these losses were added. A few new abatement options were added for the transport sector, e.g., PSA particulate filter. The list of options was also extended for agriculture. A complete list of abatement techniques, together with assumed reduction efficiencies, is provided in Table 2.7, Table 2.8, Table 2.9, Table 2.13, Table 2.14, Table 2.15.

Cost data

The cost data were revised and further developed. To facilitate transparency of the method applied, some examples of how costs were calculated are provided in Chapter 4.

New model features

The model provides several new features that allow for easier viewing of input data, the assumptions made for several parameters, and output. Specifically, the user can display emission factors in either standard RAINS units, e.g., g/MJ for energy use sectors, or as flue gas concentrations for stationary combustion sources, i.e., mg/m^3, and g/km or g/kWh for transport categories. This makes it easier to compare the model emission factors (controlled and uncontrolled) with measurement data and legislation.

The Internet version of the RAINS PM module has been updated and is available from the RAINS web site: http://www.iiasa.ac.at/rains/Rains-online.html.

2 A Module to Estimate Emissions of Fine Particulate Matter

2.1 Methodology

The emissions of particulate matter (PM) in the RAINS model are calculated for three different size classes:

- fine fraction ($PM_{2.5}$),
- coarse fraction (PM_{10} - $PM_{2.5}$) and
- large particles (PM_>10 µm).

Thereby, PM_{10} is calculated as the sum of fine and coarse fractions and total suspended particles (TSP) as the sum of fine, coarse and PM_>10 fractions.

The methodology includes the following three steps:

- In a <u>first step</u>, country-, sector- and fuel-specific "raw gas" emission factors for total suspended particles (TSP) are derived:
  - For solid fuels (excluding biomass and use of solid fuels in small residential installations) the mass balance approach is used where ash content (*ac*) and heat value (*hv*) of fuels and ash retention in boilers (*ar*) are considered:

    $$ef_{TSP} = ac/hv * (1 - ar)$$

  - For liquid fuels, biomass, solid fuels used in small residential installations, industrial processes, mining, storage and handling of bulk materials, waste incineration, agriculture[1], and transport, TSP emission factors are taken from the literature.
- In a <u>second step</u>, "raw gas" emission factors for each of the size fractions are estimated. This is done based on size fraction profiles reported in the literature for a variety of installations. They are typically given for PM_{10} and $PM_{2.5}$ and are fuel- and installation (sector)-specific. The typical profiles are applied to the country-, fuel- and sector-specific "raw gas" TSP emission rates (see first step) to derive the size-specific emission factors used in RAINS.
- In a <u>third step</u>, actual PM emissions are calculated for the three size fractions. For a given country (*i*), PM emissions of size fraction (*y*) are calculated by applying a general formula across every fuel (activity) and sector, taking into account the application rates of control technologies and size fraction specific emission removal efficiencies,

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[1] For livestock, literature emission factors refer typically to housing period. Therefore, information on the length of this period (available from the RAINS NH_3 module) was considered to derive annual animal- and country-specific values.

$$E_{i,y} = \sum_{j,k,m} E_{i,j,k,m,y} = \sum_{j,k,m} A_{i,j,k} ef_{i,j,k,y} (1 - eff_{m,y}) X_{i,j,k,m} \tag{1}$$

where:

i,j,k,m	Country, sector, fuel, abatement technology;
y	Size fraction, i.e. fine, coarse, PM_>10;
$E_{i,y}$	Emissions of PM in country *i* for size fraction *y*;
A	Activity in a given sector, e.g. coal consumption in power plants;
ef	"Raw gas" emission factor;
$eff_{m,y}$	Reduction efficiency of the abatement option *m* for size class *y*, and;
X	Actual implementation rate of the considered abatement, e.g., percent of total coal used in power plants that are equipped with electrostatic precipitators.

If no emission controls are applied, the abatement efficiency equals zero ($eff_{m,y} = 0$) and the application rate is one ($X = 1$). In that case, the emission calculation is reduced to simple multiplication of activity rate by the "raw gas" emission factor.

2.2 Aggregation of Emission Sources

Emissions of PM are released from a large variety of sources with significant technical and economic differences. Conventional emission inventory systems, such as the CORINAIR inventory of the European Environmental Agency, distinguish more than 300 different processes causing various types of emissions.

In the ideal case, the assessment of the potential and costs for reducing emissions should be carried out at the very detailed process level. In reality, however, the necessity to assess abatement costs for all countries in Europe, as well as focus on emission levels in 10 to 20 years from now, restricts the level of detail which can be maintained. While technical details can be best reflected for individual (reference) processes, the accuracy of estimates on an aggregated national level for future years will be seriously hampered by a general lack of reliable projections of many of these process-related parameters (such as future activity rates, autonomous technological progress, etc.). For an integrated assessment model focusing on the pan-European scale it is therefore imperative to aim at a reasonable balance between the level of technical detail and the availability of meaningful data describing future development, and to restrict the system to a manageable number of source categories and abatement options.

2.2.1 Criteria for Aggregations

For the RAINS PM module, an attempt was made to aggregate the emission producing processes into a reasonable number of groups with similar technical and economic properties. Considering the intended purposes of integrated assessment, the major criteria for aggregation were:

- The importance of the emission source. It was decided to target source categories with a contribution of at least 0.5 percent to the total anthropogenic emissions in a particular country.
- The possibility of defining uniform activity rates and emission factors.
- The possibility of constructing plausible forecasts of future activity levels. Since the emphasis of the cost estimates in the RAINS model is on future years, it is crucial that reasonable projections of the activity rates can be constructed or derived.
- The availability and applicability of "similar" control technologies.
- The availability of relevant data. Successful implementation of the module will only be possible if the required data are available.

It is important to define carefully the appropriate activity units. They must be detailed enough to provide meaningful surrogate indicators for the actual operation of a variety of different technical processes, and aggregated enough to allow a meaningful projection of their future development with a reasonable set of general assumptions. As explained later in the text, some of the RAINS sectors contain a number of PM emitting processes. It is often the case that for such aggregated sectors some emission control options are not necessarily applicable to all processes (emission sources) that are represented by the activity.

Table 2.1 presents major sectors included in the RAINS PM module and their contribution to total European PM emissions that are estimated in this study for 1995. The RAINS source structure shown distinguishes ten emission categories for mobile sources and three for stationary combustion sources that are split by relevant fuels (see Table 2.2), and 17 other sectors. Some categories are further disaggregated to distinguish, for example, between existing and new installations in power plants, or between tire and brake wear for non-exhaust emissions from transport (for a full list of RAINS sectors see Table 2.3, Table 2.4, Table 2.5).

The sectoral structure of the RAINS model is not directly compatible with that of CORINAIR or the UNECE reporting standard (NFR – **N**omenclature **F**or **R**eporting) (UNECE, 2002). Tables presented in this section provide a broad reference to the CORINAIR SNAP'94 and UNECE-NFR categories. In several cases the relation can be established only for a primary sector, i.e., the sum of all RAINS categories for power and district heating plants can only be compared with the sum of several SNAP entries. RAINS contains a feature to aggregate/display emissions into the CORINAIR SNAP level 1 as well as NFR level 1 and 2.

The following sections define the source categories distinguished in the RAINS model in more detail and provide the corresponding SNAP source sectors of the CORINAIR inventory as well as the UNECE-NFR categories.

2.2.2 Stationary Combustion Sources

Stationary combustion is by far the most important source of TSP emissions, followed by industrial processes; nearly 70 percent of European TSP emissions originated from these sources in 1995. For $PM_{2.5}$, industrial processes and stationary combustion sources represent a similar share of emissions and together they represent nearly 65 percent of the total (Table 2.1). An attempt has been made to design an emission source structure that represents the most important sources and factors influencing emissions of PM. The following tables present the RAINS model sectors used in the PM calculation; for the most part they are compatible with the structure of the other RAINS modules although new elements are introduced. More details are given in Section 3.

Table 2.1: Major sectors included in the RAINS PM module and their contribution to total European PM emissions in 1995 as estimated in this study.

RAINS sector		Emissions [kt]			Share of total European emissions in 1995 [%]		
Primary	Secondary	TSP	PM_{10}	$PM_{2.5}$	TSP	PM_{10}	$PM_{2.5}$
Stationary combustion	Power plants	1410	785	378	13.4	15.5	11.9
	Industrial combustion	419	182	87	4.0	3.6	2.8
	Domestic combustion	3057	993	544	29.1	19.6	17.2
Process emissions	Pig iron	287	42	28	2.7	0.8	0.9
	Sinter and pellets	277	63	34	2.6	1.2	1.1
	Basic oxygen furnaces	325	291	244	3.1	5.7	7.7
	Electric arc furnaces	103	86	73	1.0	1.7	2.3
	Other Iron and Steel	430	368	279	4.1	7.3	8.8
	Non-ferrous metals	66	57	48	0.6	1.1	1.5
	Cement and lime	283	200	144	2.7	3.9	4.5
	Other processes	510	261	154	4.9	5.1	4.9
Mining		113	57	6	1.1	1.1	0.2
Storage and handling	Industrial products	399	181	18	3.8	3.6	0.6
	Agricultural products	65	18	3	0.6	0.3	0.1
Road transport	Heavy duty vehicles	185	182	179	1.8	3.6	5.6
	Light duty vehicles	234	231	220	2.2	4.5	6.9
	Motorcycles, mopeds	13	12	11	0.1	0.2	0.4
	Non-exhaust	462	93	30	4.4	1.8	1.0
Off-road transport	Construction and Industry	32	31	29	0.3	0.6	0.9
	Agriculture	135	128	121	1.3	2.5	3.8
	Rail	34	32	30	0.3	0.6	1.0
	Inland waterways	29	27	26	0.3	0.5	0.8
	Other land-based	23	20	18	0.2	0.4	0.6
	Maritime activities	141	134	127	1.3	2.6	4.0
Open burning of waste		265	265	200	181	2.5	3.9
Agriculture	Livestock	492	221	45	4.7	4.4	1.4
	Other	511	28	0	4.9	0.6	0.0
Other sources	Construction dust	83	41	4	0.8	0.8	0.1
	Residential [(1)]	87	87	87	0.8	1.7	2.8
	Other	26	21	17	0.2	0.4	0.5
TOTAL		**10498**	**5072**	**3167**	**100.0**	**100.0**	**100.0**

[(1)] Food preparation, barbeques, cigarette smoking, and fireworks

Table 2.2: RAINS sectors related to stationary sources with energy combustion.

RAINS sector	RAINS code	NFR category	SNAP sector
Centralized power plants and district			
New power plants	PP_NEW	1A1a	0101, 0102, 020101, 020102, 020201, 020301
New power plants, grate combustion	PP_NEW1		
New power plants, fluidized bed combustion	PP_NEW2		
New power plants, pulverized fuel combustion	PP_NEW3		
Existing plants [(1)], wet bottom boilers	PP_EX_WB		
Existing plants [(1)], other types (of boilers)	PP_EX_OTH		
Other types, grate combustion	PP_EX_OTH1		
Other types, fluidized bed combustion	PP_EX_OTH2		
Other types, pulverized fuel combustion	PP_EX_OTH3		
Fuel conversion			
Energy consumed in fuel conversion process	CON_COMB	1A1c	0104
Fuel conversion, grate combustion	CON_COMB1		
Fuel conversion, fluidized bed combustion	CON_COMB2		
Fuel conversion, pulverized fuel combustion	CON_COMB3		
Residential, commercial, institutional, agricultural use			
Combustion of liquid fuels	DOM	1A4a	020103-06, 020202-03, 020302-05
Fireplaces	DOM_FPLACE	1A4b	
Stoves	DOM_STOVE		
Single house boilers (<50 kW) - manual	DOM_SHB_M		
Single house boilers (<50 kW) - automatic	DOM_SHB_A		
Medium boilers (<1 MW) - manual	DOM_MB_M	1A4a	
Medium boilers (<50 MW) - automatic	DOM_MB_A		
Fuel combustion in industrial boilers			
Combustion in boilers	IN_BO	1A2	010301-03, 010501-03, 0301
Combustion in boilers, grate combustion	IN_BO1		
Comb. in boilers, fluidized bed combustion	IN_BO2		
Comb. in boilers, pulverized fuel combustion	IN_BO3		
Other combustion	IN_OC		010304-06, 010504-06, 0302, 0303
Other combustion, grate combustion	IN_OC1		
Other combustion, fluidized bed combustion	IN_OC2		
Other combustion, pulverized fuel combustion	IN_OC3		

[(1)] Refers to all sources that came on line before or in 1990.

2.2.3 Stationary Non-combustion Sources

A number of industrial processes emit significant amounts of particulate matter that does not originate from fuel combustion (e.g., metallurgical processes, ore processing, refining, mining, waste incineration [open burning], agriculture, and storage and handling of bulk materials). Table 2.4 lists the categories distinguished in the RAINS model. A more detailed description is provided in Section 3.

Table 2.3: Fuel categories distinguished in the RAINS PM module.

Fuel type	RAINS code
Brown coal/lignite, grade 1	BC1
Brown coal/lignite, grade 2	BC2
Hard coal, grade 1	HC1
Hard coal, grade 2	HC2
Hard coal, grade 3	HC3
Derived coal (coke, briquettes)	DC
Heavy fuel oil	HF
Medium distillates (diesel, light fuel oil)	MD
Unleaded gasoline, kerosene, naphtha	GSL
Leaded gasoline	LFL
Liquefied petroleum gas	LPG
Methanol	MTH
Ethanol	ETH
Hydrogen	H2
Natural gas	GAS
Wood, biomass	OS1
High sulfur waste	OS2

Table 2.4: RAINS sectors for other stationary sources of PM emissions.

RAINS sector	RAINS code	NFR category	SNAP sector
Iron and steel industry			
Coke production	PR_COKE	1B1b	040201, 04
Pig iron production	PR_PIGI	2C1	040202,03
Pig iron production (fugitive)	PR_PIGI_F		
Pelletizing plants	PR_PELL	1A2a	030301, 040209
Sinter plants	PR_SINT		
Sinter plants (fugitive)	PR_SINT_F		
Open heart furnace	PR_HEARTH	2C1	040205
Basic oxygen furnace	PR_BAOX		040206
Electric arc furnace	PR_EARC		040207
Iron and steel foundries	PR_CAST	1A2a	030303, 040210
Iron and steel foundries (fugitive)	PR_CAST_F		
Non-ferrous metal industry			
Primary aluminum	PR_ALPRIM	2C3	040301
Secondary aluminum	PR_ALSEC	1A2b	030310
Other non-ferrous metals (lead, nickel, zinc, copper)	PR_OT_NFME		030304-09, 24; 040305, 09
Other industrial processes			
Coal briquettes production	PR_BRIQ	1A1c	0104
Cement production	PR_CEM	1A2f	030311, 040612
Lime production	PR_LIME		030312, 040614
Glass production	PR_GLASS		030314-15, 17; 040613
Petroleum refining	PR_REF	1B2a	030311, 040612
Carbon black production	PR_CBLACK	2B5	040409
Fertilizer production	PR_FERT		040404-08, 14

RAINS sector	RAINS code	NFR category	SNAP sector
Other production processes (glass fiber, PVC, gypsum, other)	PR_OTHER		040416, 040508, 040527
Small industrial plants, fugitive	PR_SMIND_F	2D	
Mining			
Brown coal mining	MINE_BC	1B1a	050101, 050102
Hard coal mining	MINE_HC		
Other (bauxite, copper, iron ore, etc.)	MINE_OTH	2A7	040616
Agriculture			
Livestock – poultry	AGR_POULT	4B9	100507-09
Livestock – pigs	AGR_PIG	4B8	100503-04
Livestock – dairy cattle	AGR_COWS	4B1	100501
Livestock – other cattle	AGR_BEEF		100502
Livestock – other animals	AGR_OTANI	4B3-7, 13	100505, 06
Ploughing, tilling, harvesting	AGR_ARABLE	4D	
Other	AGR_OTHER	7	
Waste			
Flaring in gas and oil industry	WASTE_FLR	1B2c	090206
Open burning of agricultural waste	WASTE_AGR	6C	0907, 1003
Open burning of residential waste	WASTE_RES		
Storage and handling of bulk materials			
Coal	STH_COAL	1B1a	050103
Iron ore	STH_FEORE	2A7	040616
N, P, K fertilizers	STH_NPK	2B5	040415
Other industrial products (cement, coke, etc.)	STH_OTH_IN	2A7	040617
Agricultural products (crops)	STH_AGR	2D	
Other sources			
Construction activities	CONSTRUCT	1A2f	
Meat frying, food preparation, BBQ	RES_BBQ	7	
Cigarette smoking	RES_CIGAR		
Fireworks	RES_FIREW		
Other	OTHER		

2.2.4 Mobile Sources

Table 2.5 and Table 2.6 list the categories distinguished in the RAINS model to estimate emissions and costs of controlling PM emissions from exhaust and non-exhaust mobile sources. This structure is broadly compatible with that of other RAINS modules with the exception of non-exhaust sources that are not relevant for emissions of the other pollutants (SO_2, NO_x, VOC, NH_3) considered in RAINS.

Table 2.5: Categories of PM exhaust emissions from mobile sources considered in RAINS.

RAINS sector	RAINS code	NFR category	SNAP sector
Road transport			
Heavy duty vehicles (trucks, buses and others)	TRA_RD_HD	1A3b	0703
Motorcycles, four-stroke	TRA_RD_M4		0704
Motorcycles and mopeds (also cars), two-stroke	TRA_RD_LD2		0704
Light duty cars and vans, four-stroke	TRA_RD_LD4		0701-02
Light duty cars, four-stroke, gasoline direct injection	TRA_RDXLD4		0701-02
Off-road transport			
Two-stroke engines	TRA_OT_LD2	1A4b	0801-02, 0806-10
Construction machinery	TRA_OT_CNS	1A2	
Agricultural machinery	TRA_OT_AGR	1A4c	
Rail	TRA_OT_RAI	1A3c	
Inland waterways	TRA_OT_INW	1A3d	
Air traffic (LTO)	TRA_OT_AIR	1A3a	
Other; four-stroke (military, households, etc.)	TRA_OT_LB	1A4c	
Maritime activities, ships			
Medium vessels	TRA_OTS_M	1A3d	0803, 080402-03
Large vessels	TRA_OTS_L		

Table 2.6: RAINS sectors related to non-exhaust PM emissions.

RAINS sector	RAINS code	NFR category	SNAP sector
Road transport, Tire wear			
Heavy duty vehicles (trucks, buses and others)	TRT_RD_HD	1A3b	0707
Motorcycles, four-stroke	TRT_RD_M4		
Motorcycles and mopeds (also cars), two-stroke	TRT_RD_LD2		
Light duty cars and vans, four-stroke	TRT_RD_LD4		
Light duty cars, four-stroke, gasoline direct injection	TRT_RDXLD4		
Road transport, brake wear			
Heavy duty vehicles (trucks, buses and others)	TRB_RD_HD	1A3b	0707
Motorcycles, four-stroke	TRB_RD_M4		
Motorcycles and mopeds (also cars), two-stroke	TRB_RD_LD2		
Light duty cars and vans, four-stroke	TRB_RD_LD4		
Light duty cars, four-stroke, gasoline direct injection	TRB_RDXLD4		
Road transport, abrasion of paved roads			
Heavy duty vehicles (trucks, buses and others)	TRD_RD_HD	1A3b	
Motorcycles, four-stroke	TRD_RD_M4		
Motorcycles and mopeds (also cars), two-stroke	TRD_RD_LD2		
Light duty cars and vans, four-stroke	TRD_RD_LD4		
Light duty cars, four-stroke, gasoline direct injection	TRD_RDXLD4		

2.3 Emission Factors

Emission factors are the key to assess PM emissions accurately. For the present study it has been decided to identify, as far as possible, the main factors that could lead, for a given source category, to justified differences in emission factors across countries. The aim has been to collect country-specific information to quantify such justifiable deviations from values reported in the general literature. When this was not possible or when a source category makes only a minor contribution to total emissions, emission factors from the literature were used.

Within the PM module, unabated emission factors of total suspended matter (TSP) are the basis for deriving emission factors for fractions of the total range of PM mass concentrations. Emission factors of fine PM for two size classes, PM_{10} (ø < 10 µm) and $PM_{2.5}$ (ø < 2.5 µm), are calculated from the TSP estimates by using typical (source-specific) size profiles available in the literature.

2.3.1 Emission Factors for Stationary Combustion Sources

Due to the large overall contribution of the stationary combustion of solid fuels to total PM emissions (varying between 50 and 65 percent for $PM_{2.5}$ and TSP), an attempt has been made to derive country-specific emission factors for power plants, industrial boilers, waste processing plants and domestic ovens. Emission factors have been computed by applying a mass balance approach. Country-specific information on the ash contents of different fuels (IEA, 1998), heat values (RAINS database), and the fraction of ash retained in the respective boiler type was used (e.g., Kakareka *et al.,* 1999; EPA, 1998a) (compare Equation 2). Emission factors for total suspended particulate matter (TSP) are estimated in a first step:

$$ef_{TSP} = ac/hv * (1 - ar)*10 \qquad (2)$$

where:

ef	unabated emission factor [g/MJ],
ac	ash content [%],
hv	lower heat value [GJ/t],
ar	fraction of ash retained in boiler .

In a second step, the emissions of fine particulate matter (for two size fractions: PM_{10} and $PM_{2.5}$) are calculated from the TSP estimates by using typical size profiles available in the literature (e.g., Ahuja *et al.,* 1989; Houck *et al.,* 1989; EPA, 1998a; AWMA, 2000; Kakareka *et al.*, 1999). The order of magnitude of the emission factors obtained with this method was checked against values reported in the literature, e.g., TA Luft, 1986; Soud, 1995, and summarized by Dreiseidler *et al.* (1999).

For PM emissions from the combustion of liquid fuels (gasoline, diesel, heavy fuel oil), natural gas, biomass, and solid fuels burned in small residential installations emission factors from the literature have been used (for details see relevant parts of Section 3).

2.3.2 Emission Factors for Mobile Sources

For on-road mobile sources, RAINS derives emission factors from the studies carried out in connection with the Auto Oil 1 and 2 Programmes (EC, 1999). For gasoline vehicles, additionally the following studies were used: Hildemann *et al.*, 1991; Norbeck *et al.*, 1998a; Durbin *et al.*, 1999; Kwon *et al*, 1999; CONCAWE, 1998 (see Section 3.8.1.3). Thus, the emission factors used in RAINS for the various vehicle categories are based on the full range of country-specific factors such as driving pattern, fleet composition, climatic conditions, etc. that was considered in the Auto Oil analyses. For the RAINS assessment, fuel-related emission factors for diesel vehicles were obtained by dividing the volume of PM emissions calculated in the Auto Oil project for the RAINS vehicle categories by the respective fuel consumption.

For off-road sources, a range of American and European studies were used, e.g., EPA, 1991; BUWAL, 2000a; Breadsley *et al.*, 1998; Norbeck *et al.*, 1998ab; Kean *et al.*, 2000; and specifically for shipping: Lloyd's Register, 1997 and Wright, 1997, 2000 (for details see Section 3.8.1.4).

Non-exhaust emission factors for road transport were extracted from various literature sources (see Section 3.8.2). Since such emission factors are usually reported in grams per kilometer (g/km), the fuel-efficiencies of the various vehicle categories have been used to convert them into the fuel-related emission factors. Time-dependent and country-specific fuel efficiencies are taken from the studies conducted for the Auto/Oil 2 Programme (EC, 1999). Although highly uncertain, the RAINS model treats emissions from tire lining wear, brake wear and abrasion of paved roads as separate sources (see Sections 3.8.2.1, 3.8.2.2, 3.8.2.3).

2.3.3 Emission Factors for Other Sources

The RAINS model includes a long list of non-combustion emission sources (Table 2.4). Here, only major categories and primary sources of emission factor data will be addressed. More detailed information can be found in respective sections of this document and listed literature.

Emission rates for the iron and steel industry and non-ferrous metal industry are based primarily on EPA, 1998a; Rentz e*t al.*, 1996; TA Luft, 1986; AWMA, 2000; UBA, 1998a; and a review by Passant *et al.* (2000). For agriculture, two major studies are used, i.e., Takai *et al.*, 1998 and ICC & SRI, 2000. Information on particulate emissions and emission rates for the remaining sectors, i.e., mining, storage and handling of bulk materials in industry and agriculture, open burning of waste, construction activities, and other miscellaneous sources, is scarce. The recently completed project CEPMEIP (Co-ordinated European Programme on Particulate Matter Emission Inventories, Projections and Guidance) (CEPMEIP, 2002) proved very helpful in compiling this information. Additionally, reports from EPA (1995, 1998a), Dreiseidler *et al.*(1999), Ecker and Winter (2000), Schindler and Ronner (2000), Staubenvoll and Schindler (1998) and Berdowski *et al.* (1997) were used.

2.4 Emission Control Options

2.4.1 Stationary Sources

In addition to the obvious "structural changes" that lead to a lower consumption of emission generating fuels, there are several end-of-pipe options for reducing particulate matter emissions from stationary sources, e.g., Darcovich *et al*., 1997; Soud, 1995; TA Luft, 1986; Rentz *et al.*, 1996). The following paragraphs briefly review the main options and their technical characteristics.

2.4.1.1 A Review of Available Control Options

Inertial Settlers and Cyclones

The general principle of cyclones is the inertial separation of particles from the gas stream. Particulate-laden gas is forced to change direction, and the inertia of the particles causes them to continue in the original direction. In Western Europe multi-cyclones are usually only used as pre-dedusters (pre-cleaners) for the collection of medium-sized and coarse particles. The net downward motion of particles will arise at sizes larger than 5 µm. Thus gravity settling will be efficient only on large particles (40 to 50 µm). The removal efficiency drops if the fines content of the particulate matter is significant and generally does not lead to a substantial reduction of $PM_{0.1}$ emissions.

Wet Scrubbers

In the most widely used Venturi scrubber, water is injected into the flue gas stream at the Venturi throat to form droplets. Fly ash particles impact with the droplets forming a wet by-product, which then generally requires disposal. The process can also have a high energy consumption due to the use of sorbent slurry pumps and fans.

The efficiency of wet scrubbing for particulate removal depends on the particle size distribution. The system efficiency is reduced as the particle size decreases.

Fabric Filters

Dust particles moving through fabric filters often form a porous cake on the surface of the fabric. This cake normally does the bulk of the filtration. Conventional reverse-gas-cleaned fabric filters (baghouses, RGB) are being quickly replaced by pulse-jet fabric filters (PJFF). Periodic short, powerful bursts of air are used to clean the fabric mounted in cylindrical bags.

Interception (fibrous or granular filter media) is effective on particles down to 2-3 µm. Effective processes to remove particles smaller than 0.2 µm are thermal precipitation (cold collection system) and diffusional deposition (fibrous or granular filter media and small liquid droplets).

Electrostatic Precipitators (ESP)

In electrostatic precipitators (ESP), particles are given an electric charge by forcing them through a region in which gaseous ions flow. Electrodes in the center of the flow channel maintain a high voltage, forcing particles to move out of the flowing gas stream onto collector plates. The particles are removed from the plates by knocking them loose or by washing with water. Developments in ESP technology aim especially at improving the collection of ultra-fine particles. ESP can tolerate temperatures as high as 400 ^{o}C.

The performance of fabric filters and some scrubbers can also be enhanced with electrostatic charging. Electrostatic force is the strongest process commonly used as PM removal technology that can act on fine particles smaller than 2-3 μm.

High Temperature, High Pressure (HTHP) Particulate Control

During the last decade there have been significant advances towards the commercialization of combined cycle systems, such as the integrated gasification combined cycle (IGCC) and pressurized fluidized bed combined cycle (PFBCC). Commercial- and demonstration-scale designs are currently used for power generation in the United States, Europe and Japan. An important component in combined cycle power systems is a high temperature, high pressure (HTHP) particulate control device.

Efficient hot gas particulate filtration is necessary to protect the downstream heat exchanger and gas turbine components from fouling and erosion to meet emission requirements. A range of technologies has been proposed for hot gas particulate filtration but few have been developed sufficiently to enable commercial exploitation in combined cycle power systems.

2.4.1.2 Control Options Implemented in the RAINS Model

In the interest of keeping a European-scale analysis manageable, the RAINS model considers a limited number of emission control options reflecting groups of technological solutions with similar emission control efficiencies and costs. For large boilers in industry and power stations, and industrial processes the following options are available:

- Cyclones;
- Wet scrubbers;
- Electrostatic precipitators (three stages, i.e., one field, two fields, and more than two fields);
- Wet electrostatic precipitators;
- Fabric filters;
- Regular maintenance of oil fired industrial boilers;
- Two stages (low and high efficiency) of fugitive emissions control measures.

These options are divided into three categories, i.e. power plants, industrial combustion, and industrial processes that can have different emission reduction and cost characteristics. The actual choice of options for a given sector is made on the basis of reviews of real-life applications (e.g., TA Luft, 1986; AWMA, 2000), information from industrial sources and environmental agencies, e.g., Umwelbundesamt (UBA, 1998a). The RAINS model considers size-fraction specific removal efficiencies for these control options (Table 2.7).

Table 2.7: Size-fraction specific removal efficiencies for abatement options used in RAINS for power plants and industry.

Control technology	RAINS code	Removal efficiency		
		> PM_{10}	Coarse	Fine
Cyclone	CYC, _CYC	90 %	70 %	30 %
Wet scrubber	WSCRB, _WSCRB	99.9 %	99 %	96 %
Electrostatic precipitator, 1 field	ESP1, _ESP1	97 %	95 %	93 %
Electrostatic precipitator, 2 fields	ESP2, _ESP2	99.9 %	99 %	96 %
Electrostatic precipitator, 3 fields and more	ESP3P, _ESP3P	99.95 %	99.9 %	99 %
Wet electrostatic precipitator	PR_WESP	99.95 %	99.9 %	99 %
Fabric filters	FF, _FF	99.98 %	99.9 %	99 %
Regular maintenance, oil fired boilers	GHIND	30 %	30 %	30 %
Good practice (industrial processes – fugitive), stage 1	PRF_GP1	20 %	15 %	10 %
Good practice (industrial processes – fugitive), stage 2	PRF_GP2	75 %	50 %	30 %

For small and medium size boilers in the residential/commercial sector, a number of measures, depending on the size, fuel, and operation mode (manual or automatic loading), are available:

- Cyclones;
- Fabric filters;
- Regular maintenance of oil fired boilers;
- New type of boiler, e.g., pellets or wood chips.

For domestic sources, i.e., fireplaces, single-family boilers, the principal option is a switch to a newer type of installation. Additionally for fireplaces, an option of installing a catalyst or non-catalyst insert is included. Modernization options (two stages potentially including catalytic and non-catalytic and/or primary and secondary air deflectors) are included for coal and wood stoves. The data on efficiencies (Table 2.8) and costs of these options for wood burning originates from Houck and Tiegs (1998). This study refers to the American situation and the data need to be reviewed taking into account European conditions. At this stage, however, no similar data for Europe could be found. Techniques to control emissions from coal burning installations are primarily "placeholders" that can be used when more information about possibilities to control these sources is available. As with other categories, regular maintenance of oil-fired boilers is also included. Size-fraction specific removal efficiencies for these control options are given in Table 2.8.

Table 2.8: Size-fraction specific removal efficiencies for abatement options used in RAINS for residential combustion sources.

Control technology	RAINS code	Removal efficiency		
		> PM_{10}	Coarse	Fine
Fireplaces, non-catalytic insert	FP_ENC	44 %	44 %	44 %
Fireplaces, catalytic insert	FP_CAT	47 %	47 %	47 %
New domestic stoves (coal), stage 1	COAL1	30 %	30 %	30 %
New domestic stoves (coal), stage 2	COAL2	50 %	50 %	50 %
New domestic boilers (coal)	NB_COAL	40 %	40 %	40 %
New domestic stoves (wood), non-catalytic	WOOD1	63 %	63 %	63 %
New domestic stoves (wood), catalytic	WOOD2	65 %	65 %	65 %
New wood boilers (wood chips, pellets)	MB_PELL	89 %	89 %	89 %
Regular maintenance, oil fired boilers	GHDOM	30 %	30 %	30 %
Cyclone	MB_CYC	90 %	70 %	30 %
Fabric filters	MB_BAG, _PLBAG	99.98 %	99.9 %	99 %

For several non-combustion PM sources included in the model, a range of control options is included. It has to be noted, however, that information on their removal efficiencies as well as costs is very scarce or not available at all. The only sector for which more extensive discussion of control options is available is agriculture (Takai *et al.*, 1998; ICC &SRI, 2000). Assumptions made in RAINS on removal efficiency for the included options are summarized in Table 2.9.

Table 2.9: Size-fraction specific removal efficiencies for abatement options used in RAINS for non-combustion sources.

Control technology	RAINS code	Removal efficiency		
		> PM_{10}	Coarse	Fine
Agriculture				
Feed modification (all livestock)	FEED_MOD	45 %	35 %	10 %
Hay-silage for cattle	HAY_SIL	70 %	40 %	10 %
Free range poultry	FREE	40 %	15 %	5 %
Low-till farming, alternative cereal harvesting	ALTER	40 %	15 %	5 %
Good practice (other animals) [generic option]	AGR1	40 %	15 %	5 %
Other sources				
Good practice, storage and handling	STH_GP	50 %	20 %	10 %
Good practice in oil and gas industry, flaring	FLR_GP	40 %	15 %	5 %
Ban on open burning of waste	BAN	100 %	100 %	100 %
Good practice in mining industry	MINE_GP	55 %	47 %	25 %
Spraying water at construction sites	SPRAY	50 %	20 %	10 %
Filters in households (kitchen)	FILTER	50 %	20 %	10 %
Generic, e.g., street washing	RESP1	n.d. (1)	n.d.	n.d.

(1) not defined yet

2.4.2 Mobile Sources

Primary particle emissions from mobile sources have two entirely different origins: exhaust due to fuel combustion; and non-exhaust emissions, i.e., tire and brake wear and road abrasion or re-suspension (dust swept up or entrained into the air by passing traffic). In this section options to control exhaust emissions of PM, as well as their implementation in RAINS, are discussed.

2.4.2.1 A Review of Available Control Options

Emission control options for mobile sources can be divided into the following categories:

- ***Changes in fuel quality***, e.g., decreases in sulfur content. Changes in fuel specifications may provide engine manufactures with greater flexibility to use new emission reduction technologies.
- ***Changes in engine design***, which result in better control of the combustion processes in the engine.
- ***Flue gas post-combustion treatment***, using various types of trap concepts and catalysts to convert or capture emissions before they leave the exhaust pipe.
- ***Better inspection and maintenance***. Examples are: in-use compliance testing, in-service inspection and maintenance, on-board diagnostic systems.

Diesel Fuels and Clean Diesel Engines

High sulfur or aromatics contents have an impact on the quantity and quality of particulate matter emissions. They also interfere with several technologies controlling diesel exhaust. A reduction of fuel density lowers NO_x and PM emissions, but on the other hand it increases hydrocarbon (HC) and carbon monoxide (CO) exhaust. The use of synthetic diesel fuel, gained from feedstock such as gas or coal, significantly reduces all pollutant emissions, including PM. Other measures, which may result in lower PM emissions, are the use of bio-diesel, derived from various vegetable oils, and of dimethyl ether (DME), made, for example, from natural gas and coal (http://www.dieselnet.com).

Changes in diesel engine design have reduced emissions from diesel vehicles by more than 90 percent. Important improvements are electronic controls and fuel injectors to deliver fuel at the best combination of injection pressure, injection timing and spray location, air-intake improvements, combustion chamber modifications, exhaust gas re-circulation and ceramic in-cylinder coatings (see also Cofala and Syri, 1998b).

Diesel Catalyst Technology

Catalysts increase the rate of chemical reaction. In emission control applications heterogeneous catalysts are used, which are supported on high surface area porous oxides. Two processes may cause malfunction of emission control catalysts: poisoning and thermal deactivation. The catalyst's active sites can be chemically deactivated or the catalytic surface can be masked, mainly by sulfur and phosphorus. High temperature can result in a sintering of the catalytic material or the carrier.

Diesel oxidation catalysts were first introduced in the 1970s in underground mining as a measure to control CO. Today catalysts are used on many diesel cars in Europe, primarily to control PM and hydrocarbon emissions. Early diesel catalysts utilized active oxidation formulations such as platinum on alumina. They were very effective in oxidizing emissions of CO and HC as well as the organic fraction (SOF) of diesel particles.

However, catalysts also oxidize sulfur dioxide, which is present in diesel exhaust from the combustion of sulfur-containing fuels. The oxidation of sulfur to SO_2 leads to the generation of sulfate particulate matter. This may significantly increase total primary particle emissions, although the SOF PM fraction is reduced. Newer diesel oxidation catalysts are designed to be selective, i.e., to obtain a compromise between sufficiently high HC and SOF activity and acceptably low formation of SO_2.

Diesel Particulate Traps

Diesel particulate traps physically capture diesel particles preventing their release to the atmosphere. Diesel traps work primarily through a combination of deep-bed filtration mechanisms, such as diffusional and inertial particle deposition. The most common filter materials are ceramic wall-flow monoliths and filters made of continuous ceramic fibers. A number of methods have been proposed to regenerate diesel filters.

Passive filter systems utilize a catalyst to lower the soot combustion temperature. Active filter systems incorporate electric heaters or fuel burners to burn the collected particles.

The regeneration of a diesel filter is characterized by a dynamic equilibrium between the soot being captured in the filter and the soot being oxidized. The rate of soot oxidation depends on the filter temperature. At temperatures that are typically found in diesel exhaust gases, the rate of soot oxidation is small. Therefore, to facilitate filter regeneration, either the exhaust gas temperature has to be increased or a catalyst has to be applied. The catalyst can be applied directly onto the filter media or dissolved in the fuel as a fuel additive.

Wall-flow monoliths became the most popular diesel filter design. They are derived from flow-through catalyst supports where channel ends are alternately plugged to force the gas flow through porous walls acting as filters. The monoliths are made of specialized ceramic materials. Most catalyzed diesel traps utilize monolithic wall-flow substrates coated with a catalyst. The catalyst lowers the soot combustion temperature, allowing the filter to self-regenerate during periods of high exhaust gas temperature. Filters of different sizes, with and without catalysts, have been developed and are available as standard products.

The **CRT (Continuously Regenerating Trap)** system for diesel particulate utilizes a ceramic wall-flow filter to trap particles. The trapped PM is continuously oxidized by nitrogen dioxide generated in an oxidation catalyst, which is placed upstream of the filter. The CRT requires practically sulfur-free fuel for proper operation.

Fuel additives (fuel soluble catalysts) can be used in passive diesel trap systems to lower the soot combustion temperature and to facilitate filter regeneration. The most popular additives include iron, cerium, copper, and platinum. Many laboratory experiments and field tests have been conducted to evaluate the regeneration of various diesel filter media using additives. Cerium additive is utilized in a commercial trap system for diesel cars.

Electric regeneration of diesel traps has been attempted in off- and on-board configurations. On-board regeneration by means of an electric heater puts a significant additional load on the vehicle electrical system. Partial flow layouts or regeneration with hot air are more energy efficient. An on-board, hot air regenerated diesel trap was tested on over 2000 urban buses in the U.S. A system with off-board electric regeneration has also been developed and commercialized.

Diesel **fuel burners** can be used to increase the exhaust gas temperature upstream of a trap in order to facilitate filter regeneration. Fuel burner filters can be divided into single point systems and full flow systems. The full flow systems can be regenerated during regular vehicle operation but require complex control to ensure a thermally balanced regeneration. An advanced system featuring electronically controlled full flow burner regeneration has been developed.

Diesel soot has microwave absorption properties and there are filter substrate materials that are transparent to **microwave irradiation**. Microwave heating is another method to regenerate diesel particle filters.

2.4.2.2 Control Options Implemented in the RAINS Model

The options to control vehicle emissions in RAINS simulate the effects of implementation of European legislation on mobile sources. Table 2.10 presents the development of emission standards on diesel light-duty vehicles since 1990. Standards for heavy-duty trucks are presented in Table 2.11. Emission limit values for off-road vehicles are presented in Table 2.12. The regulations for off-road diesel engines are introduced in two stages: Stage I implemented in 1999 and Stage II implemented from 2001 to 2004, depending on the engine power output. Emission limit values are similar to EURO I and EURO II standards for heavy-duty vehicles. The equipment covered by the standard includes industrial drilling rigs, compressors, construction wheel loaders, bulldozers, off-road trucks, highway excavators, forklift trucks, road maintenance equipment, snow plows, ground support equipment in airports, aerial lifts and mobile cranes. Agricultural and forestry tractors have the same emission standards but different implementation dates. Engines used in ships, railway locomotives, aircraft, and generating sets are not covered by the standards.

Table 2.10: PM emission standards for diesel light duty vehicles.

Vehicle category/class/standard name, implementation year [1]		g/km
Passenger cars and light duty trucks GVW [2] < 1305 kg	Euro I - 1992 / 94	0.14
	Euro II - 1996	0.08
	Euro III – 2000	0.05
	Euro IV – 2005	0.025
Light duty trucks GVW 1305 to 1760 kg	Class II – 1994	0.16
	Class II- 2001	0.07
	Class II – 2006	0.04
Light duty trucks GVW > 1760 kg	Class III - 1994	0.25
	Class III - 2001	0.10
	Class III - 2006	0.06

[1] Directive 98/69/EC (Diesel Cars and Light-Duty Trucks)
[2] GVW – gross vehicle weight

Table 2.11: PM emission standards for heavy-duty vehicles.

Vehicle category/class/standard name, implementation year [1]		g/kWh
Heavy duty trucks and buses	Euro I - 1992, <85 kW	0.61
	Euro I - 1992, >85 kW	0.36
	Euro II - 1996	0.25
	Euro II - 1998	0.15
	Euro III - 2000	0.10
	Euro IV and V - 2005 & 2008[2]	0.02

[1] Directive 88/77/EEC (Heavy- Duty Diesel Truck and Buses)
[2] Requires fitting the vehicle with PM traps

Table 2.12: PM emission standards for non-road machinery.

Stage, vehicle category, implementation year [1] [2]		g/kWh
Stage I	130 - 560 kW, 1999	0.54
	70 - 130 kW, 1999	0.70
	37 - 75 kW, 1999	0.85
Stage II	130 - 560 kW, 2002	0.20
	130 - 560 kW, 2003	0.30
	70 - 130 kW, 2004	0.40

[1] Directive 97/68/EC for off-road mobile equipment, Directive 2000/25/EC for agricultural and forestry tractors.
[2] Standards for tractors need to be implemented approximately two years later.

Following the current (and possible future) emission limit values for each vehicle category several emission control technologies have been introduced. Technologies for diesel road vehicles, their RAINS abbreviations and assumed PM removal efficiencies are presented in Table 2.13. Removal efficiency for each technology has been assumed based on comparison of the unabated emission factor for a vehicle built at the end of 1980's with the appropriate EURO standard. This method of estimating removal efficiencies is consistent with the assumptions made within the Auto Oil Programme (EC, 1996, EC, 1999). Because of the lack of detailed data, it has been assumed that the removal efficiencies are the same for all PM size classes. To provide the possibility of simulation of the effects of implementing stricter standards than currently decided, the model assumes for each source category at least one to two additional control options/stages. To the extent possible, removal efficiencies for those future stages are based on published sources (e.g., particle trap for diesel cars developed by Peugeot). In some cases, the information was not available at all. In such a case, the assumed efficiencies are simply placeholders.

Table 2.13: Control technologies for diesel road vehicles and their PM removal efficiencies.

Sector, control technology, implementation year	RAINS abbreviation	Removal efficiency [%]
Diesel light duty trucks and passenger cars		
EURO I -1992/94	MDEUI	60.71
EURO II - 1996	MDEUII	74.55
EURO III - 2000	MDEUIII	85.86
EURO IV - 2005	MDEUIV	92.93
EURO V - post- 2005, Stage 1	MDEUV	99.95
EURO VI - post 2005, Stage 2	MDEUVI	99.99
Heavy duty diesel trucks and buses		
EURO I - 1992	HDEUI	45.00
EURO II - 1996	HDEUII	77.00
EURO III - 2000	HDEUIII	85.00
EURO IV - 2005	HDEUIV	97.00
EURO V - 2008	HDEUV	97.00
EURO VI - post-2008	HDEUVI	99.95

Table 2.14 contains a list of technologies for off-road diesel vehicles. Efficiencies for individual stages are basically the same as for road sources. RAINS also includes three technologies for controlling emissions from seagoing ships. Characterizations of those technologies are based on data from Lloyd's Register, 1995, Wright, 1997, and Kjeld, 1995.

Table 2.14: Control technologies for diesel off-road vehicles and their PM removal efficiencies.

Sector, control technology, implementation year	RAINS abbreviation	Removal efficiency [%]
Vehicles in construction and agriculture		
Equivalent of EURO I for HDV, 1999	CAGEUI	20.00
Equivalent of EURO II for HDV, 2000/2002	CAGEUII	50.00
Equivalent of EURO III for HDV	CAGEUIII	85.00
Equivalent of EURO IV for HDV	CAGEUIV	97.00
Equivalent of EURO V for HDV	CAGEUV	97.05
Equivalent of EURO VI for HDV	CAGEUVI	99.95
Trains and inland waterways		
Equivalent of EURO I for HDV, 1999	TIWEUI	20.00
Equivalent of EURO II for HDV, 2000/2002	TIWEUII	50.00
Equivalent of EURO III for HDV	TIWEUIII	85.00
Equivalent of EURO IV for HDV	TIWEUIV	97.00
Equivalent of EURO V for HDV	TIWEUV	97.05
Equivalent of EURO VI for HDV	TIWEUVI	99.95
Maritime activities: ships		
Combustion modification, medium vessels	STMCM	20.00
Combustion modification, large vessels-fuel oil	STLHCM	40.00
Combustion modification, large vessels - diesel	STLMCM	20.00

Although there are no standards for PM emissions from gasoline (spark ignition) engines, implementation of emission control technologies aimed at mitigation of emissions of NO_x and NMVOC also reduces the emissions of particles from those engines. For gasoline exhaust it has been assumed that catalytic converters lead to a reduction of PM emissions of 50 percent (Euro I to Euro VI). This percentage is based on the difference in emission factors for unleaded fuel with and without three-way catalysts as reported by APEG (1999). Names of technologies and their RAINS abbreviations are presented in Table 2.15.

Table 2.15: Control technologies for spark ignition engines and their PM removal efficiencies.

Sector, control technology, implementation year	RAINS abbreviation	Removal efficiency [%]
Light duty gasoline direct injection (DI) engines		
EURO III	LFGDIII	50.00
EURO IV	LFGDIV	50.00
EURO V - post 2005, stage 1	LFGDV	50.00
EURO VI - post 2005, stage 2	LFGDVI	50.00
Light duty 4-stroke spark ignition engines, not DI		
EURO I	LFEUI	50.00
EURO II	LFEUII	50.00
EURO III	LFEUIII	50.00
EURO IV	LFEUIV	50.00
EURO V - post 2005, stage 1	LFEUV	50.00
EURO VI - post 2005, stage 2	LFEUVI	50.00
Motorcycles, mopeds and off-road engines 2-stroke		
Stage 1	MMO2I	30.00
Stage 2	MMO2II	70.00
Stage 3	MMO2III	70.00
Motorcycles 4-stroke		
Stage 1	MOT4I	50.00
Stage 2	MOT4II	50.00
Stage 3	MOT4III	50.00
Heavy duty vehicles, spark ignition engines		
Stage 1	HDSEI	50.00
Stage 2	HDSEII	50.00
Stage 3	HDSEIII	50.00

2.5 Activity data

The RAINS model database includes activity data for historical years, i.e. 1990 to 2000, and projections up to 2030. In fact, the model allows for several projections (activity pathways) that can be stored and used to calculate various scenarios. This section provides information on the sources of historical data and a baseline projection.

Data for the years 1990, 1995 and 2000 originate from international and national statistics, as well as the CEPMEIP (2002) database, the latter being used specifically for several of the non-energy sectors in Eastern European countries. The forecasts are derived from modeling studies or, in case information was not available, activities are kept constant at the level of the year 2000 or 1995. The database is fully compatible with the other modules of the RAINS model, i.e., the same energy, livestock, population, etc., projections are used to estimate emissions of SO_2, NO_x, ammonia or NMVOC. The sources of data for different sectors are summarized in Table 2.16.

Table 2.16: Sources of activity data in the RAINS PM model

Category / Sector	Historical data	Projections
Energy use: Stationary combustion, Road transport, Off-road transport	IEA, 1998; EC, 1999ab	EC, 1999ab; Cofala *et al.*, 2002
Energy production, conversion Solid fuels Oil and gas production	EC, 1999a; CEPMEIP, 2002; IEA, 1998	EC, 1999ab; Cofala *et al.*, 2002
Industrial processes		
Iron and Steel, Non-ferrous	UN, 2002; CEPMEIP, 2002	EC, 1999a; Cofala *et al.*, 2002
Cement and Lime	UN, 2002; EC, 1999a	EC, 1999a; Cofala *et al*., 2002
Other	UN, 2002; CEPMEIP, 2002	EC, 1999ab; constant at 1995 level
Storage and handling of bulk materials	CEPMEIP, 2002; UN, 2002	EC, 1999ab; some kept constant at 1995 level
Open burning of waste	CEPMEIP, 2002	constant at 1995 level
Agriculture		
Livestock, fertilizers	FAO, 2002; IFA, 1998; Klimont, 1998	Klimont, 1998; Amann *et al*., 1998;
Arable land	FAO, 2002	constant at 2000 level
Population	UN, 2000	UN, 2000
Other	CEPMEIP, 2002; UN, 2002	constant at 1995 level

3 Emission Source Categories

The following sections briefly characterize the PM source categories included in the RAINS model. This includes the origin of the emissions, their contribution to primary particulates, the activity data used in the model, emission factors and a list of applicable control options.

3.1 Fuel Combustion in Stationary Sources

The combustion of fossil fuels in stationary installations is a major source of PM emissions in Europe. It is estimated that in 1995 about 51, 48, and 40 percent of TSP, PM_{10}, and $PM_{2.5}$, respectively, were emitted from these sources (CEPMEIP, 2002). The share varies dramatically between countries depending on fuel structure and level of control; for TSP and PM_{10}, for example, the shares are 43 and 34 percent in UK (APEG, 1999), about 17 and 28 percent in Austria and Germany (Winiwarter *et al.*, 2001; UBA, 1998a), and only about 10 percent of PM_{10} in Switzerland (BUWAL, 2001; EWE, 2000). A very important role is played by emissions from small residential and domestic combustion installations which are typically responsible for more than a third of total stationary combustion PM emissions (UBA, 1998a; APEG, 1999) but in some countries might dominate this sector, e.g., in Austria more than 70 percent of PM emissions from stationary combustion originated from this source in 1995 (Winiwarter *et al.*, 2001).

Primary particulate emissions from combustion processes can be roughly divided into two categories (Flagan and Seinfeld, 1988):

- ash, i.e., a combustion product formed from non-combustible mineral constituents in fuel, typically containing from about two to 30 percent of non-combustible mineral material (McElroy *et al.*, 1982), and
- carbonaceous particles, e.g., char, coke and soot, which are formed by pyrolysis of unburned fuel molecules.

The largest particles of ash and unburned fuel remain in the boiler and are extracted from the process with bottom ash. Smaller particles, typically <100-300 µm, are entrained in the combustion gas, forming so-called combustion aerosols or fly ash. Part of the combustion aerosol particles might deposit on to the boiler walls or heat exchanger surfaces. Power and heat generating plants produce enormous quantities of by-product fly ash and PM emission controls are therefore essential to minimize the emissions of particles to the atmosphere. In today's power plants and industrial boilers, emission control appliances, such as cyclones or electrostatic precipitators, capture the major part of particles leaving the boiler.

This section is divided into three sub-sections, focusing on solid fuel combustion (excluding fuelwood burning), wood combustion in small residential and domestic boilers and stoves, and the combustion of liquid fuel in stationary sources.

3.1.1 Emissions from Combustion of Solid Fuels

Ash-forming species dominate the particles emitted from solid combustion under controlled conditions, e.g., in power plants and large industrial boilers. For instance, the share of unburned fuel in total particulate emissions from combustion of pulverized coal is normally less than five percent (Lammi *et al.*, 1993). Emissions from fluidized bed combustion also contain particles of the bed material and, if limestone injection into the boiler is applied, particles originating from limestone as well. For small-scale boilers and stoves that are mainly used in the domestic sector the share of unburned fuel is usually high.

RAINS Sectors

PP_EX_OTH	PP_EX_WB	PP_NEW	IN_BO
IN_OC	CON_COMB	DOM_STOVE	DOM_SHB_M
DOM_SHB_A	DOM_MB_M	DOM_MB_A	

Description

Activity: Burning of solid fuels (excluding fuelwood) in stationary sources (power plants, industry and residential sector).

Unit: **kt/PJ** fuel consumed.

Emission factors

To reflect the differences in fuel quality across countries, TSP emission factors for solid fuels are calculated with a mass balance approach using country-specific data on ash content, heat value and the fraction of ash retained in the boiler, following the methodology of Section 2.3.1. An exception is the combustion of solid fuels in small residential boilers and stoves where country-specific emission factors are derived from the literature.

Combustion conditions, especially in large boilers, have a strong influence on mass concentrations of TSP, PM_{10} and $PM_{2.5}$ in the flue gas and on PM size distribution profiles (e.g., Flagan and Seinfeld, 1988; Moisio, 1999). Ash-forming minerals account for most of the particulate matter emissions from solid fuels and form particles of different sizes depending on e.g., mineral matter composition and combustion conditions. Mineral matter, occurring as mineral inclusions or heteroatoms present in the coal molecules, consists of refractory metal oxides (SiO_2, MgO, FeO, Al_2O_3 *etc.*) and more volatile species (Na, K, Cd, As, Pb, etc.). Refractory compounds are not directly volatilized at the temperatures of normal combustion processes, and they form mainly relatively large-sized particles (1-50 μm). Volatile compounds volatilize in high temperatures. A small part of the refractory species might also volatilize in reductive high temperature conditions. Volatilized species mainly form very small particles (0.01-0.5 μm) via nucleation, condensation, agglomeration and coagulation (Flagan and Seinfeld, 1988).

The source sector split distinguished in RAINS does not allow the inclusion of all these combustion parameters. However, a distinction was made for power plants and industry between three types of boilers, which are characterized by significantly different ash retention and particle size distribution (Lind, 1999):

- Grate combustion (PP_EX_OTH1, PP_NEW1, IN_BO1, IN_OC1, DOM_MB_M, DOM_MB_A); typically smaller installations. Industrial coal plants are slowly replaced with fluidized bed combustion but remain important for biomass combustion. Particles from grate combustion are usually relatively large, with a mean size of 60-70 µm (Lammi *et al.,* 1993).
- Fluidized bed combustion (FBC) (PP_EX_OTH2, PP_NEW2, IN_BO2, IN_OC2); typically mid-size (up to 100 MW) installations. The theories of fine particle formation presented in the literature (*e.g.,* Lind, 1999) suggest that particle size distributions in fluidized bed combustion are different from pulverized fuel combustion. Since boiler temperatures in atmospheric fluidized bed combustion installations are lower, volatilization of ash takes place to a lesser extent and fewer fine particles are formed. In the coarse particle mode (particles larger than 2.5 µm), FBC produces larger ash particles than pulverized fuel combustion (Moisio, 1999). In addition, some relatively large particles of bed material and, if limestone injection is used, particles originating from limestone are also entrained with the flue gas. Mean fly ash particle sizes before ESP in circulating FB combustion of coal of 20-30 µm have been measured (Lind *et al.,* 1995, 1996).
- Pulverized fuel combustion (PP_EX_OTH3, PP_NEW3, IN_BO3, IN_OC3). Globally, pulverized coal combustion is a very common way of energy utilization, and the particle formation in these types of boilers has been widely studied. Coal is first milled to a fine powder (40-80 µm) and then blown into the boiler. Combustion temperatures are high, reaching up to 2000 K. Because of these high temperatures, volatile species and a small fraction of the refractory components of the ash-forming species are effectively volatilized. Volatilized species mainly form small particles (0.01-0.5 µm) via nucleation, condensation, agglomeration and coagulation (Flagan and Seinfeld, 1988). The fraction of the volatilized ash is usually less than ten percent. The non-volatilized mineral compounds form larger ash particles, usually above 1 µm (Moisio, 1999). Pulverized fuel combustion of peat is somewhat analogous to coal (Moisio, 1999).

The ash retention parameter is used in addition to the fuel characteristics to enable a more accurate reflection of “raw gas” emission rates. Table 3.1 and Table 3.2 below present an overview of reported emission factors and measured size fraction distributions. The size distribution used in RAINS is shown in Table 3.3, Table 3.4 and Table 3.5.

Table 3.1: Uncontrolled emission factors reported in the literature for coal combustion [kt/PJ].

Source	Installation type	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Small furnaces		0.110	0.270
	Domestic boilers		0.090	0.150
	Industrial boilers		0.045	0.050
CEPMEIP, 2002	Residential, brown coal	0.07	0.14	0.35
	Residential, hard coal ('high')	0.06	0.12	0.3
	Residential, hard coal ('low')	0.025	0.05	0.10
	Residential, low grade hard coal	0.1	0.2	0.8
Pfeiffer *et al.*, 2000	Residential, hard coal			0.26-0.28
	Residential, brown coal briquettes			0.12-0.13
	Residential, coke			0.014
Spitzer *et al.,* 1998	Residential heating			0.153±50%
	Single family house boiler, stoves			0.094±54%
Winiwarter *et al*, 2001	Residential plants	0.075	0.085	0.094
	Domestic stoves, fireplaces	0.122	0.138	0.153
UBA, 1999a	Domestic furnaces, hard coal			0.250
	Domestic furnaces, brown coal			0.350
EPA, 1998a	Small boilers, top loading			0.291
	Small boilers, bottom loading			0.273
	Pulverized coal, dry bottom boilers			1.818
	Pulverized coal, wet bottom boilers			1.273
	Hard coal, stoker firing			1.200
	Pulverized lignite boilers			1.105
Lammi *et al.*, 1993	Pulverized			3.6-5.4
	Fluidized bed			4.3-7.2
Meier & Bischoff, 1996	Grate firing, lignite			2.237

Table 3.2: Size fractions reported in the literature for coal combustion [percent of TSP emissions].

Source	Installation type	$PM_{2.5}$	PM_{10}	TSP
UBA, 1999a	Domestic furnaces, hard coal		90 %	100 %
EPA, 1998a	Small boilers, top loading	14 %	37 %	100 %
	Small boilers, bottom loading	25 %	41 %	100 %
	Pulverized hard coal, dry bottom, no control	6 %	23 %	100 %
	Pulverized hard coal, wet bottom, no control	21 %	37 %	100 %
	Pulverized lignite, no control	10 %	35 %	100 %
Moisio, 1999	Pulverized, hard coal, no control	6 %	52 %	100 %
	Fluidized bed, hard coal, no control	5 %	26 %	100 %

Table 3.3: Size fractions used in RAINS for solid fuel combustion in industry, 'raw gas' [%].

Fuel [installation type]	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Coal [grate]	7 %	13 %	20 %	80 %	100 %
Coal [fluidized]	5 %	21 %	26 %	74 %	100 %
Brown coal [pulverized]	10 %	25 %	35 %	65 %	100 %
Hard coal [pulverized]	6 %	17 %	23 %	77 %	100 %
Derived coal	45 %	34 %	79 %	21 %	100 %
Biomass	77 %	12 %	89 %	11 %	100 %
Waste	23 %	15 %	38 %	62 %	100 %

Table 3.4: Size fractions used in RAINS for solid fuel combustion in power plants, 'raw gas' [%].

Fuel [installation type]	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Coal [grate]	14 %	23 %	37 %	63 %	100 %
Coal [fluidized]	5 %	21 %	26 %	74 %	100 %
Brown coal [pulverized]	10 %	25 %	35 %	65 %	100 %
Hard coal [pulverized]	6 %	17 %	23 %	77 %	100 %
Hard coal [wet bottom]	21 %	2 %	23 %	77 %	100 %
Derived coal	45 %	34 %	79 %	21 %	100 %
Biomass	77 %	12 %	89 %	11 %	100 %
Waste	23 %	15 %	38 %	62 %	100 %

Table 3.5: Size fractions used in RAINS for solid fuel combustion in residential plants [%].

Fuel [category]	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Coal [stoves and boilers, domestic]	13 %	77 %	90 %	10 %	100 %
Coal [large boilers, residential]	7 %	13 %	20 %	80 %	100 %
Derived coal	45 %	34 %	79 %	21 %	100 %
Biomass [stoves and boilers, domestic]	93 %	3 %	96 %	4 %	100 %
Biomass [large boilers, residential]	77 %	12 %	89 %	11 %	100 %
Waste	60 %	30 %	90 %	10 %	100 %

Applicable Control Options

The control options used in the RAINS model include end-of-pipe techniques, i.e., cyclones, bag filters and electrostatic precipitators. Additionally, for small coal combustion installations in the residential and domestic sector, three types of modern boilers/stoves (see Table 2.7) are included to simulate the gradual replacement of old facilities.

3.1.2 Emissions from Wood Burning

The available literature suggests wood burning is a major source of PM emissions. However, for a number of reasons it is rather difficult to estimate PM emissions from wood burning accurately:

- There are serious questions about the accuracy of wood consumption statistics, since the non-commercial use of fuelwood is difficult to quantify;
- There are hundreds of types of wood burning devices in use, especially in the residential and domestic sector;
- Several tree species are used for fuelwood and the literature suggests a strong dependency between PM emissions and wood type;
- Practices of storing and seasoning fuel wood vary (affecting wood moisture);
- The variation of household altitude;
- The variation of chimney conditions between different homes; and
- The large variations in the operation of wood burning devices, i.e., burn rate, burn duration, damper setting, etc.

Each of these parameters has significant impacts on combustion conditions and will change emissions (Houck *et al.*, 2001).

RAINS Sectors

PP_EX_OTH	PP_NEW	IN_BO	IN_OC
CON_COMB	DOM_FPLACE	DOM_STOVE	DOM_SHB_M
DOM_SHB_A	DOM_MB_M	DOM_MB_A	

Description

Activity: Combustion of fuel wood in industry and the residential and domestic sector.

Unit: **kt/PJ** fuel consumed.

Emission Factors

So far, only limited measurement data have been used to represent a large number of appliances and variables. Some of the older emission rates reported in, for example, EPA (1998a,b) are not always appropriate for representing present European conditions because there has been a considerable improvement in the performance of devices leading to lower emissions (Houck *et al.*, 2001). As demonstrated in Table 3.6, the emission rates reported in the literature vary greatly, reflecting the large differences in combustion parameters of inspected appliances.

Another very important aspect of PM emissions from the domestic combustion of wood is the size distribution of particulate matter. Several studies indicate that up to 95 percent of the particulate mass emitted from this source is in the fine fraction (e.g., Smith, 1987; Ahuja *et al.*, 1989; Houck *et al.*, 1989; Tullin and Johansson, 2000; Baumbach *et al.*, 1999; Dreiseidler *et al.*, 1999). This might have consequences for the importance of this source when evaluating the health effects of PM emissions. Examples of the size distribution for wood combustion installations are shown in Table 3.7.

The emission factors used in the RAINS model were derived from the values reported in the literature (see Table 3.6 and Table 3.7) and are shown in Table 3.8 and Table 3.9. It was decided to use different values across European countries reflecting different operating practices, age of installations, etc.

Table 3.6: Emission factors reported in the literature for wood burning [kt/PJ].

Source	Installation type	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Domestic open fire places		0.150	0.150
	Domestic furnaces		0.150	0.150
	Domestic small boilers, manual		0.050	0.050
	Small boilers, automatic loading		0.080	0.080
Karvosenoja, 2000	Domestic furnaces			0.2-0.5
Dreiseidler, 1999	Domestic furnaces			0.200
Baumbach, 1999	Domestic furnaces			0.05-0.10
Pfeiffer *et al.*, 2000	Residential and domestic			0.041-0.065
CEPMEIP, 2002	'High emissions'	0.270	0.285	0.300
	'Low emissions'	0.135	0.143	0.150
Winiwarter *et al*, 2001	Residential plants	0.09	0.081	0.072
	Domestic stoves, fireplaces	0.118	0.133	0.148
NUTEK, 1997	Single family house boiler, conventional			1.500
	Single family house boiler, modern with accumulator tank			0.017
Smith, 1987	Residential heating stoves <5 kW			1.350
	Residential cooking stoves <5 kW			0.570
	Industrial boilers			0.350
BUWAL, 1995 (1992 Swiss limit value)	up to 1 MW			0.106
Spitzer *et al.,* 1998	Residential heating			0.148±46%
	Single family house boiler, stoves			0.090±26%
Zhang *et al.*, 2000	Firewood in China			0.76-1.08
Houck and Tiegs, 1998	Conventional stove			0.91
	Non-catalytic stove			0.33
	Catalytic stove			0.32
	Pellet stove			0.10
	Fireplace, conventional			0.60
	Fireplace, non-catalytic insert			0.33
	Fireplace, catalytic insert			0.32
	Fireplace, pellet insert			0.10
EPA, 1998b (1)	Open fireplaces		0.805	0.875
	Wood stove		0.724	0.787
EPA, 1998a	Boilers, bark			2.266
Lammi *et al.*, 1993	Fluidized bed in large boilers			1.0-3.0
	Grate firing in large boilers			0.25-1.50

(1) Original factors in lb/ton, for recalculation heating value of 16 GJ/t was assumed.

Table 3.7: Size fractions reported in the literature for wood burning [percent of TSP emissions].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
Dreiseidler, 1999	Domestic furnaces		90 %	100 %
	Wood pellets	84.4 %	94.6 %	100 %
EPA, 1998b			92 %	100 %
Baumbach, 1999	Domestic furnaces	96 %	99.7 %	100 %
UMEG, 1999	Small boilers	79 %	92 %	100 %

Table 3.8: Emission factors used in RAINS for wood burning in Eastern Europe [kt/PJ].

Sector	RAINS code	$PM_{2.5}$	PM_{10}	TSP
Fireplaces, stoves	DOM_FPLACE, DOM_STOVE	0.279	0.288	0.3
Small domestic boilers	DOM_SHB_M, DOM_SHB_A	0.093 – 0.23	0.096 – 0.24	0.1 – 0.25
Large residential boilers	DOM_MB_M, DOM_MB_A	0.077 – 0.15	0.089 – 0.18	0.1 – 0.2
Industry	PP_, IN_, CONV_COMB	0.185	0.214	0.24

Table 3.9: Emission factors used in RAINS for wood burning in Western Europe [kt/PJ].

Sector	RAINS code	$PM_{2.5}$	PM_{10}	TSP
Fireplaces, stoves	DOM_FPLACE, DOM_STOVE	0.067 – 0.186	0.07 – 0.192	0.072 – 0.2
Small domestic boilers	DOM_SHB_M, DOM_SHB_A	0.06 – 0.167	0.062 – 0.17	0.065 – 0.18
Large residential boilers	DOM_MB_M, DOM_MB_A	0.05 – 0.12	0.06 – 0.134	0.065 – 0.15
Industry	PP_, IN_, CONV_COMB	0.185	0.214	0.24

Applicable Control Options

The control options considered in the RAINS model include end-of-pipe techniques for medium and large residential boilers and industrial installations, i.e., cyclones, bag filters and electrostatic precipitators. For small installations in the residential and domestic sectors three types (stages) of modern boilers/stoves are included to simulate the gradual replacement of old facilities (see also brief discussion in Section 2.4.1.2).

3.1.3 Emission Factors for Liquid Fuels, Natural Gas and LPG

Normally, liquid fuels contain less ash-forming species than coal. For example, the major parts of emitted particulate mass from heavy fuel oil boilers are unburned carbonaceous coke particles (Flagan and Seinfeld, 1988).

RAINS Sectors

PP_EX_OTH	PP_NEW	IN_BO
IN_OC	CON_COMB	DOM

Description

Activity: Burning of liquid and gaseous fuels in stationary sources (power plants, industry, and residential sector).

Unit: **kt/PJ** fuel consumed.

Emission Factors

Coke particles from heavy fuel oil combustion are relatively large (1-50 μm). In comparison, soot particles are very small (0.01-0.5 μm) and can be produced during the combustion of gaseous fuels and from the volatilized carbonaceous components of liquid and solid fuels (Flagan and Seinfeld, 1988). An overview of the reported emission rates for the stationary combustion of heavy and light fuel oils is provided in Table 3.10 and Table 3.13. Only a few studies have reported the size distribution of PM emissions (Table 3.11 and Table 3.14).

At this stage of development, the RAINS model uses uniform emission factors across all countries (Table 3.12 and Table 3.15). However, comparing heavy fuel oil combustion in the former German Democratic Republic (GDR) and West Germany shows that there is a potentially significant international difference of up to a factor of three (Dreiseidler *et al.,* 1999). Thus, the current RAINS values might represent a lower estimate for Eastern Europe, although it is not always possible to determine the level of control for the emission rates reported in the literature.

Heavy Fuel Oil

Table 3.10: Emission factors reported in the literature for stationary combustion of heavy fuel oil [kt/PJ].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Industrial boilers		0.023	0.023 [(1)]
BUWAL, 1995	Power plants			0.023 [(1)]
	Refineries, controlled			0.043
EPA, 1998a [(2)]	Large boiler, no control			0.238
EPA, 1995 [(3)]	Power plants		0.038	
	Industry		0.020	
UBA, 1989	Power plants		0.015	0.016
	Conversion		0.028	0.031
	Industry	0.023	0.027	0.030
	Residential		0.045	0.050
UBA, 1998 [(2)]	Power plants		0.0065-0.021	0.0068-0.0219
	Residential		0.008-0.027	0.009-0.030
	Industry	0.0028-0.012	0.0033-0.014	0.0037-0.0156
CEPMEIP, 20002	Power plants, high	0.012	0.04	0.2
	Power plants, 'low'	0.0025	0.003	0.003
	Industry, 'high'	0.13	0.19	0.24
	Industry, 'low'	0.01	0.012	0.014
	Residential	0.04	0.05	0.06
Pfeiffer *et al*, 2000	Residential			0.038
Lammi *et al*, 1993	5-50 MW			0.025-0.15
Ohlström, 1998	5-50 MW			0.001-0.390 [(4)]
Berdowski *et al.*, 1997	Power plants	0.025	0.038	
	Industry	0.014	0.020	
	Residential	0.030	0.050	

[(1)] Emission limit value in Switzerland; [(2)] as quoted in Dreiseidler *et al.*, 1999;
[(3)] as quoted in Berdowski *et al.*, 1997; [(4)] Average value 0.032 kt/PJ.

Table 3.11: Size fractions reported in the literature for stationary combustion of heavy fuel oil [percent of TSP].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Large boiler, no control	52 %	71 %	100 %
	Industry, no control	56 %	86 %	100 %
	Residential boilers	23 %	62 %	100 %
CEPMEIP, 20002	Power plants, high	6 %	20 %	100 %
	Power plants, 'low'	83 %	100 %	100 %
	Industry, 'high'	54 %	79 %	100 %
	Industry, 'low'	71 %	86 %	100 %
	Residential	67 %	83 %	100 %
Lützke, 1987	Industry, no control	76 %	92 %	100 %
Berdowski *et al.*, 1997	Power plants and industry	75 %[(1)]		

[(1)] As a percent of PM_{10}.

Table 3.12: Emission factors used in the RAINS model for stationary combustion of heavy fuel oil [kt/PJ].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Power plants	PP_NEW, PP_EX	0.0093	0.0039	0.0132	0.0023	0.0155
Conversion	CON_COMB	0.0117	0.0049	0.0166	0.0029	0.0195
Industry	IN_BO, IN_OC	0.0104	0.0043	0.0147	0.0026	0.0173
Residential	DOM	0.0095	0.0152	0.0247	0.0133	0.0380

Heating Oil (Light Fuel Oil, Middle Distillates)

Table 3.13: Emission factors reported in the literature for stationary combustion of light fuel oil (middle distillates) [kt/PJ].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Domestic furnaces		0.001	0.001
	Domestic boilers		0.0002	0.0002
	Industrial boilers		0.0003	0.0003
CEPMEIP, 2002	Power plants &industry, ‘high’	0.005	0.005	0.005
	Power plants &industry, ‘low’	0.002	0.002	0.002
	Residential and domestic	0.005	0.005	0.005
UBA, 1989	Power plants, conversion			0.0033
	Industry, residential			0.0015
UBA, 1998	All			0.0015
Pfeiffer *et al.*, 2000	Residential			0.0017
	Domestic			0.0016
Ohlström, 1998	0-50 MW plants			0.003-0.100[(1)]
Berdowski *et al.*, 1997	Power plants	0.005	0.005	
	Industry	0.004	0.004	
	Residential sector	0.03	0.03	
EPA, 1998a	Conversion, industry			0.0047

[(1)] Average value 0.070 kt/PJ.

Table 3.14: Size fractions reported in the literature for stationary combustion of light fuel oil (middle distillates) [%].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Domestic boilers	42%	55%	100%
	Conversion, industry	12 %	50 %	100%
APEG, 1999 [(1)]	Power plants	43 %	100 %	
	Industry	25 %	100 %	
	Residential sector	76-94%	100 %	
Berdowski *et al.*, 1997 [(1)]	Domestic	60 %	100 %	

[(1)] The values refer to PM_{10} and not to TSP

Table 3.15: Uncontrolled emission factors used in the RAINS model for stationary combustion of light fuel oil (middle distillates) [kt/PJ]

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Power plants	PP_NEW	0.0004	0.0007	0.0011	0.0011	0.0022
	PP_EX	0.0007	0.0011	0.0018	0.0018	0.0036
Conversion	CON_COMB	0.0004	0.0014	0.0018	0.0018	0.0036
Industry	IN_BO, IN_OC	0.0003	0.0008	0.0011	0.0011	0.0022
Residential	DOM	0.0007	0.0002	0.0009	0.0008	0.0017

Natural Gas

Table 3.16 reviews the emission factors reported in the literature for the combustion of natural gas in stationary sources. Although there is some variation between the reported rates they are all relatively small and the overall contribution of this source to total PM is marginal. Only two studies have reported size fraction distribution (APEG, 1999; Berdowski *et al.*, 1997) and in both cases the assumption is that all particles are emitted in the $PM_{2.5}$ range. The same is assumed in the RAINS model (Table 3.17).

Table 3.16: Emission factors reported in the literature for stationary combustion of natural gas [kt/PJ].

Source	Sector	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Domestic furnaces		0.0005	0.0005
	Domestic boilers		0.0002	0.0002
	Industrial boilers		0.0001	0.0001
CEPMEIP, 2002	Residential and domestic	0.0002	0.0002	0.0002
Pfeiffer *et al.*, 2000	Residential and domestic			0.00003
UBA, 1989; UBA, 1998	All		0.000095	0.0001
EPA, 1998a	All, no control			0.0009

Table 3.17: Emission factors used in the RAINS model for stationary combustion of natural gas [kt/PJ].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Power plants	PP_NEW, PP_EX	0.0001	0	0.0001	0	0.0001
Conversion	CON_COMB	0.0001	0	0.0001	0	0.0001
Industry	IN_BO, IN_OC	0.0001	0	0.0001	0	0.0001
Residential	DOM	0.00003 -0.0002	0	0.00003-0.0002	0	0.00003-0.0002

Applicable Control Options

For the combustion of heavy and light fuel oil in industrial installations, the RAINS model foresees primary measures (regular inspection and maintenance program) and end-of-pipe options (fabric filters). For small installations in the residential and domestic sector a regular inspection program (for example, obligatory check-ups, tuning and exchange of working parts as required annually in Austria) is included.

The RAINS model does not include any control options for gas-fired installations.

3.2 Industrial Processes

A wide variety of industrial processes emit particulate matter. These emission rates vary substantially among the processes and between countries due to differences in technological development. Unfortunately, there is very little process- and country-specific information available, so the RAINS model uses, for the majority of sectors distinguished in the model, uniform unabated emission factors for all countries but the model structure allows the use of country-specific values. As in other inventories (e.g., Berdowski *et al.*, 1997; CEPMEIP, 2002), emission factors were often derived for entire industrial branches and not for specific processes.

3.2.1 Iron and Steel Industry

Iron and steel industry includes several distinct production processes/stages, i.e. sintering, blast furnace, basic oxygen furnace, electric arc furnace, open-hearth furnace, iron and steel foundries. More detailed characteristic of this industry and typical processes involved can be found, for example, in AWMA (2000), TA Luft (1986). Coke production is also included in this category since most of the coke produced (metallurgical coke) is used in this industry. The source sector split applied in RAINS for iron and steel industry is compatible with a recent UK study reviewing available process emission factors (Passant *et al.*, 2000) and other national (APEG, 1999; UBA, 1998a) or European PM inventories (Berdowski *et al.*, 1997; CEPMEIP, 2002).

According to CEPMEIP (2002), process emissions from the iron and steel industry contributed about 9 percent of TSP, 12 percent of PM_{10} and 8 percent of $PM_{2,5}$ in 1995 in Europe. The contribution varies significantly from country to country, e.g., UBA (1998a) estimates that about 16.5 percent of PM_{10} in Germany originate from this industry, while in UK its share is estimated at about 5 percent (APEG, 1999).

3.2.1.1 Coke Production

Coke is produced in ovens by pyrolysis of coal. There are a number of stages involved in coke production, i.e., crushing, screening, blending, charging and finally carbonization or coking when the coal is heated for several hours under low air conditions. After coking is completed, the coke is removed from the oven and moved to the quench tower where coke is cooled. After this, coke is transported on a conveyor for crushing and screening. All of these stages are potential sources of particulate matter (EPA, 2000; AWMA, 2000; EPA, 1998a; Passant *et al.*, 2000; TA Luft, 1986). It is estimated that about one percent of European PM and 0.8 percent of PM_{10} emissions originated from this source in 1995 (CEPEMEIP, 2002). UBA (1998a) estimated that in Germany about 0.6 and 0.8 percent of PM and PM_{10} came from coke production in 1998.

RAINS Sector:

	PR_COKE
Description	
Activity:	Coke production for use in iron and steel industry, in foundries and as smokeless fuel.
Unit:	**kg/t** coke produced.

Emission Factors

Emission factors from the literature are listed in Table 3.18. The fact that there are considerable differences between the reported values and the background information does not always allow distinguishing the processes included in the estimates and the level of emission controls that are applied to the various production stages. It is important to note that values from EPA (2000) are recalculated from the original unit, i.e., kg/t coal charge, assuming that about 1.6 tons of coal are used for the production of one ton of coke (AWMA, 2000). Also, when comparing these numbers to earlier EPA publications, i.e., EPA, 1998a, one should bear in mind that the 1998 version of AP-42 contained an error in the units in which emissions from coke production were reported, namely they were kg/t coke instead of kg/t of coal charge.

The size distribution examples given in Table 3.19 are derived from a more detailed analysis of the size fractions reported for specific processes in coke production. The size fraction analysis available in EPA (2000) is not repeated in this table but was used to derive emission factors presented in Table 3.18. However, since this information is not readily available for all processes, and size distribution varies greatly between the processes, the reported values should be used with great care. Passant *et al.* (2000) concludes that PM_{10} makes up about half of TSP, while there is more uncertainty about the share of $PM_{2.5}$.

The emissions factors used in the RAINS model (Table 3.20) are derived from EPA (2000) including the processes that are underlined in Table 3.18. It is assumed that clean water and baffles are used in quenching towers, which results in a slightly lower ‘uncontrolled’ emission rate than the ‘worst case’, i.e., dirty water and no baffles. However, recent UK (Passant *et al.*, 2000) and US experience (AWMA, 2000) indicate that this is a standard procedure at existing installations. Estimated emission factors for total PM and PM_{10} are about 5 and 3.4 kg/t, which are in reasonable agreement with other sources that report uncontrolled emissions (EEA, 1999; EPA, 1995). Emission factors for the controlled situation, cited after Passant *et al.* (2000), are based on a very similar (although slightly higher) level of unabated emissions. Assuming that nearly half of the emissions reported by UBA (1998a) is of fugitive nature (controlled with low efficiency) and the remaining part is controlled with an average efficiency of about 98 percent, the unabated factors derived in this way would be about 5.5 kg/t of coke, which is very close to the RAINS average.

Table 3.18: Emission factors reported in the literature for coke production [kg/ton coke], excluding emissions from fuel combustion.

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
UBA, 1989 (1)	Unknown controls			0.5-1.1
UBA, 1998a	Controlled		0.162	0.18
EPA, 2000 (Uncontrolled)				
Coal pre-heater		1.67	2.73	2.8
Oven charging		0.15	0.19	0.38
Oven door leaks		---	---	0.43
Oven pushing		0.16	0.40	0.93
Quenching (dirty water)		0.81	0.96	4.19
Quenching (clean water)		0.10	0.27	0.91
Quenching with baffles (dirty water)		0.21	0.34	1.04
Quenching with baffles (clean water)		0.03	0.04	0.43
EPA, 1995 (1)	Uncontrolled		2.8	
Passant *et al.*, 2000	Moderate control (3)	0.55	0.75	1.40
	Best control (3)	0.30	0.35	0.70
EEA, 1999 (2)	Uncontrolled			0.8 – 5.0
IPPC, 2000a(2)	Old plants			0.48–0.75
CEPMEIP, 2002[2]	Controlled, 'high emissions'	0.3	0.7	2.0
	Controlled, 'low emissions'	0.02	0.05	0.1
Berdowski *et al.*, 1997	Uncontrolled	0.15	0.6	

(1) Range given by the average emission factors reported for 1986 and 1966.
(2) As quoted in Passant *et al.*, 2000.
(3) Estimated on the basis of EPA data and assumes door leaks uncontrolled.

Table 3.19: Size fractions reported in the literature for coke production [percent of TSP].

Source	Installation	$PM_{2.5}$	PM_{10}	TSP
Passant *et al.*, 2000	UK coke plant, controlled		54 %	100 %
	Moderate control (2)	40 %	54 %	100 %
	Best control (2)	43 %	50 %	100 %
Berdowski *et al.*, 1997 (1)	Uncontrolled	25 %	100 %	

(1) Relates to PM_{10} and not to TSP emissions.
(2) Estimated on the basis of EPA data and assumes door leaks uncontrolled.

Table 3.20: Emission factors used in the RAINS model for coke production [kt/ton coke].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	>PM_{10}	TSP
Coke Production	PR_COKE	1.9971	1.3647	3.3618	1.6142	4.976

2 CEPMEIP (2002) reports emission factors for categories *low* to *high*, meaning low emissions (very efficient abatement) and high emissions (least efficient abatement) without specifying type of abatement or its assumed (or actual) efficiency.

Applicable Control Options

The RAINS model foresees several end-of-pipe control options for coke production, i.e., cyclones, wet scrubbers, fabric filters and three stages of electrostatic precipitators. However, oven door and battery top leaks can be a source of significant fugitive PM emissions that cannot be controlled with such end-of-pipe techniques. Adopting good operational practices to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options for this sector but allows specifying the share of total unabated emissions that belong to this category (NSC – Not Suitable for Control). The user can adjust this value in the control strategy for every five-year period. Currently, 1.6 percent is assumed for NSC to reflect the fact that some basic measures are already in place in most plants and that about 80 percent of PM emissions from oven door will be removed; this corresponds to PM emissions (NSC) of approximately 0.08 kg/t of coke.

3.2.1.2 Sinter Plants

Sinter plants convert basic raw materials (iron ore, coke, limestone, etc.) into agglomerated products (sinter, pellets) of suitable size (and with other special properties) for charging into the blast furnace. More details about the sinter process and emissions can be found in, e.g., EPA (1998a), AWMA (2000), EEA (1999), TA Luft (1986).

Sinter strand windboxes, crushing, raw material handling, belt charging and discharging from the breaker and hot screens are major sources of particulate emissions. Sinter strand windbox emissions are typically controlled by cyclones, followed by a dry or wet ESP, high pressure drop wet scrubber, or baghouse. Crusher and hot screen emissions (next largest source of PM) are usually hooded and ducted to a baghouse or scrubber. Other fugitive emissions occurring from handling and transportation of raw materials are often captured and vented to a baghouse (EPA, 1998a; Passant *et al.*, 2000). Since fugitive emissions represent a significant share of total PM from this process, RAINS distinguishes process and fugitive emissions separately. Additionally, plants where pellets are produced are treated separately in RAINS.

Based on CEPMEIP (2002) estimates, between two and three percent of European $PM_{2.5}$ and PM_{10}, respectively, originated from this source in 1995. However, there are large differences among countries, for example, UBA (1998a) estimated that sinter plants contributed about five and four percent of total TSP and PM_{10} in Germany in 1998, of which up to 75 percent were fugitive losses.

RAINS Sector:

	PR_SINT	PR_SINT_F	PR_PELL

Description

Activity: Sintering in the iron and steel industry (non-ferrous processes not included).

Unit: **kg/t** sinter (pellets) produced.

Emission Factors

Table 3.21 lists emission factors from the literature. As for other industrial processes there are considerable differences between reported numbers and it is often difficult to conclude about underlying emission controls and especially their efficiencies. Background information provided in EPA, 1998a, AWMA, 2000, and EEA, 1999 indicates that the reported emission rates for the uncontrolled situation most likely do not include fugitive losses from raw material handling, cooler and cold screen. Therefore, an attempt was made to compare these values with the non-fugitive UBA (1998a) emission factor, i.e., 0.155 kg/t. In order to derive the uncontrolled rate, an average efficiency of 98.32 % reported for baghouse (AWMA, 2000) used in sinter plant (referring to windbox and sinter discharge) was applied. This gives an emission factor of 9.23 kg/t sinter, which is close to the other studies. The TSP value used in RAINS (Table 3.23) represents an average of the studies mentioned above. The emission factor for fugitive losses was estimated on the basis of UBA (1998a). It was assumed that the removal efficiency of measures for fugitive losses varies from 20 to 70 percent and, consequently, a TSP emission factor was estimated at 1.6 kg/t. This value is in fair agreement with Jockel, 1992. For pellet plant the only available estimate (CEPMEIP, 2002) was used.

The reported size profiles (Table 3.22) often refer to the controlled situation, which is important for determining the efficiency of abatement, but are of limited use for establishing the size fraction profile for uncontrolled emission factors. It was assumed that, as long as other information is not available, the size distribution reported for windbox (EPA, 1998a; AWMA, 2000) is representative for all uncontrolled emissions from sinter plant.

Table 3.21: Emission factors reported in the literature for sinter processes [kg/ton sinter]

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a; AWMA, 2000	Uncontrolled (1)	0.65	1.92	8.96
EEA, 1999	Uncontrolled (2)			7.5
IPPC, 2000a (3)	Controlled			0.23-1.2
CEPMEIP, 2002	Controlled, high	0.5	0.8	2
	Controlled, low	0.1	0.1	0.2
CEPMEIP, 2002 [pellets]	Controlled	0.03	0.03	0.03
Jockel, 1992(4) (non-fugitive)	Controlled, ESP			0.5-0.65
(fugitive)	Uncontrolled			1.1-1.3
UBA, 1998a (non-fugitive)	Controlled, West		0.147	0.155
	Controlled, East		0.404	0.425
(fugitive)	Controlled, West		0.140	0.465
	Controlled, East		0.383	1.275
Berdowski *et al.*, 1997	Unknown	0.38	0.5	

(1) Emission factors for PM_{10} and $PM_{2.5}$ estimated from size distribution profiles for windbox (uncontrolled) and sinter discharge (controlled with baghouse)
(2) Includes sintering (4 kg/t) and cooling (3.5 kg/t)
(3) As quoted in Passant *et al.*, 2000. Range for five EU plants, geometric average 0.5 kg/t
(4) As quoted in Dreiseidler *et al.*, 1999; values originally given in kg/t ore, recalculated into kg/t sinter assuming that 0.68 to 0.85 tonnes of ore is needed for one ton of sinter.

Table 3.22: Size fractions reported in the literature for sinter processes [percent of TSP].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
Passant *et al*., 2000	Controlled		79 %	100 %
UBA, 1998a (non-fugitive)	Controlled		75 %	100 %
(fugitive)	Controlled		30 %	100 %
EPA, 1998a (windbox) [(1)]	Uncontrolled	6.5 %	15 %	100 %
	Cyclone	52 %	74 %	100 %
	Baghouse	27 %	69 %	100 %
	ESP	33 %	59 %	100 %
Berdowski *et al*., 1997 [(2)]	Unknown	75 %	100 %	

[(1)] average for PM_{10} for controlled processes is estimated at 66 percent (as quoted in Passant *et al.*, 2000).
[(2)] relates to PM_{10} and not TSP.

Table 3.23: Emission factors used in RAINS for sinter plants [kg/ton sinter (pellet)].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Sinter processes	PR_SINT	0.557	0.728	1.285	7.278	8.563
Sinter fugitive	PR_SINT_F	0.104	0.136	0.24	1.36	1.6
Pellet plant	PR_PELL	0.03	0	0.03	0	0.03

Applicable Control Options

The RAINS model includes for sinter plants (PR_SINT) three major categories of end-of-pipe abatement, i.e., a cyclone, three stages of electrostatic precipitators and fabric filters. However, similar to the other iron and steel sectors, fugitive emissions contribute a significant portion of total PM (PR_SINT_F). Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, the RAINS model includes two such options (low and high efficiency) and also allows specifying the share of total capacity that cannot be controlled at all (“not suitable for control” - NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.1.3 Pig Iron Production (Blast Furnace)

Iron is produced in blast furnaces by the reduction of iron-bearing materials with hot gas. The furnace is charged through its top with iron ore, pellets/sinter, flux (limestone, dolomite, sinter) and coke for fuel. The resulting molten iron and slag are removed, or cast, from the furnace periodically and the byproduct gas is collected and recovered for use as fuel (EPA, 1998a). A detailed description of these processes is outside the scope of this report. Instead, the reader is referred to, for example, AWMA, 2000; EPA, 1998a; TA Luft (1986) for more information.

The primary source of particulate emissions is the casting operation, blast furnace top, hot metal desulphurization and further hot metal transport. Occasionally, a cavity may form in the blast furnace charge leading to a pressure surge in the furnace and opening of the relief valve to the atmosphere. Particulate emissions occurring during this event, referred to as ‘slip’, may be relatively large, i.e., EPA (1998a) gives 39.5 kg/t slip. However, this does not occur very often and Passant *et al.* (2000) estimated that this equates to a total PM factor of approximately 0.002 kg/t pig iron.

Based on CEPMEIP (2002), slightly more than one percent of European PM (as well as PM_{10} and $PM_{2.5}$) originated from this source in 1995. The share varies significantly among countries depending on the structure of industrial production and level of abatement, e.g., UBA (1998a) estimated that about eight percent of total PM and nearly seven percent of PM_{10} emissions in Germany came from this sector in 1998.

RAINS Sector:

Description	PR_PIGI	PR_PIGI_F
Activity:	Production of pig iron	
Unit:	**kg/t** pig iron.	

Emission Factor

Table 3.24 lists emission factors from the literature. There seems to be quite good agreement between unabated emission factors reported by Rentz *et al.* (1996), EPA (1998a) and CEPMEIP (2002). In all cases it is assumed that blast furnace gas is cleaned. Total particulates emissions based on EPA (1998a) lay in the range 1 – 1.4 kg/t pig iron (about half are fugitive), CEPMEIP (2002) uses 2 kg/t in a 'high emission' scenario, and Rentz *et al.* (1996) about 1-2 kg/t (excluding fugitive emissions of 1 kg/t). For controlled installations, CEPMEIP assumes ('low emission' scenario) an emission factor of 0.04 kg/t (after IPPC, 2000a), which indicates a reduction efficiency of 98 percent. Applying this efficiency to emission rates reported by UBA (1998a) results in a very large unabated emission factor (about 12-24 kg/t), which can only be compared to values for raw blast furnace gas, see for example Rentz *et* al., 1996. This might either indicate that, indeed, emissions from blast furnace gas are included in the UBA (1998a) estimates or that the ratio between fugitive and non-fugitive emissions is inappropriate. It is more difficult to assess fugitive emissions, although the studies listed indicate that they are probably around 1-3 kg/t. The comparison is also affected by lack of (or limited) information on how and to what extent these fugitive losses are included in single studies. In the case of the CEPMEIP (2002) study, all fugitive losses from the iron and steel industry are included in a separate category "Hot metal transport". In RAINS, the fugitive losses are distinguished as separate sectors linked to specific processes in this industry.

For pig iron production, the RAINS emission rate for fugitive losses (PR_PIGI_F) is based on the values reported by Rentz *et al.* (1996) and UBA (1998a). The latter inventory reports controlled emissions but if it is assumed that the average removal efficiency of controls for fugitive losses varies between 20 and 70 percent, the unabated emission rate would be in the range of 1.8 to 2.5 kg/t. The resulting average emission rate for total particulates is estimated at 1.77 kg/t pig iron. However, owing to the uncertainty of the fugitive/non-fugitive ratio used in UBA (1998a) (see also discussion above), the upper bound was taken as the RAINS emission factor, i.e., 2.5 kg/t (Table 3.25). For non-fugitive emissions (PR_PIGI), the RAINS emission factor is estimated as the average of Rentz *et al.* (1996), EPA (1998a) and CEPMEIP (2002) (Table 3.25). It must be kept in mind that these (both fugitive and non-fugitive) are only theoretical values, since the emissions from several of the processes, even at older plants, are usually controlled.

Similar to other iron and steel sectors, information on the size distribution of PM emissions is very scarce and most studies refer to size profiles provided by EPA (1998a). To derive RAINS emission factors for PM_{10} and $PM_{2.5}$ (Table 3.25), EPA (1998a) size fractions for "furnace with local evacuation' and 'hot metal desulphurization' were used for non-fugitive and fugitive emissions, respectively.

Table 3.24: Emission factors reported in the literature for pig iron production [kg/ton pig iron].

Literature source	Abatement	$PM_{2.5}$	PM_{10}	TSP
BUWAL 1995	Controlled			1.3
UBA, 1989 [(1)]	Unknown			1.8 – 4.5
Rentz, *at al.*, 1996 (Blast furnace) [(2)]	Uncontrolled			1 - 2
(Casting bay area)	Uncontrolled			1
UBA, 1998a (non-fugitive)	Controlled, West		0.2375	0.25
	Controlled, East		0.4513	0.475
(fugitive)	Controlled, West		0.2250	0.75
	Controlled, East		0.4276	1.425
EPA, 1998a	Uncontrolled			
Slip		n.a.	n.a.	39.5 [(3)]
Cast house (older type)		0.07	0.15	0.3
Furnace with local evacuation		0.10	0.16	0.65
Taphole and trough only		n.a.	n.a.	0.15
Hot metal desulfurization		0.06	0.10	0.55
CEPMEIP, 2002	Controlled, 'high'	0.5	1.0	2.0
	Controlled, 'low'	0.036	0.038	0.040
Berdowski *et al.*, 1997	Unknown	0.1	0.2	

(1) Range given by the average emission factors reported for 1986 and 1966.
(2) Assuming that blast furnace gas is cleaned
(3) The value is given in kg/t slip. According to Passant *et al.* (2000) the overall contribution to emissions is small, with an estimated total particulate emission factor of 0.002 kg/t pig iron.

Table 3.25: Emission factors used in RAINS model for pig iron production [kg/ton pig iron].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Pig iron production	PR_PIGI	0.15	0.09	0.24	1.24	1.48
Pig iron production (fugitive)	PR_PIGI_F	0.15	0.1	0.25	2.25	2.5

Applicable Control Options

The RAINS model includes cyclones, wet scrubbers and three stages of electrostatic precipitators as end-of-pipe control options for pig iron production (PR_PIGI). Similar to other iron and steel processes, the issue of fugitive emissions is potentially very important and therefore RAINS distinguishes a separate sector (PR_PIGI_F). Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, the RAINS model includes two such options (low and high efficiency) and also allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" - NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.1.4 Open-Hearth Furnace

Scrap and molten iron are melted and refined into steel in the open-hearth furnace. The mixture of scrap and pig iron can vary but a half-and-half mixture is most common. Most furnaces are equipped with oxygen lances to accelerate melting and refining. The steel product is tapped by opening a hole in the base of the furnace with an explosive charge. More details on the process can be found in, for example, EPA (1998a).

Several factors affect particulate emissions from open-hearth furnaces, e.g., use of oxygen lancing increases emissions of dust. Significant fugitive emissions may occur during other furnace-related operations, i.e., transfer and charging of pig iron, charging of scrap, tapping, and slag dumping (EPA, 1998a). Emissions from the furnace are usually ducted to control equipment, typically ESP or wet scrubber. Fugitive emissions from operations listed above remain uncontrolled.

Production of steel in open-hearth furnaces has declined dramatically over recent decades and this method is not used any more in Western Europe and US. Only a handful of Eastern European countries have this type of furnace in operation. More than 90 percent of production in 1995 occurred in Russia and Ukraine, the rest in Romania, Poland and Latvia. Based on CEPMEIP (2002) slightly more than 1 percent of European PM originated from this source in 1995. Of course, in Russia and Ukraine the contribution was significantly larger, i.e., 2.5 and 3.5 percent, respectively.

RAINS Sector:

PR_HEARTH

Description

Activity: Steel production in open-hearth furnace

Unit: **kg/t** steel produced.

Emission Factor

Very few emission factors were found for this source (Table 3.26). In fact, Berdowski *et al.* (1997) adapted EPA emission factors from an earlier edition of AP-42 (EPA, 1995) using unabated PM_{10} values for Eastern Europe and abated for Western Europe but assuming a different size fraction distribution than EPA (1998a). It seems likely that fugitive losses are not included in EPA (1998a); the emission factor in Table 3.26 refers to melting and refining processes. However, no estimates of fugitive losses were found and RAINS uses emission factors directly from EPA (1998a) (Table 3.27).

Table 3.26: Emission factors reported in the literature for open-hearth furnace [kg/ton steel].

Literature source	Abatement	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled	6.33	8.76	10.55
Berdowski *et al*., 1997	Uncontrolled (Eastern Europe)	4.4	8.8	
	Controlled (ESP) (Western Europe)	0.035	0.07	

Table 3.27: Emission factors used in the RAINS model for open hearth furnace [kg/ton steel].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Open-hearth furnace	PR_HEARTH	6.33	2.43	8.76	1.79	10.55

Applicable Control Options

The RAINS model foresees several end-of-pipe control options for open-hearth furnace, i.e., cyclones, wet scrubbers, fabric filters and three stages of electrostatic precipitators. However, some of the fugitive PM sources cannot be controlled with such end-of-pipe techniques. Adopting good operational practices to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options for this sector but allows specifying the share of total unabated emissions that belong to this category (NSC – Not Suitable for Control). The user can adjust this value in the control strategy for every five-year period.

3.2.1.5 Basic Oxygen Furnace

The basic oxygen process now accounts for most steel-making capacity worldwide. It was developed in Linz-Donawitz, Austria, in the 1950s and is a variation of the older Bessemer process. Molten iron from a blast furnace (about 70%) and iron scrap (about 30%) are refined in a basic oxygen furnace by lancing (or injecting) high-purity oxygen, which oxidizes the carbon and the silicon in the molten iron, removes these products, and provides heat for melting the scrap. Three types of furnaces are currently in use, i.e. top-blown, bottom-blown (called also Quelle process), and combined-blown (about 30 percent of the oxygen is blown through the bottom). More details on the process can be found in, for example, EPA (1998a), AWMA (2000), TA Luft (1986).

The largest emissions from this process occur during the oxygen blow period while several other operations, e.g., charging, tapping, hot metal transfer, etc., will result in fugitive emissions (EPA, 1998a; AWMA, 2000; TA Luft, 1986). Emissions from the furnace can be successfully reduced typically by applying wet scrubbers or ESP (efficiencies above 99 percent are achieved). Fugitive emissions can be reduced by the use of furnace enclosure, local hoods, and partial or full building evacuation. Typical modern installations will be equipped with furnace enclosure (at least partial), several hoods, and at least partial building evacuation.

Based on CEPMEIP (2002), about one percent of European PM originated from this source in 1995. The share varies significantly among countries, e.g., UBA (1998a) estimated that about 1.5 percent of total PM and more than two percent of PM_{10} emissions in Germany came from this sector in 1998.

RAINS Sector:

PR_BAOX

Description

Activity: Steel production in basic oxygen furnace

Unit: **kg/t** steel produced.

Emission Factor

The emission factors found in the literature are listed in Table 3.28. There are considerable differences between the studies (or even within one study, i.e., Rentz *et al.*, 1996) and the available background information (especially on the level of control and processes included) is often insufficient to explain the factors given.

In order to derive emission factors for the RAINS model, UBA (1998a), Rentz *et al.* (1996), EPA (1998a), and Jockel (1992) were used. All four studies seem to confirm the range of fugitive emissions given by Rentz *et al.* (1996). It is assumed that the actual fugitive emissions from this source are about 0.3 kg/t, since EPA (1998a) data on measurements at roof monitors indicate a reduction of about 70 percent of fugitive emissions. The non-fugitive emissions vary between about 4 and 42 kg/t (Table 3.28). Recalculating UBA (1998a) values into uncontrolled coefficients, assuming a control efficiency between 99 and 99.5 percent, results in a range 16.5 – 33 kg/t. Taking an average from UBA (1998a), Rentz *et al.* (1996) and EPA (1998a) results in about 20.6 kg/t; adding the fugitive component gives an estimated total PM emission factor of 20.9 kg/t steel produced in basic oxygen furnace (Table 3.29).

Table 3.28: Emission factors reported in the literature for basic oxygen furnace [kg/steel]

Literature source	Abatement	$PM_{2.5}$	PM_{10}	TSP
UBA, 1989 [(1)]	Unknown			0.28 – 2.6
Jockel, 1992 (non-fugitive)	Unknown			0.06
(fugitive)	Unknown			0.49
Rentz, *at al.*, 1996 (Furnace)	Uncontrolled			3.75 - 41.75
(Charging)	Uncontrolled			0.5 - 1
UBA, 1998a	Controlled		0.1485	0.165
EPA, 1998a	Uncontrolled			
Top blown (melting and refining)		n.a.	n.a.	14.25
Charging (at source) [(2)]		0.1	0.2	0.43
Tapping (at source)		0.17	0.21	0.46
Hot metal transfer [(2)]		n.a.	n.a.	0.14
CEPMEIP, 2002	Controlled, 'high'	0.54	0.57	0.6
	Controlled, 'low'	0.12	0.12	0.12
ER, 1996	Controlled	0.055	0.11	
Berdowski *et al.*, 1997	Unknown	0.1	0.2	

[(1)] Range given by the average emission factors for iron and steel manufacturing in 1986 and 1966

[(2)] EPA (1998a) gives this factor in kg/ton of pig iron; here it is converted to kg/t steel assuming 0.7 t pig iron/t steel.

Information on the size distribution of PM emissions from this source is given only in EPA, 1998a. However, the information for the largest single component (oxygen blow) is missing and therefore the share of PM_{10} was estimated by recalculating the PM_{10} emission factor given by UBA (1998a). It was done assuming that a reduction efficiency of about 99 percent is achieved, leading to an unabated emission factor of about 15 kg/t (slightly above 70 percent of TSP). A size fraction of 70 percent is taken for PM_{10} with 50 percent being assumed for $PM_{2.5}$.

Table 3.29: Emission factors used in the RAINS model for basic oxygen furnace [kg/ton steel].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Basic oxygen furnace	PR_BAOX	10.45	4.18	14.63	6.27	20.9

Applicable Control Options

The RAINS model foresees several end-of-pipe control options for basic oxygen furnace, i.e., wet scrubbers, fabric filters and three stages of electrostatic precipitators. However, some of the fugitive PM sources cannot be controlled with such end-of-pipe techniques. Adopting good operational practices to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options for this sector but allows specifying the share of total unabated emissions that belong to this category (NSC – Not Suitable for Control). The user can adjust this value in the control strategy for every five-year period. Currently, 1.5 percent is assumed for NSC to reflect the fact that some basic measures are already in place in most plants and that about 70 percent of fugitive emissions are removed; this corresponds to PM emissions (NSC) of approximately 0.3 kg/t of steel.

3.2.1.6 Electric Arc Furnace

Electric arc furnaces are the primary means of recycling steel scrap into liquid steel. The technology associated with this process is developing rapidly and so the share of raw steel produced in these furnaces is growing. Electric arc furnaces are used to produce carbon and alloy steels. The production of steel is a batch process, including typically the following stages: charging and melting, refining (usually includes oxygen blowing), and tapping. More details on the process can be found in, for example, EPA (1998a), AWMA (2000), TA Luft (1986).

Emissions of particulate matter occur at all three production stages but melting and refining contribute most (EPA, 1998a; AWMA, 2000; TA Luft, 1986). Emissions from this process can be controlled by building an emission capture system and a gas cleaning system. Several types of emission capture systems are used in the industry, i.e., direct evacuation, side draft hood, combination hood, canopy hood, and furnace enclosure. The fumes collected are cleaned in fabric filters. As an alternative to the baghouse emission control system, scrubbers are still in use in rare cases today. However, high operating costs and relatively low efficiencies of these systems make them unattractive (AWMA, 2000).

Based on CEPMEIP (2002), less than 0.5 percent of European PM originated from this source in 1995. The share varies among countries, e.g., UBA (1998a) estimated that about 0.7 percent of total PM and more than one percent of PM_{10} emissions in Germany came from this sector in 1998.

RAINS Sector:

PR_EARC

Description

Activity: Steel production in electric arc furnaces.

Unit: **kg/t** steel produced.

Emission Factor

The emission factors found in the literature are listed in Table 3.30. There are considerable differences between the studies reporting uncontrolled and controlled emission rates. The available background information (especially on the level of control and processes included) is often insufficient to explain the factors given. Owing to typically high reduction efficiency achieved, the variation in values for controlled installations is smaller and they indicate an average particulate removal efficiency between 98 and 99 percent. Plants with well-designed and maintained bag filters can achieve PM emissions even below 20 g/t steel (IPPC, 2000a; Passant *et al.*, 2000).

In order to derive emission factors for the RAINS model some of the abated factors (e.g., UBA, 1998a; BUWAL, 1995; Rentz *et al.,* 1996) were first recalculated using average abatement efficiency as indicated above, and then compared to the reported values for uncontrolled plants (e.g., EPA, 1998a; Rentz *et al.*, 1996; BUWAL, 1995). An average PM emission factor of about 23.4 kg/t steel was estimated, assuming no controls on fugitive emissions. However, most electric arc furnaces are relatively modern installations and at least moderate fugitive emission control systems are assumed to be part of any plant; correcting the 'unabated' factors accordingly results in an average emission factor for particulates of 17.55 kg/t steel. Therefore, typical abated emission rates will be in the range 0.17-0.35 kg/t steel, which compares well with the actual emission rates reported (Table 3.30).

Specific information on the size distribution of PM emissions from this source is given only in EPA, 1998a (Table 3.31). For comparison, CEPMEIP (2002) emission factors were used to show shares of PM_{10} and $PM_{2.5}$ as assumed in that inventory. Comparing EPA (controlled profile) and CEPMEIP (low scenario) reveals significant differences but lack of background information does not allow a satisfactory explanation. Since a typical plant is assumed to include moderate control of fugitive emissions, the primary sources of PM will be melting and refining operations; therefore, the EPA (1998a) size distribution (uncontrolled profile) was used to derive PM_{10} and $PM_{2.5}$ factors in RAINS (Table 3.32).

Table 3.30: Emission factors reported in the literature for electric arc furnace [kg/ton steel].

Literature source	Abatement (source)	$PM_{2.5}$	PM_{10}	TSP
BUWAL 1995	Controlled (non-fugitive)			0.14
	Uncontrolled (fugitive)			13.0
	Controlled (fugitive)			1.2
IPPC, 2000a [(1)]	Controlled			0.124±0.17
UBA, 1998a	Controlled		0.252	0.28
Jockel, 1992	Controlled (non-fugitive)			0.26
	Controlled (fugitive)			0.2
ER, 1996 [(2)]	Controlled	0.26	0.46	
EPA, 1998a	Uncontrolled			
Melting and refining – carbon steel		8.17	11.02	19.0
Melting, refining, charging, tapping, slagging – alloy steel				5.65
Melting, refining, charging, tapping, slagging – carbon steel				25.0
Rentz *et al.*, 1996	Uncontrolled			2.7-10.4
	Controlled			0.009-0.17
	Controlled (fugitive)			0.05-0.26
CEPMEIP, 2002	Controlled, "high"	0.224	0.56	0.7
	Controlled, "low"	0.06	0.095	0.1
Berdowski *et al.*, 1997	Controlled (Western Europe)	0.228	0.4	
	Uncontrolled (Eastern Europe)	5.5	11.0	

(1) as quoted in Passant *et al.*, 2000; average for 34 EU plants
(2) as quoted in Berdowski *et al.*, 1997.

Table 3.31: Size fractions reported in the literature for electric arc furnace [percent of TSP].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a				
Melting and refining – C steel (uncontrolled)		43 %	58 %	100 %
Melting, refining, charging, tapping, slagging – C steel (controlled)		74 %	76 %	100 %
CEPMEIP, 2002	Controlled, "high"	32 %	80 %	100 %
	Controlled, "low"	60 %	95 %	100 %

Table 3.32: Uncontrolled emission factors used in RAINS for electric arc furnace [kg/ton steel].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Electric arc furnace	PR_EARC	7.55	2.63	10.18	7.37	17.55

Applicable Control Options

The RAINS model foresees two major control options for electric arc furnaces, i.e., wet scrubbers and fabric filters. At this stage, the RAINS model does not include options for further control of fugitive losses but allows specifying the share of total unabated emissions that belong to this category (NSC – Not Suitable for Control). The user can adjust this value in the control strategy for every five-year period.

3.2.1.7 Iron and Steel Foundries

Major processes in iron and steel foundries include: raw material handling and preparation, melting and refining, desulphurization of molten iron, slag removal, mould and core production, casting and finishing (Passant *et al.*, 2000). The largest emissions of particulate matter occur typically from metal melting and refining (cupola and electric arc furnaces) and casting and finishing. More details on the process can be found in, for example, EPA (1998a), AWMA (2000), TA Luft (1986).

Based on CEPMEIP (2002), only about 0.2 percent of European PM originated from this source in 1995. The share varies significantly among countries, e.g., UBA (1998a) estimated that about 1.6 percent of total PM and 1.3 percent of PM_{10} emissions in Germany came from this sector in 1998. CEPMEIP (2002) results for Germany confirm UBA (1998a) estimates.

RAINS Sector:

	PR_CAST	PR_CAST_F

Description

Activity:	Iron and steel production in foundries.
Unit:	**kg/t** cast iron.

Emission Factor

The emission factors found in the literature are listed in Table 3.33. There are considerable differences between the studies reporting uncontrolled and controlled emission rates. The available background information (especially on the level of control and processes included) is often insufficient to explain the differences.

Emission factors used in the RAINS model are derived on the basis of information found in reports of UBA (1998a) and EPA (1998a). The abated emission rates were recalculated assuming that the average reduction efficiency in this sector lies between 96 and 98 percent (for melting, EPA, 1998a). It was concluded that an average PM emission factor is about 20.8 kg/t iron, of which 5.75 kg/t originates from fugitive sources (assuming very basic controls on fugitive emissions). Therefore, a typical abated emission rate will be between 1.7 and 4.5 kg/t iron, depending on the level of control. This compares well with the actual reported emission rates, e.g., CEPMEIP (2002), UBA (1998a), with the exception of BUWAL (1995) where overall emissions seem to be in the order of 0.5-0.6 kg/t.

Specific information on the size distribution of PM emissions from this source is given only in EPA, 1998a (Table 3.34). For comparison, CEPMEIP (2002) emission factors were used to show shares of PM_{10} and $PM_{2.5}$ as assumed in that inventory. It is surprising that the share of $PM_{2.5}$ and PM_{10} assumed in CEPMEIP is so low, in fact even lower than in EPA profiles for uncontrolled fugitive sources. In order to derive RAINS emission factors (Table 3.35) EPA (1998a) profiles were applied; the average of cupola and electric arc furnace was used for non-fugitive emissions while the size distribution from pouring and cooling was used for fugitive sources.

Table 3.33: Emission factors reported in the literature for iron foundries [kg/ton iron].

Literature source	Abatement (source)	$PM_{2.5}$	PM_{10}	TSP
BUWAL 1995	Unknown (fugitive)			0.5
	Controlled (cupola – electric arc furnace)			0.01-0.04
UBA, 1998a	Controlled (non-fugitive), West		0.435	0.4575
	Controlled (fugitive), West		0.412	1.3725
	Controlled (non-fugitive), East		0.594	0.6250
	Controlled (fugitive), East		0.563	1.8750
EPA, 1998a (uncontrolled)	Cupola furnace	5.8	6.2	6.9
	Electric arc furnace	4.0	5.8	6.3
	Refining			1.5-2.5
	Cleaning, finishing			8.5
	Other (1)			6.6
(controlled)	Cupola furnace			0.3-4
	Electric arc furnace			0.1-0.5
CEPMEIP, 2002	Controlled	0.09	0.6	2

(1) Includes: reverberatory, scrap and charge handling, heating, magnesium treatment, pouring, cooling, shakeout, core making, baking.

Table 3.34: Size fractions reported in the literature for iron foundries [percent of TSP].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a				
Cupola furnace (uncontrolled)		84 %	90.1 %	100 %
Cupola furnace (controlled – baghouse)		94.9 %	94.9 %	100 %
Cupola furnace (controlled – venturi scrubber)		77.7 %	77.7 %	100 %
Electric arc furnace (uncontrolled)		57.5 % (1)	90 %	100 %
Pouring, cooling (uncontrolled)		24 %	49 %	100 %
Shakeout (uncontrolled)		42 %	70 %	100 %
CEPMEIP, 2002	Controlled	4.5 %	30 %	100 %

(1) Data for PM_2

Table 3.35: Unabated emission factors used in RAINS for iron foundries [kg/ton iron].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Iron foundries	PR_CAST	10.68	2.87	13.55	1.50	15.05
Iron foundries (fugitive)	PR_CAST_F	1.38	1.44	2.82	2.93	5.75

Applicable Control Options

The RAINS model includes wet scrubbers and fabric filters as control options for iron foundries (PR_CAST). Recognizing that a large share of total emissions is of fugitive nature, a separate category is included, i.e., PR_CAST_F. Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, the RAINS model includes two such options (low and high efficiency) and also allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" - NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.2 *Non-ferrous Metals Industry*

This category includes production of primary and secondary aluminum, copper, lead, zinc, and primary production of nickel. The contribution of these industries to particulate emissions in Europe is estimated at about 0.5-1 percent with the majority originating from primary aluminum production (CEPMEIP, 2002; UBA, 1998a), although the emission structure varies among countries.

The RAINS model distinguishes for this industry three sectors representing production of primary and secondary aluminum and other non-ferrous metals.

3.2.2.1 Primary Aluminum Production

Aluminum is produced from electrolytic reduction of alumina using the Hall-Heroult process. Details of this process can be found in e.g., AWMA, 2000; EPA, 1998a, EEA, 1999; TA Luft, 1986; and Passant *et al.*, 2000. The main sources of emissions include baking of the pre-baked carbon anodes, electrolytic process, tapping and casting of the aluminum product.

This activity is estimated to contribute below 0.5 percent to the total European PM emissions (CEPMEIP, 2002). UBA (1998a) assessed its contribution to total particulates and PM_{10} emissions in Germany at about 0.5 and 0.8 percent, respectively.

RAINS Sector:

PR_ALPRIM

Description

Activity: Primary aluminum production
(production of aluminum from bauxite not included).

Unit: **kg/t** aluminum produced.

Emission Factors

Table 3.36 presents emission rates reported in the literature. The analysis of these numbers shows that a controlled level of PM emissions for a primary aluminum plant varies between less than 1 kg/t to 10 kg/t depending on the type of process involved and level of control, although the latter is often difficult to determine on the basis of available background documentation. Average PM emission rates for Swiss, UK and German plants are 1.65, 2.8 and 3.3 kg/t (BUWAL, 1995; Passant *et al.*, 2000; UBA, 1998a). A large proportion of these emissions might be fugitive (Passant *et al.,* 2000).

The RAINS uncontrolled emission factor (Table 3.38) is based on the EPA (1998a) data for prebake cells. It is assumed that this type of plant is more common[3] than others. Taking this uncontrolled emission rate and applying abatement technology with particulate removal efficiency of 98 to 99.5 percent, as well as assuming that fugitive losses represent in abated

[3] In fact an average derived from all three types (prebake, vertical and horizontal Soderberg cells) is about the same as the overall emission rate for prebake cells.

emissions about 1.25 to 2.5 kg/t, results in an emission rate between 1.5 and 3.4 kg/t, which is consistent with values reported for the UK and Germany. The size-specific emission rates are derived from EPA (1998a) profiles (Table 3.37).

Table 3.36: Emission factors reported in the literature for primary aluminum production [kg/ton aluminum produced].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 1995	Unknown			1.65
Passant *et al*, 2000	Controlled, average for UK plants (pre-baked anodes)			2.8 [1]
IPPC, 2000b	Controlled, prebake cells			0.5-7
	Controlled, vertical stud Soderberg			1.5-10
EPA, 1998a, Uncontrolled	Prebake cells	13.16	27.26	47.0
	Prebake cells, fugitive only	0.70	1.45	2.5
	Vertical stud Soderberg			39.0
	Vertical stud Soderberg, fugitive only			6.0
	Horizontal stud Soderberg	8.33	15.19	49.0
	Horizontal stud Soderberg, fugitive only	0.85	1.55	5.0
UBA, 1989 [2]	Unknown			6-30
UBA, 1998a	Abated		3.135	3.3
CEPMEIP, 2002	Abated, 'high'	2.5	6	10
	Abated, 'low'	1.28	2.85	3
Berdowski *et al.*, 1997	Unknown, Western Europe	1.4	3	
	Unknown, Eastern Europe	3.2	7	

(1) Passant *et al.* (2000) estimates that about 2/3 of the emissions are fugitives.
(2) The range reflects an average emission factor in 1986 and 1966.

Table 3.37: Size fractions reported in the literature for primary aluminum production [percent].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a; AWMA, 2000; uncontrolled	Prebake cells, fugitive	28 %	58 %	100%
	Horizontal stud Soderberg,	40 %	58 %	100%
	Horizontal stud Soderberg, fugitive	17 %	31 %	100%
Berdowski *et al.*, 1997 [1]	Unknown	45 %	100 %	

(1) relates to PM_{10} and not to TSP.

Table 3.38: Emission factors used in the RAINS model for primary aluminum production [kg/ton aluminum].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Aluminum production	PR_ALPRIM	18.5	8.76	27.26	19.74	47.00

Applicable Control Options

The RAINS model includes end-of-pipe control options for aluminum production plants (fabric filters and three stages of electrostatic precipitators) that are typically used in this industry (Passant *et al.*, 2000; AWMA, 2000; UBA, 1998a). As discussed previously, the fugitive emissions contribute a significant portion of total PM. At this stage, however, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). It is currently assumed that NSC is equal to about 5.6 and 2.8 percent for basic and best fugitive controls, respectively. The user can adjust this value in the control strategy for every five-year period.

3.2.2.2 Secondary Aluminum Production

Scrap containing aluminum is converted into aluminum metal. Major production steps involve pre-treatment (sorting, processing, cleaning), smelting, refining, alloying, and pouring. Details of this process can be found in e.g., AWMA, 2000; EPA, 1998a, EEA, 1999; TA Luft, 1986; and Passant *et al.*, 2000. The largest sources of particulate emissions include smelting and processing of scrap.

It is a minor PM emission source from the European perspective, i.e., CEPMEIP (2002) estimated its share at about 0.02 percent. It might be slightly more relevant for some countries, e.g., in Germany about 0.1 and 0.2 percent of TSP and PM_{10} originated from this source in 1996 (UBA, 1998a).

RAINS Sector: PR_ALSEC

Description

Activity: Secondary aluminum production

Unit: **kg/t** aluminum produced.

Emission Factors

Table 3.39 presents emission rates reported in the literature. The analysis of these numbers shows that a controlled level of PM emissions for current secondary aluminum plants varies between 0.9 and 2 kg/t of aluminum. Average PM emission rates for UK and German plants are 1.6 and 1.2 kg/t (Passant *et al.*, 2000; UBA, 1998a). A large proportion of these emissions might be fugitive (Passant *et al.,* 2000; AWMA, 2000).

The RAINS uncontrolled emission factor (Table 3.41) is based on the EPA (1998a) data for uncontrolled installations (summing up all the processes). Taking this uncontrolled emission rate and applying abatement technology with particulate removal efficiency of 98 to 99.5 percent, as well as assuming that fugitive losses represent in abated emissions about 0.9-1.4 kg/t, results in an emission rate between 0.96 and 1.6 kg/t, which is consistent with values reported for the UK and Germany. The size-specific emission rates are derived from EPA (1998a) profiles (Table 3.40) taking into account the relative shares of the various individual processes in the total emission rate.

Table 3.39: Emission factors reported in the literature for secondary aluminum production [kg/t]

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 1995	Unknown			0.9
Passant *et al*, 2000	Abated (all)			1.6 [(1)]
EPA, 1998a	Unabated, sweating furnace			7.25
	Unabated, reverberatory	1.08	1.3	2.15
	Unabated, demagging	0.5	1.33	2.5
	Abated (baghouse), sweating furnace			1.65
	Abated (baghouse), reverberatory			0.65
	Abated (baghouse), demagging			0.125
UBA, 1989 [(2)]	Unknown			1.7-7.5
UBA, 1998a	Abated, West		1.09	1.15
	Abated, East		1.71	1.8
CEPMEIP, 2002	Abated, 'high'	0.55	1.4	2
	Abated, 'low'	0.405	0.9	1

[(1)] Based on EPA (1998a) but he suggests that abated (baghouse) emissions from sweating furnace are more likely half of the EPA value, therefore his total is 1.6 kg/t instead of 2.425 kg/t as EPA indicates.
[(2)] The range reflects an average emission factor in 1986 and 1966.

Table 3.40: Size fractions reported in the literature for secondary aluminum production [%TSP].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled, refining - reverberatory	50 %	60 %	100 %
	Uncontrolled, chlorine demagging	19.8 %	53.2 %	100 %
TÜV, 2000a	Controlled (fabric filter), smelting	75 %	99 %	100 %

Table 3.41: Emission factors used in the RAINS model for secondary aluminum production [kg/ton aluminum].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Aluminum production	PR_ALSEC	5.195	1.775	6.97	4.93	11.9

Applicable Control Options

The RAINS model includes end-of-pipe control options for secondary aluminum production plants (fabric filters and wet scrubbers) that are typically used in this industry (Passant *et al.*, 2000; AWMA, 2000; UBA, 1998a). As already mentioned above, the fugitive emissions contribute a significant portion of total PM. At this stage, however, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). It is currently assumed that NSC is equal to about 12 and 7.5 percent for basic and best fugitive controls, respectively. The user can adjust this value in the control strategy for every five-year period.

3.2.2.3 Other Non-ferrous Metals Production

This sector includes production of primary and secondary copper, lead, zinc, and primary production of nickel. Details of the production processes can be found in e.g., AWMA, 2000; EPA, 1998a, EEA, 1999; TA Luft, 1986; and Passant *et al.*, 2000.

It is a minor source of PM emissions, i.e., the contribution of these industries to particulate emissions in Europe is estimated at only 0.1 percent (CEPMEIP, 2002; UBA, 1998a). Therefore, in spite of the certain inhomogeneity in emission characteristics, all of these industries are included in one category.

RAINS Sector:

PR_OT_NFME

Description

Activity: Production of primary and secondary copper, lead, zinc, and primary production of nickel

Unit: **kg/t** produced metals.

Emission Factors

An overview of emission factors available from the literature is presented in Table 3.42 and Table 3.43. The discrepancies between uncontrolled emission rates for specific processes are very large and therefore it was decided to present only abated values and, on that basis, derive an average emission factor that can be further used to estimate an uncontrolled value for this aggregated sector. An analysis of the data reveals that, for most of the processes included, the abated emission factor is in the range of 0.1-0.4 kg/t of metal. Assuming that a typical PM removal efficiency lies between 97.5 and 99.5 percent and that basic good housekeeping options are in place, the unabated emission factor was estimated at about 15 kg/t of metal produced. In order to derive size-specific rates (Table 3.45), generalized size profiles available from EPA (1998a) were used (Table 3.44).

Table 3.42: Emission factors reported in the literature for lead and zinc production [kg/t].

Source	Process (all abated)	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 1995	All metals			0.27
Lead				
Passant *et al*, 2000	Primary		0.72	0.8
	Secondary		0.16	
EPA, 1998a	Primary			~ 0.5
	Secondary			~ 1
UBA, 1989 [1]	Not specified			0.2-3.2
UBA, 1998a	Not specified		0.11	0.12
EEA, 1999	Secondary			0.1-0.77
IPPC, 2000b	Primary			0.06-0.18
	Secondary			< 0.05
CEPMEIP, 2002	'High', primary/secondary	0.6/0.4	3/0.7	10/1
	'Low', primary/secondary	0.06/0.15	0.11/0.29	0.12/0.3
Zinc [2]				
UBA, 1989 [1]	Not-specified			0.33-9
UBA, 1998a	Not specified		0.13	0.14
CEPMEIP, 2002	'High', primary/secondary	4/0.3	5/0.4	6/0.5
	'Low', primary/secondary	0.16/0.3	0.18/0.4	0.2/0.5

(1) The range reflects an average emission factor in 1986 and 1966

(2) For primary zinc Passant *et al.* (2000), IPPC (2000b), and EPA (1998a) report the same values as for primary lead.

Table 3.43: Emission factors reported in the literature for copper and nickel production [kg/t].

Source	Process (all abated)	$PM_{2.5}$	PM_{10}	TSP
Copper				
UBA, 1989 [1]	Not specified			0.39-10.5
UBA, 1998a	Not specified		0.13	0.14
IPPC, 2000b	Secondary			0.1-1
CEPMEIP, 2002	'High', primary/secondary	1/0.6	3/0.8	10/1
	'Low', primary/secondary	0.4/0.6	0.475/0.8	0.5/1
Nickel				
CEPMEIP, 2002	'High', primary	3	6	10
	'Low', primary	0.3	0.5	0.6

(1) The range reflects an average emission factor in 1986 and 1966

Table 3.44: Size fractions reported in the literature for non-ferrous metals production [% TSP].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Smelting, refining of metals [1]	82 %	92 %	100 %

(1) Generalized particle size distribution, excluding aluminum

Table 3.45: Emission factors used in the RAINS model for other non-ferrous metals production [kg/ton metal].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Other Non-ferrous metals	PR_OT_NFME	12.3	1.5	13.8	1.2	15.0

Applicable Control Options

The RAINS model includes end-of-pipe control options for this sector, i.e., wet scrubbers, fabric filters, three stages of electrostatic precipitators, and wet electrostatic precipitators that are typically used in this industry (Passant *et al.*, 2000; AWMA, 2000; Rentz *et al.*, 1996; UBA, 1998a). At this stage, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3 Other Industrial Processes

Apart from the metallurgical industry, several other industrial processes are sources of particulates. This section discusses production of briquettes, cement, lime, glass, synthetic fertilizers, carbon black, PVC, gypsum, glass fibers, and petroleum refining. At this stage, production of sugar, ceramics, construction materials, beer, etc. are only included as emissions, based on the national reporting, in the RAINS category 'OTHER' (see Section 3.7.2).

3.2.3.1 Coal Briquettes Production

Production of briquettes from hard and brown coal is included in this category. Coal cleaning is not included here but is assumed to be part of mining (see Section 3.3). On a European scale, production of briquettes is a minor source of particulates, less than 0.1 percent of total PM (CEPMEIP, 2002). However, it might still be relatively important for some countries, e.g., Ukraine, Germany, especially on a regional scale. UBA estimated that this activity was a source of 0.8 and 0.4 percent of TSP and PM_{10} in Germany in 1996 (UBA, 1998a).

RAINS Sector:

PR_BRIQ

Description

Activity: Production of briquettes

Unit: **kg/t** produced briquettes.

Emission Factors

Although very few literature sources of emission factors were identified (Table 3.46), they show the same range of particulate matter emissions, i.e., about 0.2 to 0.4 kg/t briquettes. RAINS uses emission factors after CEPMEIP, 2002 (Table 3.47).

Table 3.46: Emission factors reported in the literature for briquettes production [kg/t].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
UBA, 1989 [(1)]	Not specified, hard coal			0.22-0.35
	Not specified, brown coal			0.4-0.9
UBA, 1998a	Not specified, hard coal		0.054	0.18
	Not specified, brown coal		0.12	0.40
CEPMEIP, 2002 [(2)]	Not specified	0.0125	0.125	0.375

[(1)] The range reflects an average emission factor in 1986 and 1966
[(2)] Emission factors recalculated from original units (Mg/PJ) assuming calorific value of 25 GJ/t

Table 3.47: Emission factors used in the RAINS model for briquette production [kg/t].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Briquette production	PR_BRIQ	0.0125	0.1125	0.125	0.25	0.375

Applicable Control Options

The RAINS model assumes that emissions can be controlled by introducing cyclones or scrubbers. At this stage, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.2 Cement Production

The production of cement includes the following stages: raw material preparation, burning of the raw material mixture to produce cement clinker, preparation of other cement components, grinding (milling) of cement components. All of the listed stages are potential sources of particulate matter emissions. Details on the specific production processes can be found in, e.g., Rentz *et al*., 1996; TA Luft, 1986; EPA, 1998a; AWMA, 2000; Passant *et al.*, 2000.

This sector is an important contributor to the total PM emissions, even in countries where strict emission limits are in place, e.g., in Germany UBA estimated its share in total PM and PM_{10} emissions in 1995 at 3 and 5 percent, respectively. APEG (1999) estimated for 1995 the contribution to the total UK PM_{10} at about two percent and Berdowski *et al.* (1997) suggest that cement production contributes typically less than one percent to total national emissions of PM_{10}. Overall, about 1.5 to 2.5 percent of all particulate fraction emissions in Europe originated from this source (CEPMEIP, 2002).

RAINS Sector:

PR_CEM

Description

Non-fuel related emissions

Activity: Cement production.

Unit: **kg/t** cement.

Emission Factors

Table 3.48 lists emission factors for cement production. Since the dust emitted is to a large extent cement, there is a strong incentive to keep emissions as low as possible and there are no plants without abatement. This explains, of course, the lack of uncontrolled emission factors. The abated emission rates for all processes fall in the range from 0.12 to about 1 kg/t, depending on the actual efficiency of the applied controls. From this, one could estimate the uncontrolled emission rate at somewhere between 60 and 200 kg/t. Currently, RAINS assumes a value of 130 kg/t (Table 3.50) and size specific emission rates are based on the EPA (1998a) data for dry process (Table 3.49). It should be pointed out that, although relevant for the estimate of the unit control costs, the exact determination of the unabated emission factor is not so important for this sector since all of the emissions are traditionally well controlled.

Table 3.48: Emission factors reported in the literature for cement production [kg/t cement].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled, kiln - wet process	4.6	15.6	65.0
	Controlled (ESP), kiln - wet process	0.24	0.32	0.38
	Controlled (f.filter), kiln - wet process			0.23
	Controlled, raw material preparation			~0.06
	Controlled (ESP), kiln – dry process			0.5
	Controlled (f.filter), kiln – dry process	0.045	0.084	0.1
	Controlled (ESP), preheater			0.13
	Controlled (ESP), clinker cooler			0.048
	Controlled, whole process			0.28-1.06 (1)
BUWAL, 1995	Not specified, fugitive emissions			0.10
UBA, 1989 (2)	Not specified			0.5-2.2
UBA, 1998a	Controlled		0.261	0.29
IPPC, 2000b(3)	Controlled, kilns			0.01-0.4
Passant *et al.*, 2000	Controlled, average for UK		0.236	0.295
EEA, 1999 (3)	Not specified			0.12-0.25
CEPMEIP, 2002	Controlled, 'high'	0.3	0.8	2
	Controlled, 'low'	0.08	0.18	0.2
Berdowski *et al.*, 1997	Not specified	0	0.15	

(1) Lower value represents BAT, the higher is for poorly operating abatement.
(2) Range given by the average emission factors reported for 1986 and 1966.
(3) As quoted in Passant *et al.*, 2000.

Table 3.49: Size fractions reported in the literature for cement production [percent of TSP].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled, kilns, wet process	7 %	24 %	100 %
	Uncontrolled, kilns, dry process	18 %	42 %	100 %
	Controlled (ESP), kiln - wet process	64 %	85 %	100 %
	Controlled (fabric filter), kiln – dry process	45 %	84 %	100 %
TÜV, 2000a	Controlled (ESP), kiln	51 %	87 %	100 %
	Controlled (ESP), clinker cooler	68 %	99 %	100 %

Table 3.50: Emission factors used in the RAINS model for cement production [kg/t cement].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Cement production	PR_CEM	23.4	31.2	54.6	75.4	130

Applicable Control Options

The RAINS model includes several end-of-pipe control options for the cement industry, particularly fabric filters and electrostatic precipitators. Fugitive emissions are normally captured in the ventilation system and ducted to the emission control system, e.g., the electrostatic precipitators. However, if this is not the case, the RAINS model allows specifying the share of total unabated emissions that represent fugitive emissions ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.3 Lime Production

Lime (calcium oxide, CaO) is the high-temperature product of the calcination of limestone (calcium carbonate, $CaCO_3$). Lime is manufactured in various kinds of kilns; the three most common types are the rotary, vertical shaft and moving grate. Kiln is a major source of particulate matter emissions, although fugitive losses occur at nearly every stage of production. Details of the specific production processes can be found in, e.g., EPA, 1998a; AWMA, 2000.

This sector is a relatively small contributor to the total PM emissions. In Germany, UBA estimated its share in total PM and PM_{10} emissions in 1995 at less than 0.3 and 0.4 percent, respectively. Overall, only about 0.2 percent of all particulate matter emitted in Europe originated from this source (CEPMEIP, 2002).

RAINS Sector:

PR_LIME

Description

<u>Non-fuel related emissions</u>

Activity: Lime (calcium oxide) production from limestone.

Unit: **kg/t** lime produced.

Emission Factors

Table 3.51 lists emission factors for lime production. There is a wide range of emission factors reported for both abated and unabated cases. Uncontrolled emission factors vary from about 50 to 250 kg/t (all processes included). Currently, RAINS assumes a value of 100 kg/t (Table 3.53) and size-specific emission rates are based on the EPA (1998a) data for the uncontrolled rotary kiln (Table 3.52). It should be pointed out that, although relevant for the estimate of the unit control costs, the exact determination of the unabated emission factor is not so important for this sector since all of the emissions are traditionally well controlled.

Table 3.51: Emission factors reported in the literature for lime production [kg/t lime].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a; AWMA, 2000	Uncontrolled, coal-fired rotary kiln		22	180
	Controlled (ESP), as above		2.2	4.3
	Uncontrolled, coal-gas fired rotary kiln			40
	Controlled (scrubber), as above			0.44
	Uncontrolled, gas-fired calcimatic kiln			48
	Uncontrolled, product cooler			3.4
	Uncontrolled, crushing, transfer			~1.5
UBA, 1989 (1)	Not specified			0.3-1.3
UBA, 1998a	Controlled		0.104	0.13
IPPC, 2000b(2)	Uncontrolled, not all processes			3.6-21.6
	Controlled, not all processes			0.12-0.96
Passant *et al.*, 2000	Controlled, average for UK		0.298	0.425
EEA, 1999 (2)	Uncontrolled, all processes			103-234 (3)
	Controlled, all processes			0.8-55 (4)
CEPMEIP, 2002	Controlled, 'high'	0.06	0.3	1
	Controlled, 'low'	0.03	0.15	0.3

(1) Range given by the average emission factors reported for 1986 and 1966.
(2) As quoted in Passant *et al.*, 2000.
(3) Wide range representing different types of kilns.
(4) Lower value represents BAT, the higher is for poorly operating abatement.

Table 3.52: Size fractions reported in the literature for lime production [percent of TSP].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled, rotary kiln	1.4 %	12 %	100 %
	Controlled (multicyclone), rotary kiln	6.1 %	16 %	100 %
	Controlled (ESP), rotary kiln	14 %	50 %	100 %
	Controlled (fabric filters), rotary kiln	27 %	55 %	100 %

Table 3.53: Emission factors used in the RAINS model for lime production [kg/t lime].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Lime production	PR_LIME	1.4	10.6	12	88	100

Applicable Control Options

The RAINS model includes several end-of-pipe control options for lime production, particularly cyclones, wet scrubbers, fabric filters and electrostatic precipitators. Fugitive emissions are normally captured in the ventilation system and ducted to the emission control system. However, if this is not the case, the RAINS model allows specifying the share of total unabated emissions that represent fugitive emissions ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.4 Petroleum Refining

The petroleum refining industry converts crude oil into more than 2500 refined products, including liquid fuels (gasoline, diesel, residual oil), by-product fuels and feedstocks (e.g., asphalt, lubricants), and primary petrochemicals (e.g., ethylene, toluene, xylene) (EEA, 1999). Detailed descriptions of the specific processes can be found in, e.g., EPA, 1998a; AWMA, 2000.

Refineries are not a major source of particulate emissions; their contribution to total PM is typically estimated below one percent (APEG, 1999). Berdowski *et al*. (1997) calculated higher shares of this source for the Eastern European countries (see also emission factors in Table 3.54), while CEPMEIP (2002) reports a contribution of less than 0.2 percent.

RAINS Sector:

PR_REF

Description

Activity: Petroleum refining.

Unit: **kg/t** crude oil.

Emission Factors

An overview of emission factors and particulate matter size distribution found in literature is summarized in Table 3.54 and Table 3.55. There is fairly good agreement between the numbers reported, apart from significantly larger values from Berdowski *et al.*, 1997. It was decided at this stage to use the value from the Dutch inventory (ER, 1996) combined with information on size distribution from Berdowski *et al.* (1997).

Table 3.54: Emission factors reported in the literature for refineries [kg/t crude oil].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
ER, 1996 [(1)]	Average, uncontrolled Dutch plants		0.12	
Ecker and Winter, 2000	Uncontrolled, East German plant			0.102
	Controlled, East German plant			0.0167
	Controlled, modern plant (Schwechat, Austria)			0.008
CEPMEIP, 2002	Controlled, 'high'	0.011	0.022	0.032
	Controlled, 'low'	0.0012	0.0024	0.0035
Berdowski et al., 1997	Unknown, Western Europe	0.16	0.2	
	Unknown, Eastern Europe	1.8	2.25	

[(1)] as quoted in Dreiseidler *et al.*, 1999 and Berdowski *et al*., 1997

Table 3.55: Size fractions reported in the literature for refineries [%]

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
CEPMEIP, 2002	Controlled	35 %	70 %	100 %
TÜV, 2000b	Controlled (cyclone, ESP), FCC	72.4 %	97.3 %	100 %
	Controlled (ESP), FCC	51.8 %	82.4 %	100 %
Berdowski *et al*., 1997	Unknown	80 %	100 %	

Table 3.56: Emission factors used in the RAINS model for refineries [kg/t crude oil].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Petroleum refining	PR_REF	0.096	0.024	0.120	0.002	0.122

Applicable Control Options

The RAINS model includes cyclones, bag filters and electrostatic precipitators as control options for refineries.

3.2.3.5 Fertilizer Production

This category includes production of nitrogen, phosphorous, and potassium fertilizers. The contribution of this sector to the total PM emissions is expected to be relatively low, estimated at about 0.1 to 0.5 percent (APEG, 1999; CEPMEIP, 2002). However, UBA estimated its contribution at about 1.5 percent for Germany in 1996 (UBA, 1998a). A possible explanation is that UBA also included emissions from the storage and handling of fertilizers, which in other studies, as well as in RAINS, are allocated to another emission category, i.e., 'STH_NPK' (see Section 3.6).

RAINS Sector:

PR_FERT

Description

Activity: Synthetic fertilizer production.

Unit: **kg/t** fertilizer produced.

Emission Factors

Several sources of emission factors for this activity were found (Table 3.57). A wide range of emission rates is reported and it is not always possible to explain the reasons since there is insufficient background information on the level of control. It was concluded that a modern plant using fabric filters is characterized by a particulate matter emission rate of about 0.3 kg/t of fertilizer produced, excluding fugitive emissions from handling of fertilizers, which are dealt with in RAINS in another category. Starting from this value and using size fraction specific removal efficiencies, unabated emission factors were calculated (Table 3.58). The estimated emission rate of 50 kg/t lies within the range of data reported in EPA, 1998a.

Table 3.57: Emission factors reported in the literature for fertilizer production [kg/t].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
UBA, 1977	Not specified			4.5
UBA, 1989	Not specified		1.6	2.5
UBA, 1998a	Not specified			2.0
EPA, 1998a, uncontrolled	Ammonium nitrate			57.2
	Ammonium sulfate			23-109
Winiwarter *et al.*, 2001	Not specified	0.048	0.151	0.32
CEPMEIP, 2002	Controlled	0.18	0.24	0.3
Berdowski *et al*., 1997	Not specified	0.18	0.25	

Table 3.58: Emission factors used in the RAINS model for fertilizer production [kg/t].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Fertilizer production	PR_FERT	18	12	30	20	50

Applicable Control Options

As with other industrial process sectors, the RAINS model includes several end-of-pipe control options for fertilizer production plants (cyclone, bag filters, electrostatic precipitators). At this stage, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy.

3.2.3.6 Carbon Black

Carbon black is used as a reinforcing agent in rubber compounds, e.g., for tires, hoses, as a black pigment in printing inks, surface coatings, etc. Carbon black is a product of endothermic hydrocarbon pyrolysis. It can be produced by partial combustion involving flames or by purely thermal decomposition processes in the absence of flames. More details on the production process can be found in, e.g., AWMA, 2000.

The contribution of this sector to total emissions of PM is very small, ranging from 0.006 percent for TSP in Europe (CEPMEIP, 2002) to 0.04 percent for PM_{10} in Germany (UBA, 1998a). The reason that this sector is recognized as a separate category in RAINS is its contribution to VOC emissions, i.e., it is already part of the RAINS structure.

RAINS Sector:

PR_CBLACK

Description

Activity: Carbon Black production.

Unit: **kg/t** carbon black produced.

Emission Factors

Emission factors found in the literature are shown in Table 3.59. RAINS uses emission factors after CEPMEIP (2002) - high scenario (Table 3.60). No further discussion of emission factors is provided owing to the low relevance of this sector for PM emissions.

Table 3.59: Emission factors reported in the literature for carbon black production [kg/t].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
UBA, 1989 [(1)]	Not specified			0.3-1
UBA, 1998a	Not specified		0.25	0.25
EPA, 1998a	Uncontrolled, tail gas			3.25
	Controlled, tail gas flared			1.35
	Controlled, tail gas incinerated			1.03
AWMA, 2000	Not specified			~ 1
	Not specified, fugitive			0.05-0.1
CEPMEIP, 2002	Not specified, 'high'	1.44	1.6	1.78
	Controlled, 'low'	0.18	0.2	0.22

[(1)] Range given by the average emission factors reported for 1986 and 1966

Table 3.60: Emission factors used in the RAINS model for carbon black production [kg/t].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Carbon Black production	PR_CBLACK	1.44	0.16	1.6	0.18	1.78

Applicable Control Options

As with other industrial process sectors, the RAINS model includes several end-of-pipe control options for this activity (cyclone, bag filters and electrostatic precipitators). At this stage, RAINS does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.7 Glass Production

This category includes production of flat glass, container glass, and pressed and blown glass, the latter two representing typically the majority of production. The manufacture of glass involves four stages: preparation of raw material, melting in a furnace, forming, and finishing. Emissions of particulates occur at all manufacturing stages. More details on the process and sources of emissions can be found in, e.g., EPA, 1998a; AWMA, 2000; Passant *et al*., 2000.

The contribution of this sector to total PM emissions is estimated at below one percent, i.e., 0.2 to 0.7 percent for TSP and $PM_{2.5}$ in Europe (CEPMEIP, 2002) and 0.1 to 0.2 for TSP and PM_{10} in Germany (UBA, 1998a).

RAINS Sector:

PR_GLASS

Description

Activity: Glass production.

Unit: **kg/t** glass produced.

Emission Factors

A number of literature sources report emission rates for the glass production industry (Table 3.61). In most cases emission factors refer to controlled installations or there is insufficient information to assess the level and type of control. An average unabated emission factor for the US could be derived based on the information that container glass and pressed and blown glass represent 51 and 25 percent of production, respectively (EPA, 1998a). This gives a value of about 2.7 kg/t, neglecting fugitive emissions from raw material handling, forming and finishing. A similar statistic for Europe was not available but assuming that the emission factor reported by UBA (1998a) represents a modern plant with well-operated equipment and that the CEPMEIP (2002) low scenario represents BAT, one can derive an unabated emission factor of 3.25 kg/t, which leads to an abated emission rate in the range of 0.03-0.06 kg/t. This emission factor is used in RAINS (Table 3.63) and size-specific rates are derived using the EPA (1998a) profile for melting (uncontrolled) (Table 3.62).

Table 3.61: Emission factors reported in the literature for glass production [kg/t].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
UBA, 1989 (1)	Not specified			0.68-2.2
BUWAL, 1995	Not specified			0.47-3.7
UBA, 1998a	Controlled		0.06	0.067
EPA, 1998a	Not specified (general)	0.64	0.66	0.68
	Controlled, raw material handling			Negligible
	Uncontrolled, melting, container glass			0.7
	Uncontrolled, melting, pressed and blown glass			8.4
	Uncontrolled, melting, flat glass			1.0
	Not specified, forming and finishing			Negligible
EEA, 1999	Controlled			0.09-0.15
Passant *et al.,* 2000	Not specified, average UK plant			0.4
CEPMEIP, 2002	Controlled, 'high'	1.6	1.8	2
	Controlled, 'low'	0.024	0.027	0.03

(1) Range given by the average emission factors reported for 1986 and 1966

Table 3.62: Size fractions reported in the literature for glass production [%]

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
EPA, 1998a	Uncontrolled, melting	91 %	95 %	100 %
	Controlled, melting	53 %	75 %	100 %
TÜV, 2000a	Controlled (ESP), flat glass	48 %	94 %	100 %
	Controlled (ESP), container glass	56 %	95 %	100 %
CEPMEIP, 2002	Controlled	80 %	90 %	100 %

Table 3.63: Emission factors used in the RAINS model for glass production [kg/t glass].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Glass production	PR_GLASS	2.96	0.13	3.09	0.16	3.25

Applicable Control Options

As with other industrial process sectors, the RAINS model includes several end-of-pipe control options for this activity (cyclone, fabric filters and electrostatic precipitators). At this stage, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.8 Other Production Processes

This sector includes production of PVC, gypsum, and glass fibers. At this stage, production of sugar, ceramics, construction materials, beer, etc. are only included as emissions, based on the national reporting, in the RAINS category 'OTHER' (see Section 3.7.2). Detailed description of these processes can be found in, e.g., AWMA, 2000; EPA, 1998a.

According to CEPMEIP, less than 0.5 percent of PM emissions in Europe originate from this source (CEPMEIP, 2002). For Germany, UBA estimated that the share might be slightly larger[4] (UBA, 1998a).

RAINS Sector:

PR_OTHER

Description

Activity: Production of PVC, gypsum, glass fiber.

Unit: **kg/t** product.

Emission Factors

Table 3.64 presents an overview of emission factors found in the literature for the products considered. For gypsum RAINS uses the emission factor from EPA (1998a) and for other products unabated emission factors were derived assuming average removal efficiencies above 98 percent for non-fugitive sources. Production structure varies among countries and will affect an average emission factor. Statistical data on production in 1995 were used to derive country-specific factors; Table 3.65 shows only ranges.

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[4] It is not possible to give a more precise estimate as this category in the German inventory includes more products.

Table 3.64: Emission factors reported in the literature for PVC, gypsum, and glass fiber production [kg/t].

Source	Abatement / process	$PM_{2.5}$	PM_{10}	TSP
PVC				
ER, 1986 [(1)]	Not specified		0.383	
Berdowski *et al.*, 1997	Not specified	0.1	0.2	
EPA, 1998a	Uncontrolled		15	17.5
	Controlled			0.2625
CEPMEIP, 2002	Controlled	0.01	0.1	0.2625
Gypsum				
UBA, 1998a [(2)]	Not specified		0.104	0.13
BUWAL, 1995	Not specified			0.05
CEPMEIP, 2002	Controlled, 'high'	0.01	0.04	0.1
	Controlled, 'low'	0.0075	0.025	0.05
Glass fibers				
CEPMEIP, 2002	Controlled, 'high'	1.4	1.8	2
	Controlled, 'low'	0.35	0.45	0.5

[(1)] as quoted in Berdowski *et al.*, 1997
[(2)] aggregated emission factor that includes several other products

Table 3.65: Emission factors used in the RAINS model for other production [kg/ton product].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Other production	PR_OTHER	0.5-8	1.5-7	2-15	2.5-3	5-17.5

Applicable Control Options

As with other industrial process sectors, the RAINS model includes several end-of-pipe control options for this activity (cyclone, fabric filters and electrostatic precipitators). At this stage, the RAINS model does not include options to control fugitive losses in this sector but allows specifying the share of total capacity that cannot be controlled at all ("not suitable for control" – NSC). The user can adjust this value in the control strategy for every five-year period.

3.2.3.9 Fugitive Emissions from Small Industrial Sources

This potentially large source of fugitive emissions of particulates includes a large number of small industrial installations, e.g., carpentry shops, small sawmills, etc. A large proportion of these facilities might fall outside the limits for environmental licensing, i.e., small production capacity, few people employed, small use of resources, or small annual emissions, etc. Owing to the number of these sources and potentially lacking or malfunctioning control equipment, they might emit, on the whole, a relatively large amount of coarse particles.

CEPMEIP estimated that as much as 3.5 percent of total European PM and more than one percent of $PM_{2.5}$ originated from this source in 1995. The Swiss inventory for 1995 (EWE, 2000; BUWAL, 2001) indicates that nearly six percent of PM_{10} in Switzerland came from small industrial facilities with the majority (about 90 percent) from wood workshops. This high share of emissions from wood preparation might be very specific to Switzerland. Several other national inventories do not include this type of source and, as indicated by Winiwarter *et al*. (2001), one of the reasons is not only the difficulty in estimating emission rates but also finding out about activity data.

RAINS Sector:

PR_SMIND_F

Description

Activity: Population is used as proxy.

Unit: **kg/capita**.

Emission Factors

Only a few sources of emission factors were found (Table 3.66). The emission factor from the inventory for Switzerland (EWE, 2000) was derived by dividing reported emissions (about 1.7 kt) by population. The factors reported in the CEPMEIP inventory (CEPMEIP, 2002) are used in RAINS at this stage, although the origin of these factors is not documented in the CEPMEIP report. The alternative option of applying the Swiss emission factor to the rest of Europe was considered less appropriate as it is heavily biased towards wood preparation activities, which are not necessarily as important in other countries.

Table 3.66: Emission factors reported in the literature for fugitive PM emissions from small industrial installations [kg/capita].

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 1995	Not specified [(1)]			0.7
EWE, 2000 [(2)]	Not specified		0.24	
CEPMEIP, 2002	Not specified	0.06	0.18	0.545

[(1)] Assuming that on average about 30 percent of dust is abated

[(2)] Emission factor derived from reported emissions.

Table 3.67: Emission factors used in the RAINS model for small industrial sources [kg/capita].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Small industrial sources - fugitive	PR_SMIND_F	0.06	0.12	0.18	0.365	0.545

Applicable Control Options

The RAINS model includes two stages (low and high efficiency) of fugitive emission control.

3.3 Mining

This section includes mining of coal (brown coal and hard coal) and metallic and non-metallic ores (zinc, iron, copper, manganese, bauxite, etc.). Information on emissions from operations associated with mining is scarce. EPA (EPA, 1995) provides some data on open excavation activities but they are very specific to American mines and it is difficult to apply them to the European situation and data.

APEG (1999) estimated PM_{10} and $PM_{2.5}$ emissions from mining and quarrying operations in the UK in 1995 at about 24 and 7 thousand tonnes, respectively. This constitutes around 11 and five percent of the total UK PM_{10} and $PM_{2,5}$ emissions and is significantly higher than the CEPMEIP (2002) estimate for UK, i.e. 1.2 and 0.2 thousand tons, which represents 0.4 and 0.1 percent of primary PM_{10} and $PM_{2.5}$ in UK. The striking difference might be due to large differences in the emission factors applied (see Table 3.68) and sources included, i.e., CEPMEIP includes only hard coal mining while it is not clear from the APEG (1999) study what is actually included. Winiwarter *et al*. (2001) estimated the contribution of mining activities to Austrian PM emissions to be 0.2 and 0.6 percent for $PM_{2.5}$ and TSP, respectively.

According to CEPMEIP (2002) PM emissions from mining activities in Europe contribute on average about one percent of TSP and PM_{10}, and only about 0.2 percent of $PM_{2.5}$, with the majority (nearly 90 percent) originating from coal mining.

RAINS Sector:

	MINE_BC	MINE_HC	MINE_OTH

Description

Activity: Mining of coal and ores.

Unit: **kg/t**.

Emission Factors

Only three sources of emission factor data were found and they differ very much (Table 3.68). It is not entirely clear which sources (operations) are included in the 'mining and quarrying' sector in the APEG (1999) inventory, and the Winiwarter *et al.* (2001) report includes only emission factors for iron and wolfram ores. Therefore, at this stage RAINS uses non-country-specific factors after the CEPMEIP study, although their origin is not documented in the CEPMEIP report (CEPMEIP, 2002). The 'high' estimate is used as the uncontrolled value (Table 3.69) and a control option is introduced that achieves the emission factors given for the "low" scenario.

Table 3.68: Emission factors reported in the literature for mining [kg/ton].

Source	Abatement (activity)	$PM_{2.5}$	PM_{10}	TSP
APEG, 1999	Unknown (mining and quarrying)	0.00029	0.001	
Winiwarter *et al.,* 2001	Unknown (iron ore)	0.03043	0.1047	0.2168
	Unknown (wolfram ore)	0.0038	0.0119	0.0251
CEPMEIP, 2002	Unknown, 'high' (mining)	0.005	0.05	0.1017
	Unknown, 'low' (mining)	0.0038	0.025	0.0509

Table 3.69: Emission factors used in the RAINS model for mining of coal and ores [kg/ton].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Brown coal mining	MINE_BC	0.005	0.045	0.05	0.0517	0.1017
Hard coal mining	MINE_HC	0.005	0.045	0.05	0.0517	0.1017
Other mining	MINE_OTH	0.005	0.045	0.05	0.0517	0.1017

Applicable Control Options

One control option is included in the RAINS model, i.e., good housekeeping/primary measures to reduce fugitive PM emissions in mining. This measure simulates the "low" emission factors given in the CEPMEIP inventory (CEPMEIP, 2002), although not giving exactly the same result, i.e., the abated emissions of PM_{10} are slightly higher in RAINS due to the modified abatement efficiencies as compared to the CEPMEIP assumptions. The reason is that using the values reported by CEPMEIP directly would result in higher removal efficiency for coarse particles than for particles larger than 10 μm, although the type of measures that can be introduced for these sources are believed to be more efficient for larger particles.

3.4 Agriculture

Several agricultural activities contribute to the emissions of primary particulate matter. Examples are livestock buildings, arable farming, managing crops, energy use (combustion), burning of agricultural waste, and unpaved roads. Some of these sources are dealt with in other sections of this document, i.e. energy use, storage and handling of agricultural products, open burning of agricultural waste. Natural sources of PM like wind-blown soil that are sometimes associated with agricultural activities are not included. The following sections are related to livestock farming, which is believed to be the largest source of fine PM from agriculture (ICC and SRI, 2000), and a brief discussion of arable farming and other sources, e.g., unpaved roads.

3.4.1 Emissions from Livestock Farming

Most of the measurements of PM concentrations were performed on poultry and pig farms (e.g., Takai *et al.*, 1998; Donham *et al.*, 1986 and 1989; Louhelainen *et al.*, 1987), which are believed to be the major source of PM from animal housing (Berdowski *et al.*, 1997; ICC and SRI, 2000; EQB, 2001). Dairy and beef cattle are less important. The predominant sources include feed and faecal material and possibly bedding. Lesser contributions originate from skin, hair, mould, pollen grains and insect parts. The ICC and SRI (2000) review indicates that the mass median diameter of dust collected in pig and poultry buildings is in the range between 11 and 17 μm. The proportion of PM_5 in total dust for pigs and poultry farms was estimated at about four to 16 percent (e.g., Heber *et al.,* 1988; Louhelainen *et al.,* 1987; Cravens *et al.,* 1981). The ICC and SRI (2000) reports used, for all animal categories, the size fraction distribution given in Louhelainen *et al.,* 1987, i.e., eight and 45 percent for $PM_{2.5}$ and PM_{10}, respectively (see Table 3.71). A recent and thorough review of the emissions from this source is available in the ICC and SRI (2000) report.

Berdowski *et al.* (1997) estimated the contribution of agriculture to total European emissions of PM_{10} and $PM_{2.5}$ at nearly nine and seven percent, respectively, indicating however that this might be on the high side. Indeed, a comparison between that study and more recent work of

ICC and SRI (2000)[5] suggests that the differences for the UK are large[6] i.e., for PM_{10} 11.5 kt by ICC and SRI (2000) and 30 kt by Berdowski *et al.* (1997), for $PM_{2.5}$, two and 13 kt, respectively. CEPMEIP estimated that in 1995 the share of PM_{10} and $PM_{2.5}$ emissions from livestock farming in Europe was 4.5 and 1.7 percent, respectively (CEPMEIP, 2002).

RAINS Sectors:

AGR_POULT AGR_PIG AGR_COWS

AGR_BEEF AGR_OTANI

Description

Activity: Animal numbers.

Unit: **kg/animal/year**.

Emission Factors

Examples of emission factors and size distributions reported in the literature are given in the tables below. Values from Takai *et al.* (1998) presented in Table 3.70 represent averages derived from the measurements done in Denmark, the Netherlands, Germany and United Kingdom. Great variation was observed between countries. For example, for cattle, estimated inhalable dust (TSP) emissions in Germany (about 1.2 kg/animal/year) were nearly twice as high as in England (0.65 kg/animal/year) while, for pig buildings, emissions measured in Denmark (about 1.4 kg/animal/building) were significantly higher than in Germany or England (about 0.82 kg/animal/year). For poultry, only the values measured in Germany were significantly lower (about 0.07 kg/animal/year) than the average reported in Table 3.70. Takai *et al.* (1998) indicates that ventilation rates, feeding practices, and bedding materials are among the main reasons for the different emission rates measured.

The RAINS model relies on the results of Takai *et al.* (1998) and the ICC and SRI (2000) study (Table 3.72). The ICC and SRI (2000) study is not included in Table 3.70 since its emission estimates for UK are based on the results of Takai *et al.* (1998) assuming a size distribution as given in Table 3.71.

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[5] Their estimates rely on the measurements done in UK by Takai *et al.* (1998).

[6] The estimates are for different years, i.e., 1990 (Berdowski *et al.*, 1997) and 1998 (ICC and SRI, 2000) but the change in the number of animals (excluding cattle) was not that significant.

Table 3.70: Uncontrolled emission factors reported in the literature for livestock farming [kg/animal/year].

Source	Animal type	$PM_{2.5}$	PM_5	PM_{10}	TSP
Takai *et al*., 1998	Cattle		0.166		0.964
	Pigs		0.123		0.972
	Poultry		0.018		0.105
CEPMEIP, 2002	Cattle	0.0885		0.396	0.885
	Pigs	0.0785		0.354	0.785
	Poultry, chickens	0.0083		0.037	0.083
	Poultry, other	0.0553		0.249	0.553
Berdowski *et al*., 1997	Pigs	0.75		2.2	
	Poultry	0.043		0.086	

Table 3.71: Size fractions reported in the literature for livestock farming [as percent of TSP].

Source	Sector	$PM_{2.5}$	PM_5	PM_{10}	$>PM_{10}$	TSP
Louhelainen *et al*. 1987a	Pigs	8 %	14 %	45 %		100 %
Cravens *et al*., 1981	Poultry			15-16 %		
Heber *et al*., 1988	Pigs		3.7 %			
TÜV, 2000b	Broilers	8.8 %		58.3 %	41.7 %	100 %
	Laying hens	3.1 %		33.1 %	66.9 %	100 %
ICC and SRI, 2000	All animals	8 %		45 %		100 %
CEPMEIP, 2002	All animals	10 %		45 %		100 %
Takai *et al*., 1998	Cattle		17.3 %			
	Pigs		12.6 %			
	Poultry		16.7 %			
Berdowski *et al*., 1997	Pigs	12 %		40 %		100 %
	Poultry	20 %		40 %		100 %

Table 3.72: Emission factors used in the RAINS model for livestock farming [kg/animal/year].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Poultry	AGR_POULT	0.0105	0.0368	0.0473	0.0578	0.1051
Pigs	AGR_PIG	0.0778	0.3598	0.4376	0.5348	0.9724
Dairy cattle	AGR_COWS	0.0964	0.3372	0.4336	0.5300	0.9636
Other cattle	AGR_BEEF	0.0964	0.3372	0.4336	0.5300	0.9636
Other animals (1)	AGR_OTANI			n.a.		

(1) Includes sheep, horses and fur animals

Note that Table 3.72 refers to 'default' (average) emission rates that are based on the results of Takai *et al*. (1998) and do not take into account the length of housing period. The emission factors actually used in RAINS are re-calculated taking the length of this period into account. In this way, RAINS estimates country-specific emission factors. Size distribution is assumed after Louhelainen *et al.* (1987a) and ICC and SRI (2000), with the exception of share of $PM_{2.5}$ for cattle and poultry where ten percent was used (as in CEPMEIP, 2002). The latter assumption seems to be justified by the measurements of Takai *et al.* (1998) where emissions from cattle and poultry buildings seem to have a higher share of respirable dust (compare Table 3.71). The default emission factors for dairy and other cattle are the same (Table 3.72), based on the average reported by Takai *et al.* (1998) for 'cattle'. It is not possible to derive separate average values for these sectors from their study although detailed results indicate significant differences for various cattle categories. It is, however, expected that more data will be available in the near future, e.g. reports similar to the one for UK (ICC and SRI, 2000), where the necessary information is provided. The emission rates for other animals (AGR_OTANI) were not reported in Takai *et al.*(1998) or any other study and, therefore, at this stage no emission factor is associated with this category.

Applicable Control Options

A discussion of abatement options to reduce PM concentrations in animal buildings, as well as in the neighborhood of farms, is available, e.g., in Visschedijk *et al.* (1997), Takai *et al.* (1998) and ICC and SRI (2000). Takai *et al.* (1998) indicates that since feed is one of the main dust sources in buildings, adding animal fat or vegetable oil reduces feed dust and a reduction of 35 to 70 percent of dust concentration in pig buildings was observed. Other methods include spaying small quantities of plant oil in a building and using 'end-of-pipe' options like dry filters, electrostatic precipitators or wet scrubbers. Although the latter options might significantly reduce PM emissions, they were found impracticable in agriculture. One novel approach discussed in the ICC and SRI (2000) report is 'strategically placed vegetation', i.e., tree belts around animal houses. Based on the discussion of availability, effectiveness, costs and acceptability of several control options (ICC and SRI, 2000), RAINS includes four abatement options: feed modifications (all animals), hay-silage (cattle only), a change to free range poultry systems, and, additionally, a generic option for other animals (this has to be seen as a "placeholder" now but can be used later when more information is available).

3.4.2 Emissions from Arable Farming

This sector includes emissions from cereal harvesting and soil preparation (ploughing, harrowing, soil tillage, post-harvest operations). European studies of these sources date back to the 1970's and 80's when the exposure of tractor drivers was studied (Batel, 1979; Noren, 1985; Louhelainen *et al*., 1987b); more recent work was performed in the US (Clausniztер and Singer, 1996). ICC and SRI (2000) made an assessment of emissions from arable farming in the UK and concluded that they represent about 5 percent of agricultural emissions of PM_{10} in UK.

RAINS Sectors:

AGR_ARABLE

Description

Activity: Arable land area.

Unit: **kg/hectare** arable land.

Emission Factors

Examples of emission factors for arable farming operations are shown in Table 3.73 (as cited in ICC and SRI, 2000). The RAINS model relies on the results of the ICC and SRI (2000) study for UK where a comprehensive review of available material and PM_{10} estimate are provided. Neither CEPMEIP (2002) nor Berdowski *et al.* (1997) includes this source in their inventories. RAINS applies one emissions factor for all operations, derived from the UK estimate.

Table 3.73: Uncontrolled emission factors reported in the literature for arable farming [kg/hectare].

Source	Operation	PM_{10}	TSP
Louhelainen *et al*., 1987b	Ploughing		0.0220
	Harrowing		0.1400
Noren, 1985	Soil tillage		1.4601
Clausnizter and Singer, 1996	Post-harvest operations	0.0250	
	Cereal harvesting	0.0104	
	Drilling		0.0771
Batel, 1979	Cereal harvesting		0.2

Table 3.74: Size fractions reported in the literature for arable farming [as percent of TSP].

Source	Operation	$PM_{2.5}$	PM_{10}	TSP
Nieuwenhuijsen *et al*., 1998 (1)	All arable farming		5.5 %	100 %

(1) as cited in ICC and SRI, 2000

Table 3.75: Emission factors used in the RAINS model for arable farming [kg/hectare].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Arable farming	AGR_ARABLE	0	0.10	0.10	1.78	1.88

Applicable Control Options

Based on the discussion of availability, effectiveness, costs and acceptability of several control options (ICC and SRI, 2000), RAINS includes one option: alternative cereal harvesting and low-till farming.

3.4.3 Emissions from Other Sources

Apart from emissions from the storage and handling of agricultural products, open burning of waste or energy use in agriculture, which are treated in other sections in this document, there are other potential sources of PM. These include, for example: small incinerators where various wastes can be burned (the heat generated is typically not utilized and not reported in any energy statistics and, therefore, is not captured in the RAINS energy use database), animal feed production, and unpaved roads on farms. ICC and SRI (2000) made an assessment of emissions from these sources in the UK. Not all of the sources could be quantified, i.e. small incinerators, but the contribution to PM_{10} is expected to be very small. Neither CEPMEIP (2002) nor Berdowski *et al.* (1997) includes this source in their inventories

RAINS Sectors:

AGR_OTHER

Description

Activity: Emissions.

Unit: **kg/kg**.

Emission Factors

Since it was decided that RAINS would rely on reported emissions from these sources rather than attempt its own estimation, no discussion of emission factors is provided. The reader is further referred to studies by ICC and SRI (2000) and USEPA AP-42 (EPA, 1998a) where some emission factors for the sources under discussion are given.

Applicable Control Options

RAINS does not include any control options for this category.

3.5 Waste

This section includes flaring in the oil and gas industry and open burning of agricultural and residential waste. The information on emissions from these sources is scarce and they are typically not included in the particulate inventories.

According to CEPMEIP (2002), waste burning might be a large source of fine particles, contributing in Europe up to five percent of total $PM_{2.5}$, and about 2-3 percent of TSP and PM_{10}. Since more than half of these emissions originate from open burning of agricultural refuse and current policies in several countries forbid this practice, the importance is expected to decline in the years to come, assuming successful enforcement of this legislation.

RAINS Sector:

WASTE_FLR WASTE_AGR WASTE_RES

Description

Activity: Gas flaring in oil and gas industry; Open burning of waste.

Unit: **kt/PJ** of gas; **kg/t** of waste.

Emission Factors

Only a few sources of emission factor data were found (Table 3.76). There are significant differences between the studies apart from CEPMEIP and EPA factors for burning of residential waste; CEPMEIP seems to use EPA (1995) factors. EPA (1995) reports a long list of PM emission factors for several agricultural crop residues but as the RAINS database does not include information about the respective activity data, only the value for 'unspecified' is quoted. Currently, RAINS uses factors from the CEPMEIP study, although their origin is not documented in the CEPMEIP report (CEPMEIP, 2002).

Table 3.76: Emission factors reported in the literature for open waste burning and flaring.

Source	Source [unit]	$PM_{2.5}$	PM_{10}	TSP
EPA, 1995	Municipal refuse [kg/t]			8 (1)
	Field crops - unspecified [kg/t]			11
BUWAL, 1995	Residential waste burning [kg/t]			30 (2)
	Agricultural waste burning [kg/t]			20
CEPMEIP, 2002	Open burning of waste [kg/t]	6	6	8
	Agricultural waste burning [kg/t]	2.82	3.3	4.7
	Gas flaring [kt/PJ]	0.064	0.064	0.064

(1) EPA indicates that most of PM is in the fine fraction

(2) This factor is based on the emission factor for open burning of waste at landfill sites.

Table 3.77: Emission factors used in the RAINS model for flaring [kt/PJ] and open burning of waste [kg/t].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Gas flaring	WASTE_FLR	0.064	0	0.064	0	0.064
Open burning of waste, agriculture	WASTE_AGR	2.82	0.58	3.3	1.4	4.7
Open burning of waste, residential	WASTE_RES	6.0	0	6.0	2.0	8.0

Applicable Control Options

The RAINS model includes one control option for all categories, i.e., good housekeeping/primary measures to reduce emissions from flaring in the oil and gas industry and a ban on burning of agricultural and residential waste.

3.6 Storage and Handling of Bulk Materials

This section includes storage and handling of coal (brown coal and hard coal), iron ore, synthetic fertilizers, and other industrial and agricultural products. Although several sources report emission factors for these activities (Table 3.78), not many inventories include them.

Storage and handling seem to be a potentially important source of coarse particles. According to the CEPMEIP study, about 4-5 percent of TSP and PM_{10} originated from this source in Europe in 1995 (CEPMEIP, 2002). The share of $PM_{2.5}$ is significantly lower, i.e. only about 0.6 percent. Major sources are storage and handling of coal (about 40 percent) and iron ore (about 30 percent). UBA (1998a) estimated that as much as 12.9 percent of TSP and 4.5 percent of PM_{10} came from this source in Germany in 1998.

RAINS Sector:

STH_COAL STH_FEORE STH_NPK

STH_OTH_IN STH_AGR

Description

Activity: Storage and handling of coal, ores, other industrial and agricultural products.

Unit: **kg/t**.

Emission Factors

A summary of information found in the literature on emission factors for categories distinguished in RAINS is presented in Table 3.78. RAINS uses factors after the CEPMEIP study since they cover all PM fractions and represent fairly well the range of values found in other studies (Table 3.79). Values for other industrial products (STH_OTH_IN) are country-specific as this sector includes a wide range of materials (e.g., coke, cement, fly ash, etc.), which are characterized by different emission factors and the amounts vary among countries. Therefore, there is no default value presented.

Table 3.78: Emission factors reported in the literature for storage and handling of bulk materials.

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
Cereals [kg/t]				
UBA, 1989	Unknown			1.4
EPA, 1995	Unabated (1)	0.042	0.147	0.3
	Unabated (2)	0.085	0.345	0.5
Dreiseidler *et al*, 1999	Abated		0.1-0.2	0.1-0.5
Mulder, 1995	Unknown	0.00005	0.035	
Trenker & Höflinger, 2000[1]	Unknown, various agricultural products	0.001 - 0.007	0.005 - 0.021	0.01 - 0.045
CEPMEIP, 2002	Unknown, various agricultural products	0.004	0.025	0.1
Coal [kg/t]				
UBA, 1989	Unknown			0.2
Dreiseidler *et al*, 1999	Abated, brown coal		0.01	0.025
	Abated, coal		0.04	0.1
Mulder, 1995	Unknown		0.0005	
Trenker & Höflinger, 2000[1]	Unknown, brown coal	0.001	0.004	0.009
	Unknown, hard coal	0.0005	0.001	0.003
CEPMEIP, 2002	Unknown	0.006	0.06	0.15
Iron ore [kg/t]				
UBA, 1989	Unknown			0.2
Jockel, 1992	Unknown			0.07-0.175
Mulder, 1995	Unknown		0.0005	
Dreiseidler *et al*, 1999	Abated		0.03	0.075
Trenker &Höflinger, 2000[1]	Unknown	0.03	0.105	0.217
CEPMEIP, 2002	Unknown	0.008	0.094	0.2

Source	Abatement	$PM_{2.5}$	PM_{10}	TSP
N,P,K - Fertilizers [kg/t]				
Mulder, 1995	Unknown		0.01	
Dreiseidler *et al*, 1999	Abated		0.02	0.05
Trenker &Höflinger, 2000[(1)]	Unknown	0.048	0.151	0.32
CEPMEIP, 2002	Unknown	0.004	0.032	0.1
Other industrial products [kg/t]				
Mulder, 1995	Unknown		0.0005-0.2	
Trenker & Höflinger, 2000[(1)]	Unknown, various industrial products	0.01 - 0.058	0.034 - 0.188	0.074 - 0.400
Dreiseidler *et al*, 1999	Abated		0.004-0.08	0.01-0.2
CEPMEIP, 2002	Unknown	0.001-0.007	0.014-0.07	0.035-0.175

[(1)] As quoted in Winiwarter *et al.*, 2001 (rounded)

Table 3.79: Emission factors used in the RAINS model for storage and handling [kg/t].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Coal	STH_COAL	0.006	0.054	0.06	0.09	0.15
Iron ore	STH_FEORE	0.008	0.086	0.094	0.106	0.2
N,P,K-Fertilizers	STH_NPK	0.004	0.028	0.032	0.68	0.1
Other products	STH_OTH_IN	Country-specific values based on CEPMEIP				
Agricultural prod.	STH_AGR	0.004	0.021	0.025	0.075	0.1

Applicable Control Options

One control option is included in the RAINS model, i.e., good housekeeping/primary measures to reduce fugitive PM emissions from storage and handling.

3.7 Other sources

This section includes several miscellaneous sources, i.e., construction, barbeques, cigarette smoking, fireworks. The information on emissions from several of these categories is scarce and current estimates of emission factors should be used with great care.

According to CEPMEIP (2002), particulate emissions from these activities in Europe contribute between about 1.4 percent of TSP and about 2.8 percent of $PM_{2.5}$. About half of the TSP originated from construction activities and slightly more than half of $PM_{2.5}$ emissions came from barbeques and meat frying.

3.7.1 Construction Activities

Although construction activities might be an important source of coarse particles locally, the overall contribution to total PM is relatively low. CEPMEIP (2002) estimated its share in

Europe at below one percent and APEG (1999) gave for UK a contribution of about 1.3 percent for TSP and PM_{10}, and about 0.2 percent for $PM_{2.5}$.

RAINS Sector:

CONSTRUCT

Description

Activity: Construction activities in the public and private sectors.

Unit: **kg/million m^2** area of floor space.

Emission Factors

In principle, only two sources of emission factor data were found, since APEG (1999) relies on EPA (1995) but is adjusted for the UK conditions (Table 3.80). Note that the factors given are not in the same units, i.e. EPA-based numbers are in kg/ha/month. Currently, RAINS uses factors based on the CEPMEIP study. Although their origin is not documented in the CEPMEIP report (CEPMEIP, 2002), comparison with estimates of PM emissions from this source for UK (APEG, 1999) - which used EPA (1995) adjusted values - indicates similarity between EPA and CEPMEIP numbers, at least for total PM. For PM_{10}, EPA recommends a share of 20 percent rather than 50 percent used by CEPMEIP. The CEPMEIP database includes information on floor area built in European countries in 1995 and this information is used to derive country-specific emission factors that are used further in RAINS. Table 3.81 presents default emission rates that can be used when other information is not available. They are derived from the CEPMEIP inventory assuming that dwellings make up 65 percent of the total floor area constructed. The resulting emission factor is close to the average European rate.

Table 3.80: Emission factors reported in the literature for construction activities [kg/million m^2, unless specified otherwise].

Source	Abatement (source)	$PM_{2.5}$	PM_{10}	TSP
APEG, 1999 [(1)]	Unknown (construction)	0.0834	0.269	
EPA, 1995 [(1)]	Unknown (construction)		0.538	2.69
CEPMEIP, 2002	Unknown (dwellings)	0.0108	0.1076	0.2152
	Unknown (utilities)	0.0061	0.0613	0.1227

[(1)] Emission factors are given in kg/ha/month

Table 3.81: Emission factors used in the RAINS model for construction sector [kg/million m^2].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Construction	CONSTRUCT	0.0092	0.0822	0.0914	0.0914	0.1828

Applicable Control Options

One control option is included in the RAINS model, i.e., spraying of water at construction sites. Assumptions about efficiency and costs of this option have to be seen as very preliminary.

3.7.2 Other

Activities like cigarette smoking, barbeques, meat frying, or fireworks are a source of particulate emissions. Their overall contribution to total PM was estimated by CEPMEIP (2002) at about 1-1.5 percent for TSP and PM_{10} and around 2.5 percent for $PM_{2.5}$. In spite of large uncertainty surrounding emission factors and activity rates, this might be an important source of fine particles.

RAINS Sector:

RES_CIGAR	RES_BBQ
RES_FIREW	OTHER

Description

Activity: Cigarette smoking, barbeques, fireworks, other (population used as proxy).

Unit: **kg/capita**.

Emission Factors

The only source of emission factor data was the CEPMEIP (2002) inventory (Table 3.82), from which RAINS factors are derived. They are defined in kg/capita, recalculating the emission rates presented in CEPMEIP. This was done for all of the relevant categories and therefore RAINS emission factors are country-specific but remain the same for projected years. For cigarette smoking and barbeques, Table 3.83 presents default emission rates that can be used when other information is not available. They are average values from the estimated country-specific factors that are in the RAINS database.

Table 3.82: Uncontrolled emission factors reported in the literature for other sources

Source	Source [unit]	$PM_{2.5}$	PM_{10}	TSP
CEPMEIP, 2002	Cigarette smoking [kg/t tobacco]	40.0	40.0	40.0
	Barbeques [kg/t charcoal]	2.4	2.4	2.4
	Barbeques [kg/t meat]	40.0	40.0	40.0
	Meat frying [kg/t meat]	1.3	1.3	1.3
	Fireworks [kg/capita]	0.035	0.035	0.035

Table 3.83: Emission factors used in the RAINS model for other sources [kg/capita].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Cigarette smoking	RES_CIGAR	0.0165	0	0.0165	0	0.0165
Barbeques, etc.	RES_BBQ	0.075	0	0.075	0	0.075
Fireworks	RES_FIREW	0.035	0	0.035	0	0.035
Other	OTHER	n.a.	n.a.	n.a.	n.a.	n.a.

Applicable Control Options

The RAINS model does not include any control options for these sources.

3.8 Mobile Sources

This section includes both exhaust and non-exhaust emissions from mobile sources. Mobile sources are important contributors to total emissions of PM, especially fine particulate matter. Berdowski *et al.* (1997) estimated that 16 and 19 percent of total European emissions of PM_{10} and $PM_{2.5}$, respectively, in 1990 originated from transport (mainly from road transport). Similarly, for 1995, CEPMEIP (2002) estimated the transport contribution at 18 and 28 percent for PM_{10} and $PM_{2.5}$ where about 70 percent originated from road transport. The picture, however, differs largely among countries and the contribution varies greatly depending on the development of the transport sector and the level of control of stationary sources. For example, in the UK the share of transport was estimated at about 29 to 40 percent for PM_{10} and 40 to 45 percent for $PM_{2.5}$ (CEPMEIP, 2002; Berdowski *et al.,* 1997). The APEG (1999) study also suggests that nearly 28 percent of PM_{10} in the UK in 1995 derives from transport sources. According to CEPMEIP (2002) more than 85 percent of transport PM emissions in UK (in 1995) came from road traffic.

This section is divided into two major parts dealing with exhaust and non-exhaust emissions, the latter being more uncertain but presumed to contribute ten to 20 percent of PM emissions from transport. This might, however, change in the future since vehicle exhaust is subject to stringent legislation and it is expected that, in spite of growing car numbers, emissions from this source should decline.

The emission factors developed in RAINS for various vehicle categories rely to the maximum extent possible on the Auto-Oil studies (EC, 1999). Activity statistics of the transport sector (fuel consumption) are taken from the energy database of the RAINS model and are supplemented by additional data from the Auto-Oil Programme, i.e., average kilometers driven, size structure of the fleet, etc.

3.8.1 Exhaust Emissions

Exhaust emissions from transport activities represent between 80 and 90 percent of the total emissions from transport. The primary contribution comes from heavy-duty diesel vehicles, but in several countries light-duty vehicles might also contribute substantial amounts of PM. Emissions from spark-ignition engines are typically of lower concern for particulate matter, but they are important when the number and size of particles is considered.

3.8.1.1 Light-Duty Vehicles, Diesel Engines

Light- and heavy-duty diesel vehicles are a major contributor to PM emissions from road transport. In the last decade, the number of light-duty diesel vehicles has grown dramatically, especially in France and Austria, where they currently represent about 50 percent of new registrations. There is a large number of published papers providing the characteristics of PM emissions from diesel engines (especially from heavy-duty vehicles) and there is ongoing research to reduce these emissions and improve the “bad” environmental image of diesel vehicles.

RAINS Sectors:

TRA_RD_LD4

Description

Activity: Road transport, light-duty vehicles.

Unit: **kt/PJ** of diesel fuel consumed.

Emission Factors

Diesel exhaust particles are mostly sub-micrometer agglomerates of carbonaceous spherical particles ranging from ten to 80 nm. For example, Harrison *et al.* (2000) estimated that a significant proportion (estimated at about 90 percent) of diesel PM is smaller than 1 μm. Larger particles contain up to 4000 individual spherical particles clustered as agglomerates up to 30 μm (Morawska *et al.*, 1998).

The fuel injection process is one of the most important factors in pollutant formation in diesel engines. The distribution of fuel injected into the cylinder is non-uniform, and the generation of unwanted emissions (not only PM) is highly dependent on the degree of the non-uniformity (Yanowitz *et al*., 2000). PM formation is expected to increase under conditions that cause incomplete combustion, such as lower combustion temperature or poor mixing. The main problem in lowering diesel emissions is the inverse correlation between NO_x and PM emissions (Yanowitz *et al*., 2000). Apart from engine operating conditions, which strongly influence the total mass and number of particles emitted, typically increasing with load (Morawska *et al.*, 1998; Durbin *et al.*, 2000), there is a range of other factors that might play a role, for example, altitude, humidity, temperature and inertial weight (Yanowitz *et al*., 2000; Bishop *et al*., 2001).

In this study, the country-specific unabated PM_{10} emission factors for light-duty diesel vehicles are based on the Auto-Oil II study (EC, 1999). For those regions not included in the Auto-Oil II study, factors for countries with a similar per capita GDP and/or from the same climate zone were chosen (Table 3.84). Information on the $PM_{2.5}$ and TSP ratios was derived (averages) from Norbeck *et al.* (1998a), Durbin *et al.* (1999) and Kerminen *et al*. (1997).

Applicable Control Options

The control options included in the RAINS model are provided in Table 2.13. They are compatible with the EURO-I to EURO-V EC standards for light-duty vehicles.

Table 3.84: Uncontrolled emission factors considered in the RAINS PM module for diesel light-duty vehicles.

Country / region	$PM_{2.5}$ g/GJ	PM_{10} g/GJ	TSP g/GJ	TSP g/km[7]
Albania	95	99	100	0.37
Austria	97	102	102	0.37
Belarus	95	99	100	0.37
Belgium	97	102	102	0.37
Bosnia-Herzegovina	95	99	100	0.37
Bulgaria	105	109	110	0.40
Czech Republic	105	109	110	0.40
Croatia	95	99	100	0.37
Denmark	97	102	102	0.37
Estonia	122	127	128	0.47
Finland	111	116	116	0.36
France	105	110	111	0.39
Germany	97	102	102	0.38
Greece	81	85	85	0.36
Hungary	105	109	110	0.40
Ireland	105	110	111	0.36
Italy	87	91	91	0.32
Latvia	122	127	128	0.47
Lithuania	122	127	128	0.47
Luxembourg	99	104	104	0.38
Macedonia, FYR	95	99	100	0.37
Moldova, Rep. of	105	109	110	0.40
Netherlands	99	104	104	0.40
Norway	111	116	116	0.42
Poland	105	109	110	0.40
Portugal	87	90	91	0.33
Romania	95	99	100	0.37
Russia, St. Petersburg	122	127	128	0.47
Russia, Kola-Karelia, Kaliningrad	122	127	128	0.47
Russia, remaining territories	105	109	110	0.40
Slovakia, Rep. of	105	109	110	0.40
Slovenia	87	90	91	0.33
Spain	92	96	97	0.35
Sweden	111	116	116	0.42
Switzerland	97	102	102	0.37
Ukraine	105	109	110	0.40
United Kingdom	104	109	110	0.43
Yugoslavia	95	99	100	0.37

[7] Coefficient expressed in g/km was calculated from the coefficient in g/GJ assuming vehicle fuel efficiency as in the base year (1990)

3.8.1.2 Heavy-Duty Vehicles, Diesel Engines

Exhaust particulate matter emissions from heavy-duty vehicles are the most important source of PM from road transport. This is also a category that faces the most stringent emission standards in the EU.

RAINS Sectors:

TRA_RD_HD

Description

Activity: Road transport, heavy-duty vehicles.

Unit: **kt/PJ** of diesel fuel consumed.

Emission Factors

PM emissions from new heavy-duty vehicles are, by about an order of magnitude, lower (in g/km) than from vehicles in the 1970s, but emissions from a modern diesel consist of smaller particles (the cluster structures are similar though) (Harrison *et al.*, 2000). A number of important factors influencing emissions from diesel engines are listed in the previous section. In the context of heavy-duty vehicles it may be important to add that the deterioration factor is of great importance since such vehicles are typically driven several thousands of kilometers between the obligatory check-ups.

The country-specific unabated PM_{10} emission factors for diesel heavy-duty trucks (Table 3.85) are based on the Auto Oil 2 study (EC, 1999). For those regions not included in the Auto-Oil II study, factors for countries with a similar per capita GDP and/or from the same climate zone were chosen. Information on the $PM_{2.5}$ and TSP ratios was derived (averages) from Norbeck *et al.* (1998c), Williams *et al.* (1989) and Durbin *et al.* (1999).

Applicable Control Options

The control options included in the RAINS model are given in Table 2.13. They are equivalent to the EURO-I to EURO-V standards for heavy-duty vehicles.

Table 3.85: Uncontrolled emission factors used in the RAINS PM module for diesel heavy-duty vehicles.

Country / region	$PM_{2.5}$	PM_{10}	TSP	TSP
	g/GJ	g/GJ	g/GJ	g/kWh[8]
Albania	62	63	64	0.57
Austria	48	48	49	0.44
Belarus	62	63	64	0.57
Belgium	48	48	49	0.44
Bosnia-Herzegovina	62	63	64	0.57
Bulgaria	68	69	70	0.63
Croatia	62	63	64	0.57
Czech Republic	68	69	70	0.63
Denmark	48	48	49	0.44
Estonia	64	65	66	0.59
Finland	58	59	60	0.54
France	51	52	53	0.47
Germany	48	48	49	0.44
Greece	57	58	59	0.53
Hungary	68	69	70	0.63
Ireland	53	54	55	0.49
Italy	58	59	60	0.54
Latvia	64	65	66	0.59
Lithuania	64	65	66	0.59
Luxembourg	53	54	55	0.49
Macedonia, FYR	62	63	64	0.57
Moldova, Rep. of	68	69	70	0.63
Netherlands	53	54	55	0.49
Norway	58	59	60	0.54
Poland	68	69	70	0.63
Portugal	56	57	58	0.52
Romania	62	63	64	0.57
Russia, St. Petersburg	64	65	66	0.59
Russia, Kola-Karelia, Kaliningrad	64	65	66	0.59
Russia, remaining territories	68	69	70	0.63
Slovenia	56	57	58	0.52
Slovakia, Rep. of	68	69	70	0.63
Spain	54	55	56	0.50
Sweden	58	59	60	0.54
Switzerland	48	48	49	0.44
Ukraine	68	69	70	0.63
United Kingdom	58	59	60	0.54
Yugoslavia	62	63	64	0.57

8 Coefficient expressed in g/kWh was calculated from the coefficient in g/GJ assuming 40 percent efficiency of diesel engine.

3.8.1.3 *Light-Duty Vehicles and Motorcycles, Gasoline and Other Spark Ignition Engines*

Although PM emission levels from gasoline engines are significantly lower than those of diesel engines (and consequently more difficult to measure accurately), they are still important. In some countries, where light-duty diesel vehicles do not form a major share, e.g., Scandinavia, the gasoline contribution to total exhaust PM emissions might be more important than diesel. Another important element of PM emissions from gasoline engines is the size distribution. Studies indicate that they are smaller than from diesel engines (e.g., Cadle *et al.*, 2001; Ristovski *et al.*, 1998) and, therefore, potentially more harmful to human health.

RAINS Sectors:

TRA_RD_LD4	TRA_RDXLD4
TRA_RD_M4	TRA_RD_LD2

Description

Activity: Road transport, light-duty vehicles and motorcycles (4-stroke and 2-stroke).

Unit: **kt/PJ** of gasoline consumed.

Emission Factors

Particulate matter is formed as a result of the incomplete combustion of gasoline. The particles are mostly carbonaceous spherical sub-micron agglomerates ranging from ten to 80 nm, consisting of a carbon core with various associated organic compounds (Ristovski *et al.*, 1998). Apart from the design of the spark-ignition engines, several other parameters describing engine-operating conditions influence the amount of PM emissions. Kayes and Hochreb (1999a) found that fuel type and fuel/air ratio are among the most important ones. The same authors demonstrate in another paper (Kayes and Hochreb, 1999b) that the difference in PM emissions with and without catalytic converters is not statistically significant. Although in some cases a reduction of PM up to 85 percent was measured, in other cases catalyst cars showed increased emissions – a phenomenon not yet fully understood. This also contradicts a few other studies that show lower emissions from catalytic cars (e.g., APEG, 1999) and different size distributions (e.g., EPA, 1995; APEG, 1999).

Most of the measurements performed for non-catalyst cars also use leaded fuel and it is difficult to obtain conclusive data for unleaded-no catalyst combinations. Durbin *et al.* (1999) reviewed a number of studies showing that for properly functioning modern gasoline cars PM emissions are typically below 1 mg/MJ. However, measurements done on in-use vehicles indicate great variability (even if 'smokers' are excluded), e.g., his own results for mid-80's vehicles indicate a PM emission rate of about 3 mg/MJ, Hildemann *et al.*, 1991 measured emissions of $PM_{2.0}$ from early US catalyst cars (1973-1983) at the level of 3.3 mg/MJ while Lang (1981) showed urban and highway cycle PM emissions for catalyst cars to be in a range from 1.3-20 and 0.9-13.4 mg/MJ, respectively. Overall, the evidence (Hildemann *et al*, 1991; Durbin *et al.*, 1999; Norbeck *et al*, 1998ba&c; Williams *et al.*, 1989) suggests for catalyst vehicles an average value of around 3 mg/MJ for sub-micron particles, which would give an approximate value of 3.6 mg/MJ of total PM. This is based to a large extent on the US studies, excluding from analysis very old (pre-1985) and new (post-1991) US vehicles and assuming an improvement in fuel efficiency from about 15 liters/100 km in the beginning of 80's to about 12 liters/100 km in the beginning of 90's. For the newest generation of light-duty vehicles, equipped with three-way catalysts, (CONCAWE, 1998; Cadle *et al.*, 2001 and Norbeck *et al.*, 1998b&c) the reported values are significantly lower than measurements for other vintages; the estimated average for sub-micron emissions is around 1 mg/MJ.

Only few studies (Hall and Dickens, 1999; Kwon *at al*., 1999; Lappi *et al.*, 2001) measured emissions of PM for gasoline direct injection (GDI) vehicles. Hall and Dickens (1999) concentrated on number and size distribution measurements, although also reporting PM mass. They concluded that number and size distributions for GDI engines resemble those of diesel engines but the total mass is significantly lower. There was a wide spread in reported emissions with an average at the lower end of measurements reported for three-way catalyst gasoline vehicles. This is not confirmed in the two other studies that basically show higher (by approximately 50 percent) PM emissions from GDI engines when compared with fuel port injection (FPI) gasoline engines. Kwon *et al*. (1999) tested the vehicle using both European and US tests and showed a spread of 0.8 to 1.4 mg/km, giving an average for the European test of 1.3 mg/km (about 5.5 mg/MJ). Lappi *et al.* (2001) reports the size distribution for GDI vehicles and black carbon (BC) and organic carbon (OC) mass emissions and not the total PM mass but on the basis of this information one could conclude that their measurements agree broadly with the range given by Kwon *et al.* (1999).

Data on the size distribution of PM emissions from gasoline vehicles is sparse. In a very recent study, Cadle *et al.* (2001) measured the size distribution for 30 light-duty gasoline vehicles (1990-1997 models) and estimated that on average 95.1, 88.7 and 83.6 percent of particle mass was smaller than 12.2, 3.0, and 1.2 μm, respectively. Although a few available papers (Williams *et al.,* 1989; Durbin *et al.*, 1999) confirm that sub-micron (<1 μm) particles represent typically 80 to 90 percent of PM, there is no good agreement for $PM_{2.5}$ and PM_{10}. Norbeck *et al.* (1998b) and Durbin *et al.* (1999) show that older vehicles (pre-1985; possibly no or early catalyst) emit a higher share of PM_{10} and $PM_{2.5}$, i.e., about 95 and 90 percent, respectively, while newer (post 1986) tend to emit more of the larger fraction, i.e. <90 percent of PM_{10} and <85 percent of $PM_{2.5}$. One possible explanation (Durbin *et al.*, 1999) is that as the exhaust emissions decrease, the relative contribution (to the total PM) of re-entrained particles, such as deposits in the exhaust system, increases. The size distribution assumed in RAINS for the unabated emission factors is based on the measurements for pre-1985 cars (Durbin *et al.*, 1999 and Norbeck *et al.* 1998b).

In this study, the unabated emission factors for gasoline cars are derived from the measurement data discussed above (principally for cars with three-way catalysts), assuming additionally that the catalyst reduces PM emissions by about 50 percent (APEG, 1999). The latter assumption needs to be reviewed in the near future when new evidence will be available. The higher emission factors for two-stroke engines were calculated using information from the CBS (1998) report. The values (Table 3.86) are not country-specific. Few data were found on emission rates for LPG and CNG (compressed natural gas) vehicles. Durbin *et al.* (1998) measured gaseous and particle emissions from CNG and other alternative fuels using several vehicles of the same make, i.e., 1994 model of Dodge Caravans with 3.3L V6 engine, which is hardly representative for the European situation. The reported PM emission rates varied between 0.2 and 1 mg/MJ. Considering the fact that the tested cars were equipped with modern three-way catalysts and relating the reported emissions to the data for off-road CNG engines (Table 3.92), the PM emission factor is estimated at 2 mg/MJ. The size fraction distribution is based on Breadsley *et al.*, 1998.

Table 3.86: Uncontrolled emission factors for unleaded gasoline (GSL), liquefied petroleum gas (LPG) and natural gas (GAS) considered in the RAINS PM module [g/GJ].

Category	RAINS Code	$PM_{2.5}$	PM_{10}	TSP
Light duty vehicles and motorcycles, gasoline four stroke engines	TRA_RD_LD4, TRA_RD_M4	6.0	6.3	6.6[9]
Light duty vehicles, GDI [(1)]	TRA_RDXLD4	10.0	10.6	11.1
Motorcycles, mopeds, cars - gasoline two stroke engines	TRA_RD_LD2	94.9	100.5	111.7
Light duty vehicles, LPG	TRA_RD_LD4	1.8	2.0	2.0
Light duty vehicles, CNG	TRA_RD_LD4	1.8	2.0	2.0

[(1)] GDI – gasoline direct injection engines

It has been assumed that vehicles fueled with hydrogen do not emit particles. Information on emissions caused by the use of other “alternative” fuels like methanol or ethanol is missing. Since these fuels do not play an important role until 2010, it has been assumed that the emission factors are the same as for gasoline engines. This assumption will need to be verified in the future.

Although leaded gasoline is not sold any more in the majority of European countries, it is important to recognize its contribution to PM emissions in the past. Tetramethyl lead has been used as a petrol additive to enhance octane rating. Due to the adverse effects of lead on human health and the growing use of catalytic converters, which are poisoned by lead, the use of leaded gasoline is declining rapidly. Lead added to gasoline results in higher PM emissions. To address this issue, additional PM emission factors for light-duty and heavy-duty vehicles (Table 3.87) were introduced.

Ganley and Springer, 1974. Hildemann *et al.*, 1991 and Williams *at al*., 1989a reviewed several studies where total PM emissions from vehicles run on leaded fuel were studied. The values reported in these studies vary between around 6 and 40 mg/MJ. Taking an average of all reported data results in 20.4 mg/MJ[10]. Assumptions about the size fraction distribution are based on the results presented in Williams *et al.* (1989a), who showed that the sub-micron share of PM for cars running on leaded gasoline is about 86 percent, and on a study by Norbeck *et al.*

[9] 20 mg/km for an average car.

[10] Note that this is different from the number found in Table 3.87, i.e., 13.8 mg/MJ, since that table refers to the ‘additional’ emissions of PM from leaded gasoline when compared with unleaded fuel. Therefore, 20.4 mg/MJ is the sum of 13.8 and 6.6 mg/MJ (see Table 3.86).

(1998b) where they found, for pre-1981 vehicles, that shares of PM_{10} and $PM_{2.5}$ are about 96 and 90 percent, respectively.

Table 3.87: Emission factors used in the RAINS model for leaded gasoline [g/GJ].

	RAINS code	$PM_{2.5}$	PM_{10}	TSP
Leaded gasoline	LFL	12.4	13.2	13.8

Applicable Control Options

Although there are no PM emission standards for gasoline vehicles, the RAINS model takes the effects of introducing three-way catalyst and oxidation catalysts on PM emissions into account. The options for cars are compatible with the abatement levels necessary to meet EU legislation for other regulated pollutants (EURO-I to EURO-V). Oxidation catalysts of various types (stage 1 to 3) are also considered for two-stroke mopeds and motorcycles. A list of available control options can be found in Table 2.15.

3.8.1.4 Off-road Machinery and Shipping

RAINS Sectors:

TRA_OT	TRA_OT_AGR	TRA_OT_CNS
TRA_OT_RAI	TRA_OT_INW	TRA_OT_LB
TRA_OT_AIR	TRA_OT_LD2	TRA_OTS_M
TRA_OTS_L		

Description

Activity: Fuel used in off-road machinery and national sea shipping.

Unit: **kt/PJ** of fuel consumed.

Emission Factors

A number of studies report emission factors for off-road diesel sources (Table 3.88). Most data are for total PM emissions or for PM_{10}, with the exception of CEPMEIP (2002) where assumptions about a share of $PM_{2.5}$ are made, i.e. 90 % of TSP. The data shown in American and European studies are fairly consistent. For shipping, data from the Lloyd's Register study (Lloyd's Register, 1995; Wright, 1997, 2000) are used assuming an average fuel oil sulfur content in Europe of 2.5 percent (Table 3.92). For other off-road diesel sources (Table 3.91) data from BUWAL (2000a) were used as they probably better represent the European situation but, at the same time, compare well with Kean *et al.* (2000) and CEPMEIP (2002). A serious deficiency in studies that report PM emissions from compression ignition engines is the lack of size distribution; the CEPMEIP (2002) data was used for all the categories[11] included.

[11] CEPMEIP (2002) assumes the same distribution for all classes of engines independent of size and fuel used, i.e. fuel oil or diesel.

Table 3.89 lists a number of studies where emission factors and size distributions for spark-ignition engines are reported. For engines running on LPG and CNG there is only one source of data and values from Breadsley *et al.* (1998) are used in RAINS for PM_{10}. There is a wide variation in emission factors reported for four-stroke gasoline engines. An average excluding two very low values and the highest one (CEPMEIP, 'high emission') was derived. Also for two-stroke engines an average was derived from the numbers reported in the literature.

Information regarding size fraction distribution for off-road engines is inadequate; CEPMEIP (2002) assumes all particles are $PM_{2.5}$ while Breadsley *et al.* (1998) assumes that all are smaller than PM_{10} and 92 percent is $PM_{2.5}$. This is contradictory to the information that is available for, for example, gasoline cars (Norbeck *et al.*, 1998ab), where about 95 percent is PM_{10}. Owing to typically worse maintenance of off-road equipment, when compared with cars, the emissions are assumed to be characterized by a higher share of larger particles and, therefore, 90 percent was taken as the share of PM_{10}. For $PM_{2.5}$ the Breadsley *et al.* (1998) assumption that $PM_{2.5}$ represents 92 percent of PM_{10} was used. Recognizing great uncertainty in these emission factors, no distinction is made between rates for agricultural machinery, construction, etc., but one value is used for all off-road machinery. Similarly, no country- or region-specific values have been defined as yet. The emission factors used in RAINS are presented in Table 3.92.

Table 3.88: Summary of emission factors for off-road compression ignition engines; [g/GJ] unless specified otherwise.

Source	Type	$PM_{2.5}$	PM_{10}	TSP
BUWAL, 2001	Railways		13.9 g/km	
	Trams		0.33 g/km	
	Aircrafts LTO		191 g/LTO	
	Construction machinery		15.4 g/h	
	Agricultural machinery		39.1 g/h	
	Industrial machinery		1.92 g/h	
	Military vehicles		40.7 g/h	
Lloyd's Register, 1995[(1)]; Wright, 1997[(1)], 2000[(1)]	Shipping, fuel oil (2.8% S)			190
	Shipping, gas oil (0.17% S)			28.6
Cooper, 2001[(1)]	High speed ferry, diesel			15
Berdowski *et al.*, 1997[(1)] and APEG, 1999	Marine vessels, fuel oil		150±90	
	Marine vessels, diesel		40±20	
CEPMEIP, 2002	Inland navigation, fuel oil	132	139	146
	Inland navigation, diesel	88	93	97
	Other off-road, diesel	132	139	146
Miersch & Sachse, 1999[(1)]	Diesel engines (18-560kW)			76-51
BUWAL, 2000a	Rail, diesel			107
	Inland navigation, diesel			117
	Construction, diesel			152
	Agriculture, diesel			159
	Forestry, diesel			155
	Industry, diesel			145
	Off-road, diesel (average)			133

Source	Type	$PM_{2.5}$	PM_{10}	TSP
Kean *et al.*, 2000[(1)]; EPA, 1991[(1)]; Breadsley and Lindhjem, 1998[(1)]	Industrial machinery, diesel		148	
	Agriculture, diesel		090	
	Construction, diesel		131	
	Off-road, diesel (average)		120±55	
	Rail, diesel (average)		50±7	

[(1)] Values reported in g/kg of fuel were converted assuming heating values for fuel oil and diesel of 40 MJ/kg and 42 MJ/kg, respectively.

Table 3.89: Summary of emission factors for off-road spark ignition engines; [g/GJ]

Source	Type	$PM_{2.5}$	PM_{10}	TSP
CEPMEIP, 2002	Gasoline, 'high emission'	93	93	93
	Gasoline, 'low emission'	23.25	23.25	23.25
Breadsley *et al.*, 1998	Gasoline, 4-stroke	4.6	5	5
	Gasoline, 2-stroke	590	642	642
	LPG/ CNG, 4-stroke	4.2	4.2	4.2
	Off-road [(1)], 2-stroke		26.83	
EPA, 1991	Gasoline tractors (farm)			28.6
	Gasoline non-tractors (farm)			24.5
	Construction equipment			34 -44
	Industrial equipment			36.9
	Lawn and garden (4-stroke)			14.7
	Lawn and garden [(2)] (4-stroke)			45.8
	Lawn and garden (2-stroke)			177
	Lawn and garden [(2)] (2-stroke)			437
	Recreational boats (inboard gasoline engine)			6

[(1)] Refers to motorcycles, all terrain vehicles, snowmobiles, specialty vehicles, and underground mining equipment.
[(2)] Reported by another contractor.

Table 3.90: Emission factors used in the RAINS PM module for heavy fuel oil (HF) for off-road sources and shipping.

Sector	RAINS code	$PM_{2.5}$	PM_{10}	TSP	TSP
		g/GJ	g/GJ	g/GJ	g/kWh[12]
Other land-based machinery	TRA_OT_LB	135	143	150	1.2
Ships, medium vessels	TRA_OTS_M	113	119	125	1.0
Ships, large vessels	TRA_OTS_L	113	119	125	1.0

[12] Coefficient expressed in g/kWh has been calculated from the coefficient in g/GJ assuming 45 percent efficiency of diesel engine.

Table 3.91: Emission factors used in the RAINS PM module for diesel (MD) off-road sources and shipping.

Sector	RAINS code	$PM_{2.5}$	PM_{10}	TSP	TSP
		g/GJ	g/GJ	g/GJ	g/kWh[13]
Agriculture	TRA_OT_AGR	141	149	157	1.41
Construction	TRA_OT_CNS	134	141	149	1.34
Railways	TRA_OT_RAI	96.4	102	107	0.96
Inland navigation	TRA_OT_INW	0.105	111	117	1.05
Other land-based machinery	TRA_OT_LB	0.112	127	133	1.2
Medium vessels	TRA_OTS_M	25.7	27.2	28.6	0.26
Large vessels	TRA_OTS_L	25.7	27.2	28.6	0.26

Table 3.92: Emission factors used in the RAINS PM module for off-road spark ignition engines [g/GJ].

Sector	RAINS code	$PM_{2.5}$	PM_{10}	TSP
Land-based machinery gasoline (4-stroke)	TRA_OT_LB	28.0	30.4	33.8
Land-based machinery LPG/CNG (4-stroke)	TRA_OT_LB	3.90	4.20	4.24
Land-based machinery gasoline (2-stroke)	TRA_OT_LD2	289	381	423

Applicable Control Options

The control options included in the RAINS model reflect the requirements of EU legislation for off-road diesel machinery used in construction and agriculture (compare Section 2.4.2.2). The RAINS model also includes options to control emissions from gasoline engines, equivalent to the EURO-I to EURO-V standards for gasoline cars. Abatement options for ships include the switch to low sulfur fuel and engine modifications that affect emissions of PM (Lloyd's Register, 1995; Kjeld, 1995).

3.8.2 Non-exhaust Emissions from Mobile Sources

Non-exhaust emissions from mobile sources make significant contributions to total PM emissions in Europe. The importance of this source will grow in the future since effective control programs are in place to reduce exhaust emissions from transport.

The RAINS model distinguishes three categories of non-exhaust emissions from mobile sources; tire wear, brake wear and road abrasion.

[13] Coefficient expressed in g/kWh was calculated from the coefficient in g/GJ assuming 40 percent efficiency of diesel engine.

3.8.2.1 Tire Wear

According to current estimates, tire wear contributes around 2.8 and 0.3 percent to total European TSP and PM_{10} (CEPMEIP, 2002). This can vary from country to country, e.g., Swiss estimates suggest that 4.2 percent of PM originates from this source (BUWAL, 2001; EWE, 2000) and Winiwarter *et al*. (2001) estimated for Austria a share of around nine and four percent for TSP and PM_{10}, respectively. Excluding re-suspension, tire wear is probably the largest source of non-exhaust TSP and PM_{10} emissions from road transport. Approximately half of the non-exhaust PM_{10} originates from this source and possibly as much as 80 percent of TSP.

In the last decades, emission rates per kilometer declined due to the introduction of radial tires that replaced traditional bias plies. Radial tires are characterized by lower wear rates. However, recent research indicates that the particles from radial tires are smaller than from bias plies and may have greater health impacts (SENCO, 1999)[14]. Measurements reported by Rautenberg-Wulff (1998) and Weingartner *et al.* (1997) found relatively low shares of PM_3.

RAINS Sectors:

TRT_RD_LD4	TRT_RDXLD4	TRT_RD_LD2
TRT_RD_M4	TRT_RD_HD	

Description

Activity: Light-duty and heavy-duty vehicles and motorcycles (4-stroke and 2-stroke).

Unit: **g/km** driven.

Emission Factors

The emission factors for tire wear used in the RAINS PM module (

Table 3.95) are based on a summary of the TSP and PM_{10} emission factors shown in Table 3.93 and Table 3.94. Most of the available inventories or measurements programs do not provide detailed size fractions, which makes estimating the $PM_{2.5}$ fraction difficult. Older studies indicated that the $PM_{2.5}$ emissions from tire wear are important, e.g., EPA (1995) (based on EPA 1985 estimates), Berdowski *et al.* (1997) and Israel *et al.* (1994), while more recent measurements (Rautenberg-Wulff, 1998; Weingartner *et al.*, 1997; Israel *et al.*, 1996 and later versions of PART5 model of EPA) do not confirm this. Accordingly, the assumed $PM_{2.5}$ emission factors in RAINS are relatively low, i.e., five percent of PM_{10}.

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[14] There is no precise definition of "smaller" and consequently the following sentence referring to the measurements of PM_3 does not have to be in contradiction with this statement.

Table 3.93: Summary of emission factors for tire wear of light-duty vehicles given in the literature [g/km].

Source	Vehicle type	PM_{10}	TSP
EPA, 1995	Passenger cars, light-duty vehicles	0.0050	---
Environment Australia, 2000	Motorbikes	0.0025	---
Baumann *et al*., 1997	Passenger cars	---	0.0800
Dannis, 1974	Cars	---	0.024-0.36
SENCO, 1999	Cars	---	0.163
Rautenberg-Wulff, 1998	Passenger car, station wagon	0.0061	---
Garben *et al*., 1997	Passenger car	---	0.0640
	Light-duty vehicle	---	0.1120
	Motorbikes	---	0.0320
CEPMEIP, 2002	Passenger car	0.0018	0.069
	Light-duty vehicle	0.0045	0.09
	Motorbikes	0.0018	0.0345
EMPA (2000)	Light duty vehicles	0.0130	0.0530
	Motorbikes	0.007	---
Gebbe *et al*., 1997	Passenger car	---	0.0528
	Light-duty vehicles	---	0.1100
	Motorbike	---	0.0264
	Passenger car, petrol	---	0.0525
	Passenger car, diesel	---	0.0563

Table 3.94: Summary of emission factors for tire wear of heavy-duty vehicles given in the literature [g/km].

Source	Vehicle type	PM_{10}	TSP
EPA, 1995	Heavy-duty vehicles	0.0075	---
	Articulated lorry	0.0225	---
Baumann *et al*., 1997	Heavy-duty vehicle	---	0.1890
	Articulated lorry	---	0.2340
	Bus	---	0.1920
SENCO, 1999	Truck	---	1.403
Rautenberg-Wulff, 1998	Heavy duty vehicles	0.0310	---
Garben *et al*., 1997	Heavy-duty vehicle	---	0.7680
CEPMEIP, 2002	Heavy-duty vehicle	0.0186	0.3713
EMPA (2000)	Heavy duty vehicles	0.2000	0.7980
Gebbe *et al*., 1997	Heavy-duty vehicles	---	0.5394
	Heavy duty vehicles, petrol	---	0.0784
	Heavy duty vehicles, diesel	---	0.2041

Table 3.95: Emission factors for tire wear used in RAINS [g/km].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Light duty vehicles [(1)]	TRT_RD_LD4	0.0003	0.0062	0.0065	0.0596	0.0661
Motorbikes [(2)]	TRT_RD_M4	0.0001	0.0031	0.0032	0.0250	0.0282
Heavy duty vehicles	TRT_RD_HD	0.0020	0.0380	0.0400	0.3808	0.4208

[(1)] The same emission factor assumed for gasoline direct injection vehicles (TRT_RDXLD4)
[(2)] The same emission factor assumed for mopeds (TRT_RD_LD2).

Applicable Control Options

Technical control options to reduce PM emissions from tire wear are not considered in the RAINS model.

3.8.2.2 Brake Lining Wear

This category is not a major source of PM emissions, typically below one percent of total emissions. The Swiss inventory (BUWAL, 2001; EWE, 2000) estimated its share at 0.4 percent, while CEPMEIP calculated for Europe shares of around 0.3, 0.5, and 0.8 percent for TSP, PM_{10}, and $PM_{2.5}$, respectively. However, its importance might increase in the future since tailpipe emissions will be reduced and traffic volumes continue to grow.

RAINS Sectors:

TRB_RD_LD4	TRB_RDXLD4	TRB_RD_LD2
TRB_RD_M4	TRB_RD_HD	

Description

Activity: Light-duty and heavy-duty vehicles and motorbikes (4-stroke and 2-stroke)

Unit: g/km driven.

Emission Factors

The emission factors for brake wear reported in the literature are summarized in Table 3.96. The values are sometimes difficult to compare because the types of vehicles tested vary; in some cases only aggregated categories are reported (e.g., the sum of cars and trucks), in others background information was not identified. The values used in the RAINS model at this stage (Table 3.97) are derived primarily from Cadle *et al.* (2000) and Rautenberg-Wulff (1998). The widely used U.S. EPA emission factors (EPA, 1995) rely on fairly old measurements done in 1983 by Cha *et al.* (1983) for asbestos brakes and are therefore not considered in estimating the RAINS rates. Emission factors for motorbikes are assumed to be about 15 percent of those for cars (own assumption), which results in slightly lower values than reported by BUWAL (2001). Overall, RAINS values are lower than emission factors used in the CEPMEIP (2002) study; however, the sources of CEPMEIP emission rates were not identified.

The size fraction distribution as reported in several studies varies even more than the emission rates. It was, therefore, decided to use the most recent measurements (Cadle *et al.*, 2000).

Table 3.96: Literature values of emission factors for brake lining wear [g/km].

Source	Vehicle type	$PM_{2.5}$	PM_{10}	TSP
BUWAL (2001), derived from Carbotech (1999)	Motorbikes	---	0.0009	---
	Passenger cars	---	0.0018	---
	Heavy duty vehicles	---	0.0035	---
	Light duty vehicles	---	0.0049	---
Rautenberg-Wulff (1998)	Passenger cars	---	0.0010	---
	Passenger cars, truck	---	---	0.012 - 0.018
	Heavy duty vehicles	---	0.0245	---
CEPMEIP, 2002	Motorbikes	0.003	0.003	0.003
	Passenger cars	0.006	0.006	0.006
	Light duty vehicles	0.0075	0.0075	0.0075
	Heavy duty vehicles	0.03225	0.03225	0.03225
Cadle *et al.*, 2000	Small cars	0.0018	0.0029	0.0034
	Large cars	0.0028	0.0045	0.0053
	Trucks	0.0048	0.0076	0.0088
EPA (1995), Environment Australia (2000), Cha *et al.,* 1983	Cars and trucks	0.0037	0.0078	0.0080

Table 3.97: Emission factors for brake lining wear used in RAINS [g/km].

Sector	RAINS code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Light duty vehicles (1)	TRB_RD_LD4	0.0022	0.0014	0.0036	0.0008	0.0044
Motorbikes (2)	TRB_RD_M4	0.0003	0.0002	0.0005	0.0001	0.0006
Heavy duty vehicles	TRB_RD_HD	0.0071	0.0157	0.0228	0.0047	0.0275

(1) The same emission factor assumed for gasoline direct injection vehicles (TRT_RDXLD4)
(2) The same emission factor assumed for mopeds (TRT_RD_LD2).

Applicable Control Options

Technical control options to reduce PM emissions from brake wear are not considered in the RAINS model.

3.8.2.3 Road Abrasion

Estimating the emissions from road abrasion is very difficult since there are no emission factors specifically related to road wear. Any abrasion of paved roads is typically included in total non-exhaust emission rates where tire, brake and road wear, as well as re-suspension, are included. There are some studies addressing tire and brake wear (see previous sections), but it is difficult to compare them directly with reported total non-exhaust emissions from traffic.

There is a clearly defined interface, in the RAINS integrated assessment model framework, between emission inventory (estimates of 'net' emissions) and the atmospheric dispersion calculations. Therefore, in order to avoid double-counting, it is assumed that the category "road abrasion" in the RAINS model should not include re-suspension of road dust. Unfortunately, several published inventories either do not clearly distinguish between abrasion and re-suspension or do not specify if the latter is included or not.

Several studies suggest that road abrasion, together with re-suspension, is a major source of PM emissions (Nicholson, 1988). For example, Gaffney *et al.* (1995) and Zimmer *et al.* (1992) estimated that the contribution of emissions from paved roads to total PM_{10} might be as high as 30 percent in California and 40 to 70 percent in the Denver Metropolitan area. A more recent study for France (Jaecker-Voirol and Pelt, 2000) suggests that re-suspension emissions may be three to seven times higher than exhaust emissions from road transport. All these studies used an approach based on the U.S. EPA methodology (EPA, 1995, 1997). It is important to mention here that the EPA AP-42 model has recently been the subject of critique, e.g., in an *Atmospheric Environment* journal article (Venkatram, 2000; Nicholson, 2000). It was claimed that this model is not likely to provide adequate estimates of PM_{10} emissions from paved roads and that more research is needed to establish reliable methods for measuring and estimating emissions from this source. A step towards improving the understanding of these sources has been made recently by a TRAKER measurement program started in Las Vegas (Kuhns *et al.*, 2001), but final results are not yet available.

RAINS Sectors:

TRD_RD_LD4	TRD_RDXLD4	TRD_RD_LD2
TRD_RD_M4	TRD_RD_HD	

Description

Activity: Light-duty and heavy-duty vehicles and motorbikes (4-stroke and 2-stroke)

Unit: g/km driven.

Emission Factors

As indicated in the introduction to this section, it is not an easy task to develop a set of emission factors for this category, especially in view of the latest discussions about the AP-42 method (Venkatram, 2000). The emission factors as reported in several studies are presented in Table 3.98, however, a direct comparison is very difficult as the reporting basis varies. In order to derive emission factors appropriate for the RAINS model, an attempt was made to subtract tire and brake wear, and re-suspension, from reported total non-exhaust emission factors. In doing so, tunnel studies were not considered because the various sources of non-exhaust emissions cannot be easily distinguished in such studies and they often include exhaust components.

Another difficulty was to decide about the size fraction split. It has been assumed that 50 percent of TSP is PM_{10} and that $PM_{2.5}$ represents about 50 percent of PM_{10}, which might lead to a slight overestimate of $PM_{2.5}$ emissions. The current RAINS values should be seen as a preliminary set subject to further review.

Comparison of RAINS emission factors with CEPMEIP shows a good match for PM_{10} but a very big discrepancy for TSP, i.e., in the case of light- and heavy-duty vehicles CEPMEIP factors are an order of magnitude larger than RAINS. The reason for this was not found and the CEPMEIP database does not include a reference for these emission rates.

Table 3.98: Emission factors for road abrasion given in the literature [g/km].

Source	Vehicle type	PM_{10}	TSP
CBS, 1998 (including tire, brake and road wear)	Heavy-duty vehicles	0.0380	---
	Light-duty vehicles	0.0090	---
	Passenger cars	0.0070	---
	Motorbikes < 50cc	0.0020	---
	Motorbikes > 50cc	0.0040	---
Berdowski *et al*., 1997 (includes tire, brake, road wear and re-suspension)	Light-duty vehicles	0.07	---
	Motorcycles	0.023	---
	Heavy-duty vehicles	1.17	---
EMPA, 2000 (including re-suspension)	Heavy-duty vehicles on paved roads	0.450	---
	Light-duty vehicles and cars on paved roads	0.030	---
Israel *et al*., 1994	Passenger cars (tunnel measurement)	---	0.12
	Truck (tunnel measurement)	---	2.00
CEPMEIP, 2002	Heavy-duty vehicles	0.0269	0.738
	Light-duty vehicles	0.0095	0.190
	Passenger cars	0.0073	0.145
	Motorbikes	0.0037	0.073
Israel *et al*., 1996	Passenger cars (tunnel measurement)	0.0380	---
	Truck (tunnel measurement)	0.5970	---
Rautenberg-Wulff, 1998	Passenger cars (tunnel measurement)	0.0320	---
	Truck (tunnel measurement)	0.8340	---

Table 3.99: Emission factors for road abrasion used in the RAINS model [g/km].

Sector	RAINS Code	$PM_{2.5}$	Coarse	PM_{10}	$>PM_{10}$	TSP
Light duty vehicles (1)	TRD_RD_LD4	0.0042	0.0033	0.0075	0.0075	0.0150
Motorbikes (2)	TRD_RD_M4	0.0016	0.0014	0.0030	0.0030	0.0060
Heavy duty vehicles	TRD_RD_HD	0.0209	0.0171	0.0380	0.0380	0.0760

(1) The same emission factor assumed for gasoline direct injection vehicles (TRT_RDXLD4)
(2) The same emission factor assumed for mopeds (TRT_RD_LD2).

Applicable Control Options

Technical control options to reduce PM emissions from road abrasion are not considered in the RAINS model.

4 Cost Calculations

The basic intention of a cost evaluation in the RAINS model is to identify the values to society of the resources diverted in order to reduce PM emissions in Europe. In practice, these values are approximated by estimating costs at the production level rather than prices to the consumers. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Certainly, there will be transfers of money with impacts on the distribution of income or on the competitiveness of the market, but these should be removed from a consideration of the efficiency of a resource. Any taxes added to production costs are similarly ignored as transfers.

As in the cost modules for other pollutants, a central assumption in the RAINS PM module is the existence of a free market for abatement equipment throughout Europe that is accessible to all countries at the same conditions. Thus, the capital investments for a certain technology can be specified as being independent of the country. Simultaneously, the calculation routine takes into account several country-specific parameters that characterize the situation in a given region. For instance, those parameters include: average boiler sizes, capacity/vehicles utilization rates, emission factors etc.

The expenditures on emission controls are differentiated into:

- investments,
- fixed operating costs, and
- variable operating costs.

From these three components RAINS calculates annual costs per unit of activity level. Next, these costs are related to ton of pollutant abated (PM_{10}, $PM_{2.5}$ or TSP).

Some of the parameters are considered common for all countries. These include technology-specific data, such as removal efficiencies, unit investment costs, fixed operation and maintenance costs, as well as parameters used for calculating variable cost components like extra demand for labor, energy, and materials.

Country-specific parameters characterize more closely the type of capacity operated in a given country and its operation regime. To these parameters belong: average size of installation in a given sector, plant factors, annual fuel consumption and/or mileage for vehicles. In addition, the prices for labor, electricity, fuel and other materials as well as cost of waste disposal also belong to that category.

The following sections introduce the cost calculation principles used in RAINS and explain the construction of the cost curves that will be further used in the optimization module of the RAINS model. To illustrate the methodology, examples of cost calculations are given. Values of all parameters used to calculate country-specific costs and the national cost curves are provided on the RAINS web site (http://www.iiasa.ac.at/rains).

Although based on the same principles, the details of cost calculations for individual sectors differ. Thus the formulas used for stationary combustion sources, the so-called process sources and mobile sources (vehicles) are discussed separately below.

All costs in the RAINS PM model are in constant 1995 prices.

4.1 Costs for Stationary Combustion Sources

Estimates of costs of dust control for stationary sources in the power plant sector and industrial boilers are based on data published by Rentz *et al.* (1996), Takeshita (1995), Soud (1995), and UN/ECE (1996).

4.1.1 Investments

Investments cover the expenditure accumulated until the start-up of an abatement technology. These costs include, e.g., delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement and capital. The RAINS PM model uses investment functions where these cost components are aggregated into one function. For stationary combustion sources the investment costs for individual control installations depend on flue gas volume treated. This in turn can be related to the boiler size *bs.* The form of the function is described by its coefficients ci^f and ci^v. Coefficients *ci* are valid for hard coal fired boilers. Thus, coefficient *v* is used to account for the different flue gas volume to be handled when other fuel is used. Additional investments, in the case of retrofitting existing boilers/furnaces, are taken into account by the retrofitting cost factor *r*. The shape of this investment function is given in Equation 4.1:

$$I = (ci^f + \frac{ci^v}{bs}) * v * (1 + r) \tag{4.1}$$

Coefficients *ci* are estimated based on investment functions presented in Rentz et al., 1996. The original investment functions relate capital investments in Euro/1000 m^3 flue gases/h to the volume of flue gases treated (in 1000 m^3/h). These functions have been converted to the function that uses boiler size (in MW_{th}). Parameters of the function are different for three capacity classes: less than 5 MW_{th}, from 5 to 50 MW_{th} and above 50 MW_{th}.

Investments are annualized over the technical lifetime of the plant *lt* by using the real interest rate *q* (as %/100):

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \tag{4.2}$$

4.1.2 Operating Costs

The annual **fixed expenditures** OM^{fix} cover the costs of repairs, maintenance and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for annual fixed expenditures, a standard percentage f of the total investments is used:

$$OM^{fix} = I * f \tag{4.3}$$

In turn, the **variable operating costs** OM^{var} are related to the actual operation of the plant and take into account:

- additional labor demand,
- increased energy demand for operating the device (e.g., for the fans and pumps), and
- waste disposal.

These cost items are calculated with the specific demand λ^x of a certain control technology and its (country-specific) price c^x.

$$OM^{var} = \lambda^l c^l / pf + \lambda^e c^e + ef_{TSP} * \eta_{TSP} * \lambda^d c^d \tag{4.4}$$

where

η_{TSP}	dust (TSP) removal efficiency,
λ^l	labor demand (per thermal capacity unit),
λ^e	additional electricity demand (per unit of fuel used),
λ^d	demand for waste disposal (per unit of dust reduced),
c^l	labor cost,
c^e	electricity price,
c^d	waste disposal cost,
pf	plant factor (annual operating hours at full load),
ef_{TSP}	unabated TSP emission factor

4.1.3 Unit Reduction Costs

Unit costs per PJ fuel used

Based on the above-mentioned cost items, the unit costs for the removal of PM emissions can be calculated. In Equation 4.5, all the expenditures of a control technology are related to one unit of fuel input (in PJ). The investment-related costs are converted to fuel input by applying the capacity utilization factor pf (operating hours/year):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} \tag{4.5}$$

Unit costs per ton of pollutant removed

The cost effectiveness of different control options can only be evaluated by relating the abatement costs to the amount of reduced emissions. For this purpose Equation 4.6 is used:

$$c_{PM_k} = c_{PJ} / (ef_k * \eta_k) \tag{4.6}$$

where:

k PM size fraction, i.e., $PM_{2.5}$, PM_{coarse}, PM_{10}, TSP

While the fuel- and activity-specific unit costs are unique for each abatement option, emission related unit costs obviously depend on the size fraction of PM emissions considered. This means that the same technology has different unit costs, depending on whether fine, coarse or PM_{10} is considered.

4.1.4 Parameters used and example cost calculation

Cost parameters of technologies to control emissions from stationary combustion sources in the power plant sector and in industry are shown in Table 4.1. They are based on average values from investment functions published by Rentz et al., 1996. The differences between the average and the maximum and the minimum values are up to ± 30 percent, which clearly demonstrates the variation and uncertainty of cost parameters. Since the functions are based on relatively detailed studies performed by the authors, the values seem to be appropriate for integrated assessment at the European level. From the other side, they should not be used for calculation of costs for a particular plant.

In the current version of the model, it has been assumed that the replacement of existing control equipment with the new, possibly more efficient technology occurs after amortization of the existing equipment. Thus, the retrofit cost factor equals zero and has not been shown in the table. All available sources say that installation of PM control equipment does not require additional personnel and this parameter has also been set to zero.

Table 4.1: Cost parameters for technologies used to control emissions from stationary combustion sources in power plants and industry

Technology	Investment coefficient (ci^f)	Investment coefficient (ci^v)	Fixed O+M (f)	Electricity demand (λ^e)	Capacity range, MW_{th}	
	€/kW_{th}	10^3 €	%	kWh/GJ fuel	from	to
ESP1 (1 field)	26.0	0.0	0.5	0.11	0	5
	6.9	95.9	0.5	0.11	5	50
	3.7	254.6	0.5	0.11	>50	
ESP2 (2 fields)	32.5	0.0	0.5	0.13	0	5
	8.6	119.9	0.5	0.13	5	50
	4.6	318.2	0.5	0.13	>50	
ESP3 (3 and more fields)	35.4	0.0	0.5	0.15	0	5
	10.2	126.4	0.5	0.15	5	50
	5.6	353.6	0.5	0.15	>50	
CYC (cyclones)	10.4	0.0	0.5	0.15	0	5
	2.7	38.4	0.5	0.15	5	50
	1.5	101.8	0.5	0.15	>50	
FF (fabric filters)	21.5	0.0	1.0	0.20	0	5
	11.0	52.3	1.0	0.20	5	50
	7.9	212.1	1.0	0.20	>50	
Wet scrubbers	31.9	0.0	1.0	1.50	0	5
	9.1	113.8	1.0	1.50	5	50
	5.0	318.2	1.0	1.50	>50	
Good housekeeping oil boilers	2.0	0.0	4.0	0.00	>0	

To illustrate the method of calculation, the costs for fabric filter technology installed on a brown coal fired boiler have been calculated in the example presented on the next page (see EXAMPLE 1). Technology-specific parameters used in this example are taken from the shadowed row in Table 4.1. Other parameters used in the calculation are listed[15] below (country-specific parameters assumed in the example are identical to those for Germany).

[15] Normally the installation of control equipment does not generate additional labor demand (λ^l). However, a non-zero value has been adopted in the example in order to better illustrate the calculation method.

EXAMPLE 1:

Unit cost calculation for fabric filters installed on brown coal fired boiler

Assumptions

Parameter	*Symbol*	*Value*
Retrofit cost factor	r	0
Interest rate	q	4 %
Flue gases volume relative to hard coal boiler	v	1.2
Additional labor demand	λ^l	0.001 man-year/MW_{th}
Waste byproduct disposal	λ^d	1 t/t TSP reduced
Lifetime of control equipment	lt	20 years
Efficiency of fabric filter	η_{TSP}	99.9 %
(as calculated by the PM module)	η_{PM10}	99.6 %
Unabated TSP emission factor	ef_{TSP}	3924 t/PJ
Unabated PM_{10} emission factor	ef_{PM10}	785 t/PJ
Wages	c^l	25000 €/man-year
Electricity costs	c^e	0.05 €/kWh
Boiler size (grate boiler)	bs	30 MW_{th}
Plant factor (annual operating hours at full load)	pf	4500 h
Cost of byproduct disposal	c^d	21 €/t
Other parameters	ci^f, ci^v, f, λ^e	Table 4.1

Individual cost components:

Capital investment: $I = (11.0 + 52.3/30)*1.2*(1+0.0) = 15.3$ €/kW_{th}

Annualized capital costs: $I^{an}=15.3*(1+0.04)^{20}*0.04/((1+0.04)^{20}-1)= 1.13$ €/kW_{th}-year

Fixed O+M costs: $OM^{fix} = 0.01*15.3 = 0.15$ €/kW_{th}- year

Variable costs: OM^{var} = 0.001[m-yr/MW_{th}]*25000[€/m-yr]/(4500[h]* *3600[s/h])*10^9[MJ/PJ] + 0.2[kWh/PJ_{fuel}]*10^6[GJ/PJ]* *0.05[€/kWh] + 3924[t dust/PJ]*0.999* *1.0[t/t]*21[€/t] = 93865 €/PJ

Unit costs

Per PJ fuel used: c_{PJ} = (1.13+0.15)[€/kW_{th}-year]/(4500[h/year]*3600[s/h])* *10^{12}[kJ/PJ] + 93865 = 172877 €/PJ

Per ton of PM_{10} removed: c_{PM10} = 172877/(0.996*785) = 221.1 €/t_{PM10}

4.2 Costs for Industrial Process Emission Sources

Costs of controlling pollution from industrial process sources take into account available estimates from the BAT reference documents prepared by the Integrated Pollution Prevention and Control (IPPC) Bureau (e.g., IPPC, 1999a,b) and by CONCAWE (1999). In addition, information about costs for individual processes from Rentz et al., 1996 as well as from a series of Austrian studies on possibilities of controlling pollutants from industrial installations was used (compare Staubenvoll and Schindler, 1998, Schindler and Ronner, 2000, Huebner et al., 2000, and Ecker and Winter, 2000). It must be noted that all sources stress that costs of controlling process emissions are highly site/process-specific. Besides, it is very often the case that particulate control installation is part of the flue gases treatment plant and thus it is difficult to separate costs of PM control from the costs of controlling other pollutants. The differences between individual sources are up to ± 50 percent. Thus, costs calculated by RAINS for this source category should be treated as indicative only. It is expected that the quality of information will improve as a result of the work of the Expert Group on Techno-Economic Issues (EGTEI) that has been established within the UN/ECE Convention on Long-range Transboundary Air Pollution.

4.2.1 Investments

For process sources the investment costs are related to the activity unit of a given process. For the majority of processes these are annual tons produced. For refineries the investment function is related to one ton of raw oil input to the refinery. The investment function and annualized investments are given by Equations 4.7 and 4.8:

$$I = ci^f * (1 + r) \tag{4.7}$$

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \tag{4.8}$$

4.2.2 Operating Costs

The operating costs are calculated with formulas similar to those used for stationary combustion. However, since the activity unit is different the formulas have a slightly different form:

$$OM^{fix} = I * f \tag{4.9}$$

$$OM^{var} = \lambda^l c^l + \lambda^e c^e + ef_{TSP} * \eta_{TSP} * \lambda^d c^d \tag{4.10}$$

The coefficients λ^l, λ^e, and λ^d are per ton of product.

4.2.3 Unit Reduction Costs

Unit costs per ton of product

This cost is calculated from the following formula:

$$c_{ton} = I^{an} + OM^{fix} + OM^{var} \quad (4.11)$$

Unit costs per ton of pollutant removed

As for combustion sources, one can calculate costs per unit of PM removed:

$$c_{PM_k} = c_{ton} / (ef_k * \eta_k) \quad (4.12)$$

where:

k PM size fraction, i.e., $PM_{2.5}$, PM_{coarse}, PM_{10}, TSP

4.2.4 Parameters used and example cost calculations

Cost parameters of technologies to control emissions from process sources are shown in Annex 2. The costs are expressed per ton of product produced in the process and include the necessity of controlling emissions from several operations during the whole production cycle. For instance, in cement plant the three major production installations included are: clinker kilns, clinker coolers, and cement mills. All costs are average values from the range given in the literature. These averages are valid for typical (in European conditions) average sizes of production installations. In spite of their large uncertainty, such cost parameters can be used in integrated assessment at the European level. However, they are not appropriate for the assessment of emission control costs for a specific plant.

In the current version of the model, it has been assumed that the replacement of existing control equipment with the new, possibly more efficient technology occurs after amortization of the existing equipment. Thus, the retrofit cost factor is zero and has not been shown in the table. As with combustion sources, installation of PM control equipment does not require additional personnel so this parameter has also been set to zero.

To illustrate the method of calculation, the costs for fabric filters installed in cement plant have been calculated below (see box on the next page with EXAMPLE 2). Technology-specific parameters used in this example are taken from the shadowed row in the table from Annex 2. They have been estimated based on the BAT document (IPPC, 1999)[16] (country-specific parameters assumed in the example are identical to those for Germany).

[16] Normally the installation of control equipment does not generate additional labor demand (λ^l). However, a non-zero value has been adopted in the example in order to better illustrate the calculation method. The assumption that there is no byproduct disposal means that all dust is either returned to the process or used as a useful product.

EXAMPLE 2:

Unit cost calculation for fabric filters installed in a cement plant

Assumptions

Parameter	*Symbol*	*Value*
Investment coefficient	ci^f	3.8 €/t cement/year
Retrofit cost factor	r	0
Interest rate	q	4 %
Fixed O+M cost coefficient	f	5.5 %
Additional electricity demand	λ^e	2.85 kWh/t cement
Additional labor demand	λ^l	0.2 m-year/Mt cement
Waste byproduct disposal	λ^d	0 t/t TSP reduced
Lifetime of control equipment	lt	20 years
Efficiency of fabric filter	η_{TSP}	99.78 %
(as calculated by the PM module)	η_{PM10}	99.51 %
Unabated TSP emission factor	ef_{TSP}	0.195 t/t
Unabated PM_{10} emission factor	ef_{PM10}	0.0819 t/t
Wages	c^l	25000 €/man-year
Electricity costs	c^e	0.05 €/kWh
Cost of byproduct disposal	c^d	21 €/t

Individual cost components (*eq. 4.7 to 4.10*):

Capital investment: I = 3.8 €/t

Annualized capital costs: I^{an}=3.8*(1+0.04)^{20}*0.04/((1+0.04)^{20}-1)= 0.28 €/t-year

Fixed O+M costs: OM^{fix} = 0.055*3.8 = 0.21 €/t- year

Variable costs: OM^{var} = 0.2[m-yr/Mt]*25000[€/m-yr]*10^{-6}[Mt/t] +
+ 2.85*[kWh/t]*0.05[€/kWh] + 0.195[t/t]*0.9978*0[t/t]*
*21[€/t] = 0.148 €/t cement

Unit costs (eq. 4.11 and 4.12):

Per ton cement produced: c_{ton} = (0.28+0.21+0.148) [€/t] = 0.638 €/t

Per ton of PM_{10} removed: c_{PM10} = 0.638/(0.9951*0.0819) = 7.83 €/t_{PM10}

4.3 Mobile Sources

Costs of controlling PM emissions from mobile sources are based on data used in the RAINS NO_x module (Cofala and Syri, 1998). The estimates developed for the NO_x module were derived from German sources (Rodt et al., 1995, 1996) as well as from the results of costing studies done within the AUTO OIL Programme (compare EC, 1996; Touche Ross & Co, 1995; Barrett, 1996). This information has been extended, taking into account cost assessments made within the AUTO OIL II Study (EC, 1999) as well as recent publications on new emerging technologies for controlling exhaust emissions from vehicles (Elvingson, 2002, Lerch, 2000, BUWAL, 2000). Literature estimates originated mainly from producers' expectations on the increase in production costs of vehicles meeting the new emission standards. In the meantime, a large part of the control equipment is already in series production. Thus, the costs used by the RAINS model will need to be verified when the costs based on real life experience become available.

4.3.1 Investments

The cost evaluation for mobile sources follows the same basic approach as for stationary sources. The most important difference is that the investment costs are given **per vehicle**, not per unit of production capacity. The number of vehicles is then computed based on information on total annual fuel consumption by a given vehicle category and average fuel consumption per vehicle per year.

The following description uses the indices *i, j*, *k* and *l* to indicate the nature of the parameters:

i	denotes the country,
j	the transport (sub)sector/vehicle category,
k	the control technology,
l	PM size class fraction (FINE, COARSE, or >PM10).

The costs of applying control devices to the transport sources include:

- additional investment costs;
- increase in maintenance costs expressed as a percentage of total investments; and
- change in fuel cost resulting from the inclusion of emission control.

The investment costs $I_{i,j,k}$ are given in €/vehicle and are available separately for each technology and vehicle category. They are **annualized** using Equation 4.13:

$$I^{an}_{i,j,k} = I_{j,k} \cdot \frac{(1+q)^{lt_{i,j,k}} \cdot q}{(1+q)^{lt_{i,j,k}} - 1} \tag{4.13}$$

where:

$lt_{i,j,k}$ lifetime of control equipment.

4.3.2 Operating Costs

The increase in maintenance costs (**fixed costs**) is expressed as a percentage *f* of total investments:

$$OM^{fix}_{i,j,k} = I_{i,j,k} \cdot f_k \tag{4.14}$$

The change in fuel cost is caused by:

- change in fuel quality required by a given stage of control[17]
- change in fuel consumption after inclusion of controls

It can be calculated as follows:

$$OM^{e}_{i,j,k}(t) = \Delta c^{e}_{j} + \lambda^{e}_{j,k} * (c^{e}_{i,j} + \Delta c^{e}_{j}) \tag{4.15}$$

where:

$\lambda^{e}_{j.k}$	percentage change in fuel consumption by vehicle type *j* caused by implementation of control measure *k,*
$c^{e}_{i,j}$	fuel price (net of taxes) in country *i* and sector *j* in the base year,
Δc^{e}_{j}	change in fuel cost caused by the change in fuel quality,

This change in fuel cost is related to one unit of fuel used by a given vehicle category.

Annual fuel consumption per vehicle is a function of the consumption in the base year (t_0=1990), **fuel efficiency improvement,** and **change in activity per vehicle** (i.e., change in annual kilometers driven) relative to the base year:

$$fuel_{i,j}(t) = fuel_{i,j}(t_0) * fe_{i,j}(t) * \Delta ac_{i,j}(t) \tag{4.16}$$

where

$fe_{i,j}(t)$ - fuel efficiency improvement in time step *t* relative to the base year (1990 = 1)
$\Delta ac_{i,j}(t)$ - change in activity per vehicle in time step *t* relative to the base year (1990 = 1)

4.3.3 Unit Reduction Costs

The unit costs of abatement ce_{PJ} (related to one unit of fuel input) add up to

$$ce_{PJ,i,j,k}(t) = \frac{I^{an}_{i,j,k} + OM^{fix}_{i,j,k}}{fuel_{i,j}(t)} + OM^{e}_{i,j,k}(t) \tag{4.17}$$

[17] This cost component takes into account higher fuel price caused by the change in fuel specification (e.g., different contents of aromatics or benzene, different cetane number)

These costs can be related to the emission reductions achieved. In the current version of the PM module the costs of emissions control in the transport sector are fully attributed to reductions of fine, coarse and >PM_{10} fractions, respectively. The costs per unit of PM abated are as follows:

$$cn_{i,j,k}(t) = \frac{ce_{i,j,k}(t)}{ef_{i,j,k,l} * \eta_{j,k.l}} \tag{4.18}$$

The most important factors leading to differences among countries in unit abatement costs are: different annual energy consumption per vehicle and country-specific unabated emission factors. The latter difference is caused by different compositions of the vehicle fleet as well as differences in driving patterns (e.g., different share of urban vs. highway driving depending on available infrastructure in a given country).

4.3.4 Parameters used and example cost calculation

Data on investments per vehicle and operation and maintenance costs of each control technology considered in the RAINS PM module are given in Annex 3. In order to illustrate the method, an example of calculating costs of controlling PM_{10} emissions from diesel heavy-duty trucks (RAINS sector TRA_RD_HD) equipped with an engine meeting the EURO IV standard is presented below (see box with EXAMPLE 3). The example is calculated assuming values of country-specific parameters as for Germany and other parameters as given in Annex 3 (compare shadowed row in the table). It is important to note that the additional cost of better quality diesel oil (Δc^e) includes the extra cost of producing diesel oil with higher cetane number and lower content of polyaromatics; To avoid double counting, the cost of reducing sulfur content is included in the SO_2 module of RAINS. We also assumed that there is a 0.5 percent increase (λ^e) in fuel consumption due to the implementation of the EURO-IV measures. However, operating experience with vehicles meeting stricter emission standards has shown that fuel consumption did not increase; a non-zero value was adopted in the example to better illustrate the calculation method.

EXAMPLE 3:

Unit cost calculation for heavy-duty trucks meeting EURO-IV standard

Assumptions

Parameter	*Symbol*	*Value*
Investment costs	I	7967 €/vehicle
Additional O+M costs	f	2.41 %/year
Interest rate	q	4 %
Lifetime of control equipment	lt	12 years
Diesel oil price	c^e	6.6 €/GJ
Additional cost of better quality diesel oil	Δc^e	0.0463 €/GJ
Fuel consumption in 1990	$fuel(t_0)$	621 GJ/veh-year
Change in fuel consumption caused by implementation of the EURO-IV measures	λ^e	0.5 %
Unabated PM_{10} emission factor	ef_{PM10}	48.4 t/PJ
Efficiency of EURO-IV measures (as calculated by the PM module)	η_{PM10}	97.0 %
Average fuel consumption in period 2005 – 2010 relative to 1990	fe	0.87
Activity per vehicle in period 2005 – 2010 relative to 1990	Δac	0.86

Individual cost components (*eq. 4.13 to 4.16*):

Annualized capital costs: I^{an}=7967*(1+0.04)^{12}*0.04/((1+0.04)^{12}-1)= 848.9 €/veh-y

Fixed O+M costs: OM^{fix} = 7967*0.0241 = 192 €/veh-y

Change in fuel costs: OM^{e} = 0.0463 + 0.005(6.6 + 0.0463) = 0.0795 €/GJ

Annual fuel consumption: $fuel(t)$ = 621*0.87*0.86 = 464.4 GJ/veh-y

Unit costs (eq. 4.17 and 4.18):

Per PJ fuel used: ce_{PJ} = ((848.9+192)[€/veh-y]/464.6[GJ/veh-y] +
+ 0.0795[€/GJ])*10^6[GJ/PJ] = 2.32*10^6 €/PJ

Per ton of PM_{10} removed: c_{PM10} = 2.32*10^6[€/PJ]/(48.4[t/PJ]*0.97) = 49416 €/t_{PM10}

4.4 Agriculture

As was discussed in Section 3.4 of this document, RAINS includes a number of control technologies for particulate matter sources in agriculture.

In principle, for techniques to control emissions from livestock housing, an algorithm similar to that developed for the NH_3 module may be used (see Klaassen, 1991). However, the necessary information on costs to estimate this function could not be found; even the ICC and SRI (2000) report provides only qualitative information about the acceptability of abatement options. To include the full control potential, RAINS considers these agricultural options but, in absence of solid data, assumes costs that are higher than those for the abatement options in other sectors. A similar approach is applied to other options that are related to arable farming. The assumed unit costs have to be seen as preliminary and subject to further change as soon as the relevant information is found.

4.5 Other Sectors

The RAINS model distinguishes control options for several other sectors like mining, storage and handling, open waste burning, construction (see appropriate sections in the document). The information on costs of these techniques or procedures is, however, not readily available and, therefore, the assumed unit costs have to be seen as preliminary and subject to further change as soon as the relevant information is found.

4.6 Marginal Reduction Costs

Marginal costs relate the extra costs for an additional measure to the extra abatement of that measure (compared to the abatement of the less effective option). RAINS uses the concept of marginal costs for ranking the available abatement options, according to their cost effectiveness, into the so-called "national cost curves" (see Section 4.7).

If, for a given emission source (category), a number of control options M are available, the marginal costs mc_m for control option m are calculated as

$$mc_m = \frac{c_m \eta_{l_m} - c_{m-1} \eta_{l_{m-1}}}{\eta_{l_m} - \eta_{l_{m-1}}} \qquad (4.19)$$

where

c_m	unit costs for option m and
η_{lm}	pollutant l removal efficiency of option m *(* $l = PM_{2.5}$, PM_{coarse}, PM_{10} *or TSP)*

The method of calculating the marginal cost is illustrated in the example below (see box with EXAMPLE 4) where marginal cost of increasing the removal efficiency in a given sector from 94.3 percent to 99.6 percent is calculated.

EXAMPLE 4:

Marginal cost calculation for industrial grate-fired boiler burning brown coal

Assumptions for fabric filter (FF)

Parameter	*Symbol*	*Value*
Unit costs per ton of PM_{10} removed	c_m	221 €/t_{PM10}
PM_{10} Removal efficiency (as calculated by the PM module)	η_m	99.6 %

Assumptions for one-field electrostatic precipitator (ESP1)

Parameter	*Symbol*	*Value*
Unit costs per ton of PM_{10} removed	c_m	194 €/t_{PM10}
PM_{10} Removal efficiency (as calculated by the PM module)	η_m	94.3 %

Marginal cost calculation (*eq. 4.19*):

$$mc_m = (221*99.6 - 194*94.3)/(99.6 - 94.3) = 701.4 \text{ €}/t_{PM10}$$

4.7 Constructing a Cost Curve

For each emission scenario RAINS creates a so-called emission reduction cost curve. Such cost curves define - for each country and year - the potential for further emission reductions beyond a selected initial level of control and provide the minimum costs of achieving such reductions. For a given abatement level a cost-optimal combination of abatement measures is defined.

In the optimization module of RAINS, cost curves capturing the remaining measures beyond the baseline scenario are used to derive the internationally cost-optimal allocation of emission reductions to achieve pre-selected environmental targets (e.g., desired human health or ecosystems protection level).

Cost curves are compiled by ranking available emission control options for various emission sources according to their cost-effectiveness and combining them with the potential for emission reductions determined by the properties of sources and abatement technologies. Based on the calculated unit cost, the cost curve is constructed first for every sector and then for the whole region (country), employing the principle that technologies characterized by higher costs and lower reduction efficiencies are considered as not cost-efficient and are excluded from further analysis. The marginal costs (costs of removing an additional unit of PM by a given control technology) are calculated for each sector. The remaining abatement options are finally ordered according to increasing marginal costs to form the cost curve for the country being considered.

RAINS computes two types of cost curves:

- The ‘total cost’ curve displays total annual costs of achieving certain emission levels in a country. These curves are piece-wise linear, with the slopes for individual segments determined by the costs of applying the various technologies.

- The ‘marginal cost’ curve is a step-function, indicating the marginal costs (i.e., the costs for reducing the last unit of emissions) at various reduction levels. The algorithm for calculating the marginal costs is explained in Section 4.6.

The cost curve can be displayed in RAINS in tabular or graphical form. Each curve concerns a selected country (or region of a country), emission scenario and year. The table includes columns listing activity type (e.g. fuel combustion), economic sector, control technology combinations, marginal costs (in €/ton pollutant removed), remaining emissions (i.e., initial emission less cumulative emissions removed, in kt), and total cumulative control costs in million €/year.

Examples of cost curves for TSP, PM_{10}, and $PM_{2.5}$ are presented in Table 4.2, Table 4.3, and Table 4.4. The first row in all tables shows initial emissions for a given year and in a given country. The codes of sectors and control technologies are explained in Section 2 of this document. The amount of particulate matter reduced by a particular technology can be derived by comparing the emissions given for this option in the column *“Remaining emissions”* with the preceding value. The *"Total cost"* column displays cumulative costs. This means that for any emission level a cost value in this column represents total costs incurred to achieve this level of emissions. The examples presented in these tables contain only part of a cost curve, which typically includes up to 300 control options ordered according to increasing marginal costs (such a complete cost curve is presented in Figure 4.2).

A graphical representation of Table 4.2 is presented in Figure 4.1. The remaining emissions of TSP are on the x-axis and the total cost on the y-axis. The highest emission value is called the initial emissions and the lowest level is often referred to as maximum feasible reduction (MFR). In the literature, cost curves are often presented in different ways such that instead of showing remaining emissions, the amount of pollutant reduced is shown on the x-axis. As can be seen, the abatement achieved, as well as the cost involved, varies substantially from technology to technology. Note the marked points that indicate the technologies appearing in the same order as in Table 4.2.

Table 4.2: Example of a no-control cost curve for TSP (only part of it).

Activity code	Sector code	Technology code	Marginal cost €/t TSP	Remaining emissions 10^6 tons	Total cost 10^6 €/a
	Initial emissions			15.07	0.0
NOF	PR_CEM	PR_CYC	2.6	12.39	7.0
NOF	PR_FERT	PR_CYC	3.4	12.29	7.3
NOF	PR_LIME	PR_CYC	7.3	11.90	10.2
NOF	PR_CEM	PR_ESP1	7.5	11.13	15.9
NOF	PR_FERT	PR_FF	9.9	11.08	16.5
NOF	PR_ALPRIM	PR_CYC	17.5	11.06	16.8
NOF	PR_EARC	PR_CYC	19.4	10.90	19.9
NOF	PR_SINT	PR_CYC	21.7	10.73	23.6
BC2	PP_NEW3	ESP1	23.3	10.18	36.5
BC2	PP_NEW2	ESP1	23.5	10.03	40.0
NOF	PR_COKE	PR_CYC	23.8	10.01	40.4
BC2	PP_EX_OTH3	ESP1	23.9	6.72	119.1
NOF	PR_ALPRIM	PR_ESP1	24.2	6.71	119.3
BC2	PP_EX_OTH2	ESP1	24.4	5.81	141.2
NOF	PR_CEM	PR_ESP2	26.4	5.70	144.2
HC2	PP_NEW3	ESP1	27.3	5.52	149.1
HC2	PP_NEW2	ESP1	27.6	5.47	150.5
HC2	IN_OC3	IN_ESP1	28.6	5.32	154.9
HC2	IN_OC2	IN_ESP1	29.0	5.21	157.9
HC2	PP_EX_OTH3	ESP1	29.2	3.03	221.7
BC2	PP_EX_OTH1	CYC	29.2	3.00	222.6
NOF	PR_COKE	PR_ESP1	30.1	2.99	222.9
HC2	PP_EX_OTH2	ESP1	30.1	2.36	241.9
HC2	IN_BO3	IN_ESP1	32.2	2.34	242.6
BC2	IN_BO3	IN_ESP1	32.5	2.32	243.0
HC2	IN_BO2	IN_ESP1	33.1	2.31	243.6
BC2	IN_BO2	IN_ESP1	34.2	2.30	243.8
BC2	PP_NEW3	ESP2	36.4	2.28	244.5
NOF	PR_EARC	PR_FF	36.5	2.18	248.1
HC2	IN_OC1	IN_CYC	38.7	2.16	249.2
….	….	….	….	….	….

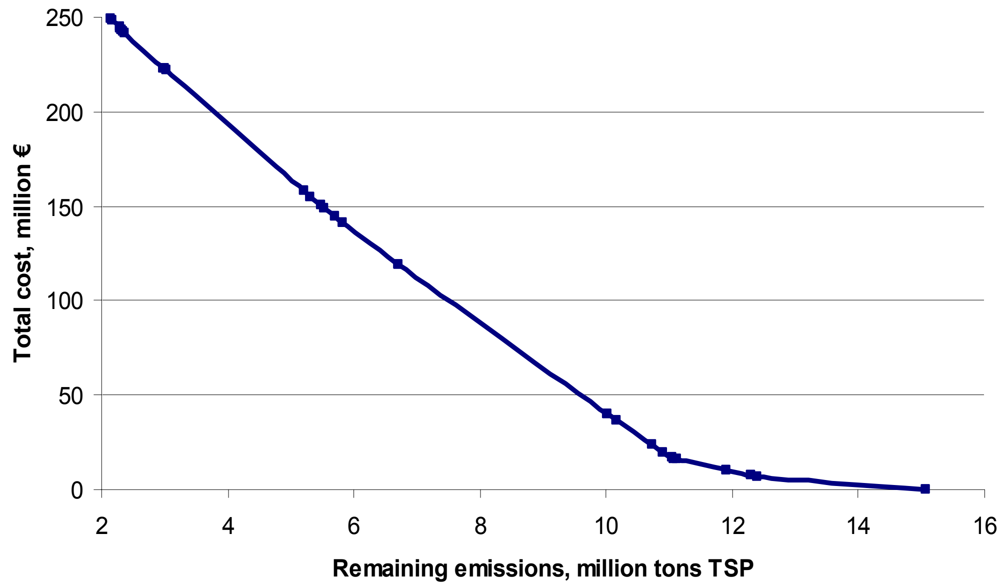

Figure 4.1: Graphical illustration of the part of the TSP cost curve presented in Table 4.2.

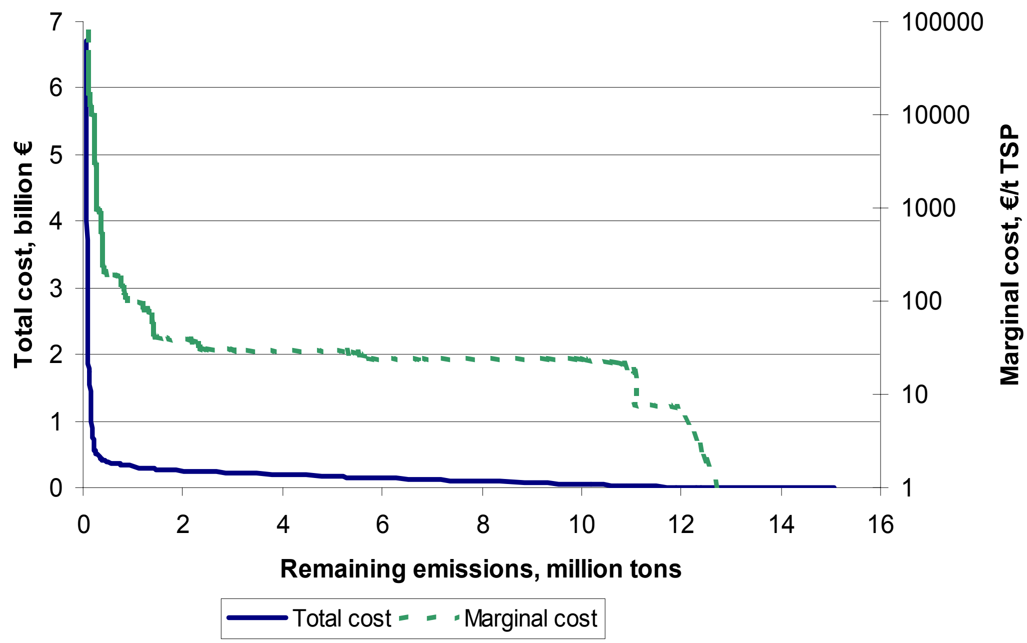

Figure 4.2: Example of the complete no-control TSP cost curve.

Comparing the example cost curves for different size fractions also reveals differences which stem from varying unit reduction costs for the same technology but different size fractions (as discussed in Section 4.1.3 of this document). This means that the sequence of cost-efficient technologies is different for each size fraction. The marginal costs for smaller PM fractions are also consistently higher than for TSP.

Table 4.3: Example of a no-control cost curve for PM_{10}.

Activity code	Sector code	Technology code	Marginal cost €/t PM_{10}	Remaining emissions 10^6 tons	Total cost 10^6 €
	Initial emissions			5.34	0.0
NOF	PR_FERT	PR_CYC	7.8	5.30	0.3
NOF	PR_CEM	PR_CYC	8.8	4.50	7.3
NOF	PR_CEM	PR_ESP1	9.2	3.88	13.1
NOF	PR_FERT	PR_FF	11.2	3.83	13.6
NOF	PR_ALPRIM	PR_ESP1	34.7	3.81	14.2
NOF	PR_COKE	PR_ESP1	39.0	3.80	14.9
NOF	PR_EARC	PR_FF	45.0	3.65	21.6
NOF	PR_CEM	PR_ESP2	56.0	3.59	24.7
NOF	PR_CEM	PR_FF	62.1	3.57	26.3
BC2	PP_NEW3	ESP1	67.7	3.37	39.3
BC2	PP_EX_OTH3	ESP1	69.6	2.24	118.0
NOF	PR_CBLACK	PR_CYC	75.6	2.24	118.0
NOF	PR_CBLACK	PR_FF	77.9	2.24	118.0
NOF	WASTE_RES	BAN	80.0	2.24	118.1
NOF	PR_LIME	PR_CYC	81.0	2.21	121.0
BC2	PP_NEW3	ESP2	89.4	2.20	121.7
BC2	PP_NEW2	ESP1	92.1	2.16	125.2
BC2	PP_EX_OTH1	ESP1	94.0	2.15	126.5
BC2	IN_BO3	IN_ESP1	94.5	2.14	126.9
BC2	PP_EX_OTH2	ESP1	95.7	1.91	148.8
NOF	PR_OTHER	PR_CYC	100.0	1.91	149.2
NOF	PR_OTHER	PR_ESP1	100.8	1.91	149.5
BC2	PP_EX_OTH3	ESP2	101.1	1.86	154.0
HC2	PP_NEW2	ESP1	108.1	1.85	155.4
HC2	PP_EX_WB	ESP1	108.6	1.64	178.2
HC2	IN_OC2	IN_ESP1	113.7	1.61	181.2
HC2	PP_EX_OTH2	ESP1	118.1	1.45	200.2
BC2	PP_NEW3	ESP3P	121.0	1.45	200.5
HC2	PP_NEW3	ESP1	121.1	1.41	205.4
BC2	PP_NEW2	ESP2	122.4	1.41	205.6
….	….	….	….	….	….

Table 4.4: Example of a no-control cost curve for $PM_{2.5}$.

Activity code	Sector code	Technology code	Marginal cost €/t$PM_{2.5}$	Remaining emissions 10^6 tons	Total cost 10^6 €/a
	Initial emissions			2.18	0.0
NOF	PR_FERT	PR_FF	16.0	2.12	0.9
NOF	PR_CEM	PR_ESP1	21.2	1.52	13.6
NOF	PR_ALPRIM	PR_ESP1	51.5	1.51	14.2
NOF	PR_EARC	PR_FF	60.8	1.40	20.9
NOF	PR_COKE	PR_ESP1	66.2	1.39	21.6
NOF	WASTE_RES	BAN	80.0	1.39	21.7
NOF	PR_CBLACK	PR_FF	85.7	1.39	21.8
NOF	PR_CEM	PR_FF	121.0	1.35	26.5
NOF	PR_GLASS	PR_ESP1	144.8	1.33	28.7
OS1	PP_NEW	ESP1	181.7	1.33	29.7
NOF	PR_ALPRIM	PR_ESP3P	190.1	1.33	29.8
HC2	PP_EX_WB	ESP1	193.1	1.21	52.6
NOF	PR_OT_NFME	PR_WESP	195.7	1.19	56.3
OS1	PP_EX_OTH	ESP1	226.6	1.19	57.1
BC2	PP_NEW3	ESP1	240.5	1.13	70.1
BC2	PP_EX_OTH3	ESP1	247.3	0.81	148.8
BC2	PP_EX_OTH1	ESP1	251.9	0.81	150.2
NOF	PR_OTHER	PR_ESP1	264.5	0.81	150.9
NOF	PR_BAOX	PR_ESP1	281.2	0.54	224.7
OS1	IN_OC	IN_ESP1	283.7	0.54	224.7
NOF	PR_CAST	PR_ESP1	285.3	0.51	234.5
NOF	PR_COKE	PR_ESP3P	290.8	0.51	234.7
BC2	PP_NEW3	ESP3P	299.1	0.50	235.8
NOF	PR_REF	PR_ESP1	302.7	0.50	238.1
BC2	IN_BO3	IN_ESP1	335.8	0.50	238.5
BC2	PP_EX_OTH3	ESP3P	351.1	0.48	245.7
HC2	PP_EX_OTH1	ESP1	419.5	0.47	247.3
OS1	IN_BO	IN_ESP1	419.8	0.47	248.4
NOF	PR_SINT	PR_ESP1	469.5	0.46	254.1
HC2	PP_NEW3	ESP1	471.4	0.45	259.0
….	….	….	….	….	….

5 The RAINS PM Web Module

The present implementation (version 2.0) of the RAINS PM module on the Internet (http://www.iiasa.ac.at/rains/Rains-online.html) provides free access to the input data and results to facilitate interaction with national experts.

The following options are available for selected countries and scenarios:

- Display country-specific activity data;
- Display general and country-specific input parameters for the calculation of primary PM emissions at the most resolved level;
- Display general and country-specific input parameters for the calculation of PM control costs at the most resolved level;
- Display control strategy;
- Display resulting emission estimates at the most resolved level and in aggregated form (including CORINAIR SNAP 1 aggregation);
- Display estimates of emission control costs at the most resolved level and in aggregated form; and
- Display "no-control" cost curves for different PM size fractions and years.

Currently, two scenarios are available: (i) a "baseline – current legislation" scenario that can be compared with national emission estimates, and (ii) a (hypothetical) "no control" scenario.

Further features will be added to the Internet version of the RAINS PM module in due course. IIASA continues to work on an implementation that will allow users to develop their own emission inventories and projections in a fully interactive way and to examine the implications on PM emission control cost curves. Ultimately, IIASA aims to provide full access to the RAINS model via the Internet.

6 Results

Based on the methodology and data introduced above, an estimate of the PM emissions in Europe was derived. Although new European and national studies have become available recently, one should stress that PM emission estimates are still highly uncertain and more work is needed to narrow down this uncertainty. Thus, all numbers presented in this chapter should be considered as preliminary and subject to future revision.

6.1 Emissions

Table 6.1 lists the total European emissions of PM for the years 1990, 1995 and 2010. The projections for the year 2010 assume full implementation of the current emission control legislation (CLE), e.g., the EURO-IV emission standards for cars and trucks, or stricter emission limit values for large combustion plants resulting from the recent revision of the Large Combustion Plant Directive. Results are provided for TSP, PM_{10} and $PM_{2.5}$. Major reductions in PM emissions occurred between 1990 and 1995, mainly because of the economic restructuring in Eastern Europe where old and obsolete plants in the power sector and in industry were either closed or rehabilitated. The emissions in the European Union have also decreased, mainly due to switching to cleaner fuels and implementation of better control equipment on existing plants. Between 1990 and 1995, TSP emissions in Europe declined by 50 percent; for 2010 a decline of 60 percent is projected. Since the emission reductions are more difficult for smaller particles, the $PM_{2.5}$ emissions decrease less, i.e. by 55 percent. Consequently, the fine fraction ($PM_{2.5}$) will be relatively more important in the future (28 percent of TSP in 2010 compared to 25 percent in 1990). It is interesting to note that the trends in reduction of coarse and fine particles in the periods 1990 – 2010 and 1995 – 2010 are different. The fine fraction is reduced more than the coarse after 1995. $PM_{2.5}$ and PM_{10} are calculated to decline by 26 and 25 percent, respectively, while the total PM are reduced by only 21 percent between 1995 and 2010. This is due to a number of sources that emit mostly 'large' particles but for which the control possibilities are limited. Examples of such sources include construction activities, arable farming, storage and handling of bulk products, etc.

Table 6.1: Changes in "Current legislation" (CLE) PM emissions in Europe, 1990 – 2010, kt.

	TSP			PM_{10}			$PM_{2.5}$		
	1990	1995	2010	1990	1995	2010	1990	1995	2010
EU	5188	3182	2369	2655	1701	1161	1593	1136	736
Non-EU	15469	7196	5768	6465	3258	2509	3533	1923	1500
Sea regions [1)]	121	121	121	115	115	115	109	109	109
Total Europe	20778	10499	8258	9235	5074	3785	5235	3168	2344

[1)] includes Atlantic Ocean, North Sea, Baltic Sea, and Mediterranean Sea within EMEP emission domain.

The sectoral origins of PM emissions in Europe (by SNAP code) are presented in Table 6.2 and Table 6.3. In 1995, the major sources of TSP emissions in EU-15 were stationary combustion with a share of 32 percent, followed by mobile sources (road- and off-road vehicles) contributing 26 percent, industrial production processes (19 percent), and agriculture (14 percent). Since the estimates did not include any reductions of non-exhaust emissions from transport, the contribution of that sector in 2010 increases to 35 percent, making it by far the most important source of particulate emissions in the EU. The relative contribution of combustion processes decreases by about a half, i.e. reduced to 18 percent, while industrial processes and agriculture remain important, contributing about 18 percent each. It is characteristic that the relative importance of individual sectors and the development of emissions are different for fine particles ($PM_{2.5}$). In this case the role of transport is even more pronounced (42 percent of emissions in 1995). However, because of strict controls on exhaust emissions (first of all from road transport and to a lesser extent from the off-road sector), the share of mobile sources in total $PM_{2.5}$ emissions decreases in 2010 to 35 percent of the total. The relative contributions of all other sectors either remain the same (stationary combustion; about 32 percent) or increase compared to 1995.

Table 6.2: PM emissions in the EU-15 countries by SNAP 1 sectors.

SNAP 1 sector	1995	2010	1995	2010	1995	2010
	TSP		PM_{10}		$PM_{2.5}$	
1: Combustion in energy industries	278	119	180	92	105	61
2: Non-industrial combustion plants	379	139	200	110	145	98
3: Combustion in manufacturing industry	374	173	185	96	124	75
4: Production processes	612	451	282	216	157	114
5: Extraction and distribution	83	38	41	20	5	2
7: Road transport	683	683	395	215	335	132
8: Other mobile sources and machinery	153	138	145	130	137	123
9: Waste treatment	45	44	34	33	32	31
10: Agriculture	435	426	136	134	26	26
12: Other (not included in CORINAIR)	140	160	103	115	71	74
TOTAL	3182	2369	1701	1161	1136	736

Table 6.3: PM emissions in the non-EU countries by SNAP 1 sectors.

SNAP 1 sector	1995	2010	1995	2010	1995	2010
	TSP		PM_{10}		$PM_{2.5}$	
1: Combustion in energy industries	1185	671	632	395	287	195
2: Non-industrial combustion plants	2678	2481	793	696	399	356
3: Combustion in manufacturing industry	621	372	288	204	174	134
4: Production processes	1262	739	873	520	634	375
5: Extraction and distribution	210	129	93	68	9	8
7: Road transport	212	291	123	140	105	111
8: Other mobile sources and machinery	119	119	112	113	106	107
9: Waste treatment	221	221	166	166	150	150
10: Agriculture	633	691	131	163	22	29
12: Other (not included in CORINAIR)	56	54	46	44	37	35
TOTAL	7196	5768	3258	2509	1923	1500

The situation looks different for non-EU countries. In this case the emissions are dominated by stationary combustion and industrial processes, representing together nearly 80 percent of total emitted PM. The share of mobile sources in 1995 is below five percent for TSP and about 11 percent for $PM_{2.5}$. Although the relative importance of transport emissions increases in the future for all PM size classes, it is calculated that even for fine particles its share will not exceed 15 percent in 2010. In 2010, the largest source of PM in non-EU countries remains stationary combustion (61 and 46 percent share for TSP and $PM_{2.5}$, respectively).

Table 6.4 presents the hypothetical emissions if no control measures were applied and thereby illustrates the significant extent to which PM emissions are already controlled. In 1990, 90 percent of dust (TSP) in raw gas was eliminated by various types of measures, and this share is expected to increase to 95 percent by 2010. For $PM_{2.5}$, however, control measures reduced PM in raw gas by only about 82 percent, and 90 percent of control is anticipated for 2010 with present legislation. The need for accurate information on the status and performance of installed emission control devices is obvious, and minor inaccuracies in such information lead to significant changes in the estimates of overall emissions.

Table 6.5 presents the maximum technical potential (maximum feasible reductions – MFR) to reduce PM emissions through the implementation of the best available control technology (BAT) on all sources. That potential is rather theoretical, at least in the short-run, since not all existing sources can be retrofitted and premature scrapping of equipment would induce prohibitive costs. Nevertheless, this scenario illustrates the long-term emission control possibilities. The analysis reveals that, despite the far-reaching controls that are implemented today in many European countries, it is possible to further cut the PM emissions by about 63 – 69 percent from the CLE level assuming full implementation of BAT and activity levels as projected for 2010. However, for the current EU member countries this potential is lower (37 percent for TSP and 51 percent for fine particles).

Table 6.4: PM emissions in Europe for the hypothetical "No control" scenario, kt.

	TSP			PM_{10}			$PM_{2.5}$		
	1990	1995	2010	1990	1995	2010	1990	1995	2010
EU	95167	80446	75181	32850	28056	26864	12973	11454	11174
Non-EU	122368	95126	96877	41353	31841	32582	15147	11384	11809
Sea Regions	121	121	121	115	115	115	109	109	109
Total Europe	217656	175693	172179	74318	60012	59561	28561	22947	23092

Table 6.5: PM emissions in Europe for the hypothetical "Maximum feasible reductions" scenario, kt.

	TSP			PM_{10}			$PM_{2.5}$		
	1990	1995	2010	1990	1995	2010	1990	1995	2010
EU	1512	1396	1493	792	691	661	471	398	361
Non-EU	1816	1429	1326	823	750	679	551	425	306
Sea Regions	73	73	73	69	69	69	65	65	65
Total Europe	3401	2897	2892	1684	1509	1409	1087	888	732

Table 6.6 presents the reductions in PM emissions by country between 1995 and 2010, assuming full implementation of current legislation (CLE). Reductions are expected for all countries and for all size fractions. They are particularly large for accession countries owing to continuation of economic restructuring and adoption of EU emission standards. The simulations done with the RAINS model demonstrate that the combination of these two factors will cause a substantial decrease in environmental pressures caused by PM emissions in those countries.

Table 6.7 compares the PM emissions as calculated by RAINS with the results from the CEPMEIP inventory. Whereas the differences for Europe as a whole are below ten percent (remarkably, for $PM_{2.5}$ it is less than two percent), the differences for individual countries are large. Because of limited resources available within the current study, it was not possible to trace back the reasons for those differences for all countries. Analysis of the differences for Germany is presented in Section 6.3. For Austria, France, the Netherlands and the United Kingdom an in-depth comparison and analysis of national estimates submitted to the UNECE (http://webdab.emep.int), CEPMEIP (CEPMEIP, 2002) and RAINS results are presented in EMEP (2002). It should be stressed that the CEPMEIP approach is not fully compatible with the RAINS methodology. For instance, CEPMEIP uses abated emission factors specified for four arbitrarily assumed emission control levels: low, medium, medium-high, and high. The country-specific unabated factors are not determined. Thus, a full explanation of differences and further tuning of RAINS require in-depth analysis for each country, which is only possible in close collaboration with national experts.

The necessity for further verification and consistency checks of emission estimates for individual countries is reinforced by data presented in Table 6.8, which compares results from available national inventories with RAINS and CEPMEIP.

Table 6.6: Estimates of PM emissions by country for the years 1995 and 2010 assuming full implementation of current legislation, kt.

Country	TSP		PM_{10}		$PM_{2.5}$	
	1995	2010	1995	2010	1995	2010
Albania	18	11	8	6	5	5
Austria	77	77	44	39	31	26
Belarus	135	111	61	60	38	40
Belgium	163	92	78	43	50	27
Bosnia-Herzegovina	94	68	45	36	18	16
Bulgaria	182	319	107	135	65	75
Croatia	31	35	18	20	13	14
Czech Republic	241	116	142	66	84	39
Denmark	56	47	31	24	20	13
Estonia	116	24	58	17	23	11
Finland	50	44	31	24	24	17
France	527	417	289	198	205	126
Germany	513	415	281	195	184	119
Greece	93	99	57	62	40	42
Hungary	127	65	63	32	37	19
Ireland	39	37	21	16	12	8
Italy	449	316	244	154	170	100
Latvia	27	15	13	7	8	4
Lithuania	33	26	15	12	9	7
Luxembourg	10	5	5	3	3	2
Netherlands	118	101	62	49	38	28
Norway	65	58	50	45	44	40
Poland	575	387	340	221	192	128
Portugal	75	60	43	31	30	21
R. of Moldova	34	85	15	26	9	12
Romania	319	305	193	172	126	109
Russia	3323	2918	1322	1114	813	680
Slovakia	85	64	45	34	26	19
Slovenia	25	17	15	10	9	6
Spain	383	308	216	159	148	104
Sweden	71	60	38	29	26	18
Switzerland	32	32	18	16	13	10
FYR Macedonia	50	30	25	16	11	8
Ukraine	1483	948	611	397	337	227
United Kingdom	556	292	261	138	155	84
Yugoslavia	201	133	94	68	41	32
Sea regions	121	121	115	115	109	109
Total	10499	8258	5074	3785	3168	2344

Table 6.7: Comparison of RAINS estimates of particulate matter emissions for 1995 with the results of the CEPMEIP inventory (CEPMEIP, 2002).

Country	TSP		PM_{10}		$PM_{2.5}$	
	RAINS	CEPMEIP	RAINS	CEPMEIP	RAINS	CEPMEIP
Albania	18	13	8	8	5	6
Austria	77	83	44	46	31	34
Belarus	135	129	61	62	38	39
Belgium	163	143	78	84	50	57
Bosnia-Herzegovina	94	21	45	10	18	6
Bulgaria	182	226	107	93	65	38
Croatia	31	41	18	21	13	14
Czech Republic	241	279	142	125	84	57
Denmark	56	61	31	33	20	23
Estonia	116	81	58	33	23	14
Finland	50	50	31	30	24	22
France	527	693	289	450	205	351
Germany	513	686	281	335	184	217
Greece	93	97	57	62	40	42
Hungary	127	111	63	62	37	36
Ireland	39	46	21	23	12	13
Italy	449	518	244	319	170	232
Latvia	27	27	13	13	8	9
Lithuania	33	40	15	20	9	13
Luxembourg	10	9	5	5	3	3
Netherlands	118	127	62	64	38	41
Norway	65	65	50	49	44	43
Poland	575	643	340	314	192	127
Portugal	75	81	43	51	30	37
R. of Moldova	34	32	15	16	9	10
Romania	319	404	193	186	126	93
Russia	3323	3649	1322	1709	813	896
Slovakia	85	74	45	41	26	23
Slovenia	25	26	15	13	9	7
Spain	383	367	216	226	148	159
Sweden	71	77	38	42	26	30
Switzerland	32	42	18	21	13	16
FYR Macedonia	50	70	25	27	11	10
Ukraine	1483	1296	611	608	337	281
United Kingdom	556	473	261	260	155	164
Yugoslavia	201	368	94	144	41	49
Sea regions	121	n.a	115	n.a	109	n.a.
Total	10499	11149	5074	5607	3168	3208

Table 6.8: Comparison of national emission estimates with RAINS and CEPMEIP results, kt.

Country	Year	Substance	National estimate	RAINS 1995 estimate	CEPMEIP 1995 estimate
Austria [(1)]	1995	$TSP/PM_{10}/PM_{2.5}$	75/45/26	77/44/31	83/46/33
France [(2)]	1995	$TSP/PM_{10}/PM_{2.5}$	1527/579/319	527/289/205	693/450/351
Germany [(3)]	1996	$TSP/PM_{10}/PM_{2.5}$	343/198/ --	513/281/184	686/335/217
Switzerland [(4)]	1995	$TSP/PM_{10}/PM_{2.5}$	-- /28/ --	32/18/13	42/20/15
UK [(5)]	1995	$TSP/PM_{10}/PM_{2.5}$	-- /220/143	556/261/155	473/260/164
UK [(6)]	1995	$TSP/PM_{10}/PM_{2.5}$	-- /238/132		

[(1)] Winiwarter *et al.*, 2001; [(2)] CITEPA, 2001; [(3)] UBA, 1998a; [(4)] BUWAL, 2000;
[(5)] APEG, 1999; [(6)] UK submission to EMEP in 2002.

6.2 Emission Control Costs

Preliminary cost estimates are presented in Table 6.9. In 1995, RAINS estimates that about eight billion Euro/year were spent in the EU-15 on measures to reduce PM emissions. While this level of expenditure remains similar for stationary sources (with the exception of residential combustion), the recently adopted EU legislation for mobile sources (the Auto Oil emission standards) will increase total abatement costs to about 40 billion Euro in 2010, if the full costs of the PM control measures are taken into account. In the non-EU countries the total costs rise between 1995 and 2010 by a factor of three, driven primarily by the introduction of legislation for transport sources similar to that in the EU.

Table 6.9: Costs for measures that reduce PM emissions, for 1995 and for present legislation in the year 2010. Note that these costs include the full costs of controls in the transport sector, although they also affect emissions other than PM [Mio €/year].

Sector	EU-15		Non-EU	
	1995	2010	1995	2010
Power plants	1218	1045	1482	1453
Industrial combustion	169	135	197	180
Residential/commercial combustion	554	1891	163	1006
Industrial processes	1394	1911	781	1372
Transport	4232	34842	433	5689
Other	439	453	70	786
Total	8006	40276	3126	10486

6.3 PM Emission Estimates for Germany

Table 6.10 and Table 6.11 present RAINS model estimates of PM emissions for Germany in 1995 and 2010. Overall, emissions of TSP, PM_{10}, and $PM_{2.5}$ are expected to decline by 20, 32, and 37 percent, respectively, by 2010. Transport and industrial processes are the dominating sources of PM in 1995, contributing about 56 percent of TSP and PM_{10} and nearly 70 percent of $PM_{2.5}$. Transportation alone emits 33 and 47 percent of total PM and $PM_{2.5}$, respectively.

Table 6.10: Estimated PM emissions in Germany in 1995.

RAINS sector		Emissions [kt]			Share of total German emissions in 1995 [%]		
Primary	Secondary	TSP	PM10	PM2.5	TSP	PM10	PM2.5
Stationary combustion	Power plants	38.8	32.6	23.4	7.6	11.6	12.7
	Industrial combustion	8.1	5.8	3.7	1.6	2.1	2.0
	Domestic combustion	22.3	16.3	11.3	4.3	5.8	6.2
Process emissions	Pig iron	31.8	5.5	3.8	6.2	1.9	2.1
	Sinter and pellets	19.1	3.5	1.8	3.7	1.2	1.0
	Basic oxygen furnaces	5.0	4.8	4.5	1.0	1.7	2.5
	Electric arc furnaces	2.5	2.3	2.1	0.5	0.8	1.1
	Other Iron and Steel	7.4	4.8	3.1	1.4	1.7	1.7
	Non-ferrous metals	2.1	1.6	1.3	0.4	0.6	0.7
	Cement and lime	11.3	9.8	8.4	2.2	3.5	4.6
	Other processes	38.2	17.2	9.1	7.4	6.1	4.9
Mining		12.6	6.8	0.9	2.5	2.4	0.5
Storage and Handling	Industrial products	34.3	18.8	1.9	6.7	6.7	1.1
	Agricultural products	4.4	1.5	0.3	0.9	0.5	0.1
Road transport	Heavy duty vehicles	26.0	25.6	25.2	5.1	9.1	13.7
	Light duty vehicles	35.9	35.4	33.8	7.0	12.6	18.4
	Motorcycles, mopeds	0.4	0.4	0.3	0.1	0.1	0.2
	Non-exhaust	81.0	16.4	5.4	15.8	5.8	2.9
Off-road transport	Construction and Industry	6.0	5.7	5.4	1.2	2.0	2.9
	Agriculture	8.8	8.3	7.9	1.7	3.0	4.3
	Rail	3.3	3.1	2.9	0.6	1.1	1.6
	Inland waterways	2.7	2.6	2.4	0.5	0.9	1.3
	Other land-based	3.3	2.9	2.6	0.6	1.0	1.4
	Maritime activities	0.0	0.0	0.0	0.0	0.0	0.0
Open burning of waste		3.0	2.5	2.5	0.6	0.9	1.3
Agriculture	Livestock	49.0	22.0	4.4	9.5	7.8	2.4
	Other	22.2	1.2	0.0	4.3	0.4	0.0
Other sources	Construction dust	16.9	8.5	0.9	3.3	3.0	0.5
	Residential (1)	10.7	10.7	10.7	2.1	3.8	5.8
	Other (2)	6.2	5.0	4.0	1.2	1.8	2.2
TOTAL		**513**	**281**	**184**	**100**	**100**	**100**

(1) Food preparation, barbeques, cigarette smoking, and fireworks
(2) Includes emissions from production of sugar, ceramics, construction materials, and a few other minor sources reported in the UBA (1998a) inventory.

Although the contribution of transport and industrial processes is expected to drop by 2010, they remain the largest sources, emitting more than 50 percent of particulates. For PM_{10} and $PM_{2.5}$, the share of transport declines by nearly 30 percent by 2010, while an increase is observed for TSP. This is explained by growing non-exhaust emissions that are an important source of coarse particles. In fact, exhaust emissions from traffic are expected to be reduced by about 70 percent but lack of controls and increase in mileage lead to a higher contribution from non-exhaust sources. Other sectors that either lack efficient control options or are not yet regulated also gain importance, i.e., their share of fine PM increases to about 16 percent.

Table 6.11: PM emissions in Germany estimated for 2010.

RAINS sector		Emissions [kt]			Share of total German emissions in 2010 [%]		
Primary	Secondary	TSP	PM10	PM2.5	TSP	PM10	PM2.5
Stationary combustion	Power plants	21	16	13	5.1	8.3	10.9
	Industrial combustion	4	3	2	0.9	1.7	2.0
	Domestic combustion	15	13	12	3.6	6.9	10.4
Process emissions	Pig iron	14	2	1	3.4	0.9	1.0
	Sinter and pellets	11	2	1	2.6	1.0	0.9
	Basic oxygen furnaces	4	4	4	1.0	2.1	3.3
	Electric arc furnaces	4	3	3	0.9	1.8	2.6
	Other Iron and Steel	6	4	2	1.5	1.9	2.0
	Non-ferrous metals	2	2	1	0.6	0.9	1.3
	Cement and lime	11	10	9	2.6	5.1	7.3
	Other processes	30	14	8	7.1	7.1	6.6
Mining		8	5	1	2.0	2.3	0.5
Storage and Handling	Industrial products	25	14	1	6.2	7.2	1.2
	Agricultural products	4	1	0	1.0	0.8	0.2
Road transport	Heavy duty vehicles	5	5	5	1.2	2.6	4.2
	Light duty vehicles	13	13	12	3.1	6.5	10.1
	Motorcycles, mopeds	0	0	0	0.1	0.2	0.3
	Non-exhaust	125	25	8	30.1	12.9	6.9
Off-road transport	Construction and Industry	3	3	3	0.8	1.6	2.5
	Agriculture	6	5	5	1.4	2.8	4.4
	Rail	0	0	0	0.0	0.1	0.1
	Inland waterways	2	2	2	0.4	0.9	1.4
	Other land-based	3	3	3	0.8	1.5	2.2
	Maritime activities	0	0	0	0.0	0.0	0.0
Open burning of waste		3	2	2	0.7	1.2	2.0
Agriculture	Livestock	40	18	4	9.7	9.3	3.1
	Other	22	1	0	5.4	0.6	0.0
Other sources	Construction dust	15	8	1	3.7	3.9	0.7
	Residential (1)	11	11	11	2.6	5.5	9.0
	Other (2)	6	5	4	1.4	2.5	3.2
TOTAL		**414**	**190**	**115**	**100**	**100**	**100**

(1) Food preparation, barbeques, cigarette smoking, and fireworks
(2) Includes emissions from production of sugar, ceramics, construction materials, and a few other minor sources reported in the UBA (1998a) inventory.

Table 6.12, Table 6.13, and Table 6.14 compare 1995 emissions for major emission categories as calculated by RAINS with values from the German emission inventories for 1996 (UBA, 1998a; IER, 1999) and the CEPMEIP study estimates for 1995 (CEPMEIP, 2002). It needs to be stressed that the two German sources use not only different base years but also different data sets on activity levels. RAINS activity levels are based on international statistics and on the CEPMEIP inventory (CEPMEIP, 2002) (see Table 2.16). These data are not always the same as those used in the German studies.

Table 6.12: Comparison of estimates of 1995 total particulate emissions (TSP) for Germany, kt

RAINS sector		Data source			
Primary	Secondary	RAINS	CEPMEIP, 2002	UBA, 1998a (1)	IER, 1999 (1)
Stationary combustion	Power plants	38.8	51.0	33.4	42.8
	Industry	8.1	13.4	7.0	15.0
	Residential	22.3	69.8	22.6	77.4
Process emissions	Iron and steel	65.8	55.5	66.3	63.9
	Non-ferrous metals	2.1	2.1	2.3	1.9
	Cement and lime	11.3	8.3	11.6	10.8
	Other processes	38.2	51.3	14.1	50.2
Mining, storage and handling		51.3	83.2	52.5	50.6
Road transport	Exhaust	62.2	54.3	41.0	50.4
	Non-exhaust	81.0	202.3	73.0	82.0
Off-road transport		24.1	16.8	19.0	4.7
Open burning of waste		3.0	3.0	n.d.	n.d.
Agriculture		71.1	47.0	n.d.	n.d.
Other sources		33.8	27.7	n.d.	n.d.
TOTAL		**513.2**	**685.8**	**342.9**	**449.7**

(1) Data for 1996

For a number of individual sectors a comparison is rather difficult because of differences in sector classification and different activity data. For instance, the activity aggregation in RAINS, which is compatible with the activity list from the CEPMEIP inventory, does not explicitly include emissions from the production of bricks and roof tiles, sugar, calcium carbide, wooden palettes, zinc coating, etc. Emissions from those processes have been shown in the row "Other sources/other". From the other side, it is evident that the German inventory does not provide estimates for such sectors as open burning of waste, agriculture, construction dust, or non-energy sources in the residential sector (barbecues, tobacco smoking, fireworks). It is also not known which processes are included in the German inventory under the heading "Storage and handling" (Schüttgutumschlag) and if all emissions from coal mining and preparation are included under "Mining". Thus, the sectors "Mining" and "Storage and handling" should be compared at a more aggregated level, i.e., the sum of the two. In the category “Other processes”, fugitive emissions from small industrial and business facilities are included (they actually represent most of emissions reported there) in the same way as in the CEPMEIP study. The UBA inventory (UBA, 1998a), however, does not include these sources. Therefore, RAINS emissions for the sector “Process emissions/Other sources” are higher by 30 kilotons TSP than the corresponding UBA number. The CEPMEIP and IER estimates for this sector are similar, and higher than RAINS and UBA; the reasons for the difference include: different levels of control and activity data, as well as the number of processes considered.

Table 6.13: Comparison of estimates of 1995 PM_{10} emissions for Germany, kt

RAINS sector		Data source			
Primary	Secondary	RAINS	CEPMEIP, 2002	UBA, 1998a (1)	IER, 1999 (1)
Stationary combustion	Power plants	32.6	49.4	31.8	40.7
	Industry	5.8	10.2	6.7	13.6
	Residential	16.3	45.8	20.3	69.7
Process emissions	Iron and steel	20.9	40.0	34.8	33.8
	Non-ferrous metals	1.6	2.0	2.2	1.8
	Cement and lime	9.8	6.8	10.5	9.7
	Other processes	17.2	18.6	12.0	31.7
Mining, storage and handling		27.1	34.6	12.4	24.6
Road transport	Exhaust	61.3	54.3	41.0	50.4
	Non-exhaust	16.4	14.7	7.3	10.8
Off-road transport		22.6	15.8	19.0	4.4
Open burning of waste		2.5	2.5	n.d.	n.d.
Agriculture		23.3	21.2	n.d.	n.d.
Other sources		24.3	19.4	n.d.	n.d.
TOTAL		**281.6**	**335.3**	**198.0**	**291.1**

(1) Data for 1996

On an aggregated level (the sum of stationary combustion, process emissions, mining, and storage and handling) the estimates of TSP and PM_{10} emissions by RAINS and UBA differ by less than 10 percent. However, subtracting from RAINS the estimate of fugitive emissions from small sources (see discussion in previous paragraph) that are not included in the UBA inventory reduces the difference to a mere one percent. Obviously, the differences for individual processes and/or sub-sectors are greater. Also, the ratio PM_{10}/TSP is different for many emission categories. This is of particular importance for the process sector, where the UBA inventory usually assumes a higher share of PM_{10} in total dust. However, the PM_{10} emissions for mining and storage and handling are lower compared with RAINS. A similar comparison with the CEPMEIP and IER inventories reveals large difference of about 30 to 50 percent in total estimates of PM_{10} and TSP. The main reasons are higher emission factors for domestic combustion (especially biomass) and lower level of control in the power plant sector, as well as discrepancies in the 'other processes' category addressed above. The most significant differences to the RAINS and UBA estimates are the nearly three times higher emissions from residential combustion sources calculated in the CEPMEIP and IER studies.

According to RAINS, the 1995 exhaust emissions from road transport were approximately 62 kilotons. UBA and IER estimated 41 and 50 kilotons for 1996. When comparing the emissions from that sector, one should bear in mind that RAINS includes the emissions not only from diesel engines but also from gasoline vehicles. The emissions caused by gasoline use (both two-stroke mopeds and motorcycles, as well as four-stroke cars and light-duty trucks) are estimated at 7.3 kilotons. After allowing for that correction the difference between RAINS and UBA is less than 18 percent, which is within the uncertainty band for this estimate. The CEPMEIP estimate lies between the RAINS and German inventories.

The RAINS estimate for off-road sources is about 20 percent higher than that from UBA, which is due to inclusion of the emissions from two-stroke mobile machinery used in forestry and the domestic sector (motor saws, lawn mowers, small motorboats, etc.). The CEPMEIP estimate is comparable with UBA. IER estimated significantly lower emissions from this sector.

RAINS estimates of non-exhaust emissions of TSP from transport are in the same range as those of UBA and IER; only CEPMEIP calculates significantly higher (by a factor of nearly three) emissions from this source. This is most likely due to the inclusion of re-suspension, as the emissions of PM_{10} are comparable with other studies. German inventories assume a lower share of PM_{10} in total non-exhaust emissions from transport, which leads to a large difference between RAINS, UBA and IER estimates.

For $PM_{2.5}$, only RAINS and the CEPMEIP inventory are available (Table 6.14) for Germany. The overall difference is below 20 percent and significant discrepancies exist for power plants, residential combustion, industrial combustion, and emissions from production of cement and lime. Some of the reasons for these differences have been discussed above, i.e., lower level of control assumed in the CEPMEIP study for power plants and higher emission factors for residential wood combustion. RAINS assumptions on the level of control in power plant are a result of calibration of the model to UBA estimates for TSP and PM_{10} emissions from this sector. Similarly, for residential wood combustion in Germany RAINS relies on the emission rates reported by Pfeiffer *et al.* (2000), a study contracted by German UBA.

Table 6.14: Comparison of estimates of 1995 $PM_{2.5}$ emissions for Germany, kt

RAINS sector		Data source			
Primary	Secondary	RAINS	CEPMEIP, 2002	UBA, 1998a	IER, 1999
Stationary combustion	Power plants	23.4	44.8		
	Industry	3.7	7.7		
	Residential	11.3	36.3		
Process emissions	Iron and steel	15.3	19.6		
	Non-ferrous metals	1.3	1.0		
	Cement and lime	8.4	2.8		
	Other processes	9.1	7.0		
Mining, storage and handling		3.1	3.8		
Road transport	Exhaust	59.3	54.3		
	Non-exhaust	5.4	5.6		
Off-road transport		21.3	15.0		
Open burning of waste		2.5	2.5		
Agriculture		4.4	4.7		
Other sources		15.7	12.0		
TOTAL		**184.0**	**217.1**	**n.d.**	**n.d.**

The differences discussed above illustrate the large uncertainties in PM emission inventories. Thus, further tuning of the RAINS PM module is necessary. This will need to be done in close collaboration with national experts within the process of review of input data to integrated assessment studies.

7 Conclusions

This report presents a first approach for estimating, in an internationally consistent way, present and future emissions of fine particulate matter in Europe, the potential for further emission reductions and the associated costs. The approach was implemented for all European countries, covering the period from 1990 to 2010, so that now, for the first time, consistent estimates are available for all European countries.

It must be emphasized that the preliminary results are still associated with significant uncertainties. There are important gaps in the understanding of the emission factors for many processes and of the causes that lead to differences in emission factors across countries. Furthermore, there is only scarce solid information about the applicability of emission control measures under the specific national conditions, so that all estimates presented in this report must be considered as preliminary.

A comparison of the preliminary RAINS estimates with results of other national and international emission inventories reveals important discrepancies between the estimates of individual countries. To some extent these might be caused by the aggregation of important country-specific details that are unavoidable for Europe-wide calculations. On the other hand, however, methodologies that were used by national experts for their emission inventories are not always fully consistent in an international context. Therefore, it is now important to start a dialogue with national experts to clarify these discrepancies and to generate a common understanding about the sources of fine particles in Europe and to reach a common perspective on the available potential for further control measures.

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Annex 1: Basic Terminology used in RAINS

Activity data:

Examples of activity data include consumption of hard coal in power plants, kilometers driven by heavy-duty trucks, production of cement, numbers of animals, etc. This kind of data is stored in activity pathways.

Activity pathways:

These are sets of data files that include country- and sector-specific data on energy consumption (energy pathway), agricultural activities (agricultural pathway), other activities like production of steel, cement, etc. The data are available for five-year periods between 1990 and 2010. It is possible to have several alternative development pathways for either single countries or groups of countries that can be used in the subsequent calculations.

Uncontrolled (”raw gas”) emission factors:

Since one of the objectives of the RAINS model is to assess the extent and costs of controlling emissions, the emission calculation starts from an unabated level. In other words, even if abatement is considered an integral part of the process, e.g., in the metallurgical industry, the distinction is made between 'raw gas' concentrations (before any abatement) and after the control equipment. The concentration of pollutant in the 'raw gas' is used to derive an uncontrolled ('raw gas') emission factor that is ultimately defined per unit of energy input (or, more generally, per unit of activity). The values of these coefficients are either estimated on the basis of fuel type and combustion conditions or taken from the literature.

Size fractions:

Typically, the emitted mass or concentration of particulate matter is given as TSP (total suspended particles), PM_{10} (particles with an aerodynamic diameter less than 10 microns), $PM_{2.5}$, PM_1, $PM_{0.1}$, etc. The RAINS model distinguishes three size fractions:

Fine particles - $PM_{2.5}$ - (< 2.5 microns);
Coarse particles (> 2.5 and < 10 microns); and
Larger than PM_{10} - PM_>10 - (> 10 microns).

Of course the model also allows calculation of TSP and PM_{10} emissions.

Control option:

The model distinguishes major categories of abatement equipment for both stationary and mobile sources. Each technique, e.g., cyclone, electrostatic precipitator, EUROI to IV for vehicles, etc. is called a control option and can be used to construct a control strategy or a cost curve. The full list of RAINS control options and their efficiencies is available from the RAINS

PM Web model under the option Display Emissions: Regional coefficients: Emission factors & removal efficiency.

Control strategy:

A selection of control options applied to a certain percentage of total capacities in specific sectors and years constitutes a control strategy. A control strategy can be defined for a single country, a group of countries or for the whole of Europe. At this stage, it is possible only to view the illustrative strategies provided.

Initial controls:

Since RAINS also attempts to reproduce the official emission inventories, the initial controls file contains a set of control options that were present in 1990 or 1995. In RAINS PM Web these initial controls can be viewed by displaying the region-specific control strategy.

Emission control scenario:

A set of activity pathway - control strategy pairs for each country defines an emission control scenario. In a future version of the model it will be possible to create "scenarios" in an interactive way. In principle, every calculation of emissions or costs in RAINS is performed for a selected scenario.

Unit cost of emission control:

Unit costs are calculated by relating the annual costs to the abated particulate matter emissions. The average annual costs are calculated considering lifetime of the abatement technologies. The expenditures are differentiated into investments, fixed and variable operating costs.

Marginal cost:

Marginal costs relate the extra costs for an additional measure to the marginal abatement of that measure (compared to the abatement of the less effective option). For details and discussion see Forsund, 2000.

Cost curve:

The cost curve can be calculated for a selected country, year and scenario. Two principal calculation stages can be distinguished, i.e.

A. The elimination of non-cost-effective control options (techniques that have higher costs and lower efficiency than the preceding option are excluded); and

B. Final ranking of the remaining options with increasing marginal cost to form a national cost curve.

Annex 2: Cost Parameters for Technologies to Control Emissions from Industrial Processes

Process	Technology	Investment coefficient [€/t]	Fixed O+M coefficient [%]	Additional electricity demand [kWh/t]	Byproduct [t/t product]
PR_PIGI	PR_ESP1	2.7	5.00	1.25	0.50
PR_PIGI	PR_ESP2	3.3	5.00	1.47	0.50
PR_PIGI	PR_ESP3P	3.9	5.00	1.70	0.50
PR_PIGI	PR_CYC	1.1	5.00	1.70	0.50
PR_PIGI	PR_WSCRB	3.9	5.00	8.50	0.50
PR_CAST	PR_ESP1	22.8	3.00	6.60	0.50
PR_CAST	PR_ESP2	28.3	3.00	7.80	0.50
PR_CAST	PR_ESP3P	33.3	3.00	9.00	0.50
PR_CAST	PR_FF	36.5	3.00	12.00	0.50
PR_CAST	PR_CYC	9.2	3.00	9.00	0.50
PR_CAST	PR_WSCRB	33.3	3.00	90.00	0.50
PR_COKE	PR_ESP1	0.6	4.00	0.22	0.50
PR_COKE	PR_ESP2	0.7	4.00	0.26	0.50
PR_COKE	PR_ESP3P	0.8	4.00	0.30	0.50
PR_COKE	PR_FF	0.9	4.00	0.40	0.50
PR_COKE	PR_CYC	0.2	4.00	0.30	0.50
PR_COKE	PR_WSCRB	0.8	4.00	3.00	0.50
PR_SINT	PR_ESP1	1.2	6.00	0.88	0.20
PR_SINT	PR_ESP2	1.5	6.00	1.04	0.20
PR_SINT	PR_ESP3P	1.8	6.00	1.20	0.20
PR_SINT	PR_FF	2.0	6.00	1.60	0.20
PR_SINT	PR_CYC	0.5	6.00	1.20	0.20
PR_REF	PR_ESP1	0.2	4.00	0.06	1.00
PR_REF	PR_ESP2	0.2	4.00	0.07	1.00
PR_REF	PR_ESP3P	0.3	4.00	0.08	1.00
PR_REF	PR_FF	0.3	4.00	0.11	1.00
PR_REF	PR_CYC	0.1	4.00	0.08	1.00
PR_HEARTH	PR_ESP1	3.6	4.00	1.83	0.50
PR_HEARTH	PR_ESP2	4.4	4.00	2.17	0.50
PR_HEARTH	PR_ESP3P	5.2	4.00	2.50	0.50
PR_HEARTH	PR_FF	5.7	4.00	3.33	0.50
PR_HEARTH	PR_CYC	1.4	4.00	2.50	0.50
PR_HEARTH	PR_WSCRB	5.2	4.00	25.00	0.50
PR_BAOX	PR_ESP1	21.9	4.00	0.81	0.50
PR_BAOX	PR_ESP2	27.3	4.00	0.95	0.50
PR_BAOX	PR_ESP3P	32.0	4.00	1.10	0.50
PR_BAOX	PR_FF	35.1	4.00	1.47	0.50
PR_BAOX	PR_CYC	8.8	4.00	1.10	0.50
PR_BAOX	PR_WSCRB	32.0	4.00	11.00	0.50
PR_EARC	PR_FF	1.9	4.00	1.10	0.50
PR_EARC	PR_CYC	0.5	4.00	0.83	0.50
PR_EARC	PR_WSCRB	1.7	4.00	8.25	0.50
PR_ALPRIM	PR_ESP1	3.3	4.00	0.83	0.50
PR_ALPRIM	PR_ESP2	4.1	4.00	0.98	0.50
PR_ALPRIM	PR_ESP3P	4.8	4.00	1.13	0.50
PR_ALPRIM	PR_FF	5.3	4.00	1.50	0.50
PR_ALPRIM	PR_CYC	1.3	4.00	1.13	0.50
PR_ALSEC	PR_FF	23.0	3.00	8.90	0.50
PR_ALSEC	PR_CYC	5.8	3.00	6.68	0.50

Process	Technology	Investment coefficient [€/t]	Fixed O+M coefficient [%]	Additional electricity demand [kWh/t]	Byproduct [t/t product]
PR_ALSEC	PR_WSCRB	21.0	3.00	66.75	0.50
PR_OT_NFME	PR_WESP	19.5	3.00	4.13	0.50
PR_OT_NFME	PR_FF	21.4	3.00	5.50	0.50
PR_OT_NFME	PR_CYC	5.4	3.00	4.13	0.50
PR_OT_NFME	PR_WSCRB	19.5	3.00	41.25	0.50
PR_BRIQ	PR_ESP1	0.6	4.00	0.22	0.00
PR_BRIQ	PR_ESP2	0.8	4.00	0.26	0.00
PR_BRIQ	PR_ESP3P	0.9	4.00	0.30	0.00
PR_BRIQ	PR_FF	1.0	4.00	0.40	0.00
PR_BRIQ	PR_CYC	0.3	4.00	0.30	0.00
PR_BRIQ	PR_WSCRB	0.9	4.00	3.00	0.00
PR_GLASS	PR_ESP1	2.7	4.00	0.61	1.00
PR_GLASS	PR_ESP2	3.3	4.00	0.72	1.00
PR_GLASS	PR_ESP3P	3.9	4.00	0.83	1.00
PR_GLASS	PR_FF	4.3	4.00	1.10	1.00
PR_GLASS	PR_CYC	1.1	4.00	0.83	1.00
PR_FERT	PR_FF	1.9	4.00	1.40	0.00
PR_FERT	PR_CYC	0.5	4.00	1.05	0.00
PR_FERT	PR_WSCRB	1.7	4.00	10.50	0.00
PR_CEM	PR_ESP1	3.1	5.20	1.39	0.00
PR_CEM	PR_ESP2	3.9	5.20	1.64	0.00
PR_CEM	PR_ESP3P	4.6	5.20	1.89	0.00
PR_CEM	PR_FF	3.8	5.50	2.85	0.00
PR_CEM	PR_CYC	1.3	5.20	1.89	0.00
PR_CEM	PR_WSCRB	4.6	5.20	18.90	0.00
PR_LIME	PR_ESP1	11.4	4.00	1.69	0.00
PR_LIME	PR_ESP2	14.1	4.00	1.99	0.00
PR_LIME	PR_ESP3P	16.6	4.00	2.30	0.00
PR_LIME	PR_FF	13.8	4.00	3.40	0.00
PR_LIME	PR_CYC	4.6	4.00	2.30	0.00
PR_LIME	PR_WSCRB	16.6	4.00	23.00	0.00
PR_CBLACK	PR_FF	0.9	4.00	0.40	0.00
PR_CBLACK	PR_CYC	0.2	4.00	0.30	0.00
PR_OTHER	PR_ESP1	3.6	4.00	1.10	1.00
PR_OTHER	PR_ESP2	4.5	4.00	1.30	1.00
PR_OTHER	PR_ESP3P	5.3	4.00	1.50	1.00
PR_OTHER	PR_FF	5.8	4.00	2.00	1.00
PR_OTHER	PR_CYC	1.5	4.00	1.50	1.00
PR_OTHER	PR_WSCRB	5.3	4.00	15.00	1.00
PR_SINT_F	PRF_GP1	1.5	4.00	1.04	0.00
PR_SINT_F	PRF_GP2	1.8	4.00	1.20	0.00
PR_CAST_F	PRF_GP1	31.1	3.00	10.40	0.00
PR_CAST_F	PRF_GP2	36.5	3.00	12.00	0.00
PR_PIGI_F	PRF_GP1	13.6	4.00	1.13	0.00
PR_PIGI_F	PRF_GP2	16.0	4.00	1.30	0.00
PR_SMIND_F	PRF_GP1	31.1	3.00	10.40	0.00
PR_SMIND_F	PRF_GP2	36.5	3.00	12.00	0.00

Annex 3: Cost Parameters for Control Technologies in Transport Sector

Technology	Unit investment [€/vehicle]	Fixed O+M [%]
MDEUI	165	9.8
MDEUII	303	6.3
MDEUIII	858	3.5
MDEUIV	1199	3.1
MDEUV	1400	2.9
MDEUVI	1500	2.9
HDEUI	660	7.9
HDEUII	1980	4.0
HDEUIII	4452	2.9
HDEUIV	7967	2.5
HDEUV	8852	2.4
HDEUVI	9452	2.4
CAGEUI	660	7.9
CAGEUII	1980	4.0
CAGEUIII	4452	2.9
CAGEUIV	7967	2.5
CAGEUV	8852	2.4
CAGEUVI	9452	2.4
TIWEUI	1716	7.8
TIWEUII	5148	3.9
TIWEUIII	11575	2.9
TIWEUIV	20714	2.5
TIWEUV	23015	2.4
TIWEUVI	24575	2.4
LFGDIII	891	3.5
LFGDIV	1122	3.2
LFGDV	1200	3.1
LFGDVI	1300	3.0
LFEUI	330	5.9
LFEUII	451	4.9
LFEUIII	891	3.5
LFEUIV	1122	3.2
LFEUV	1200	3.1
LFEUVI	1300	3.0
MMO2I	80	9.5
MMO2II	120	7.0
MMO2III	150	6.0
MOT4I	110	7.5
MOT4II	160	5.8
MOT4III	200	5.0
HDSEI	3025	5.3
HDSEII	3300	5.0
HDSEIII	3600	4.8
STMCM	219522	2.0
STLHCM	439043	2.0
STLMCM	371250	2.0

Annex 4: Explanation of abbreviations used in RAINS for sectors

Abbreviation	Sector
CON_COMB1	Fuel production & conversion: Combustion, grate firing
CON_COMB2	Fuel production & conversion: Combustion, fluidized bed boiler
CON_COMB3	Fuel production & conversion: Combustion, pulverized fuel combustion
CON_COMB	Fuel production & conversion: Combustion
CON_LOSS	Losses during transmission & distribution of final product
DOM	Combustion in residential-commercial sector (liquid fuels)
DOM_FPLACE	Residential-Commercial: Fireplaces
DOM_STOVE	Residential-Commercial: Stoves
DOM_SHB_M	Residential-Commercial: Single house boilers (<50 kW) - manual
DOM_SHB_A	Residential-Commercial: Single house boilers (<50 kW) - automatic
DOM_MB_M	Residential-Commercial: Medium boilers (<1 MW) – manual
DOM_MB_A	Residential-Commercial: Medium boilers (<50 MW) – automatic
IN_BO1	Industry: Combustion in boilers, grate firing
IN_BO2	Industry: Combustion in boilers, fluidized bed boiler
IN_BO3	Industry: Combustion in boilers, pulverized fuel combustion
IN_BO	Industry: Combustion in boilers
IN_OC1	Industry: Other combustion, grate firing
IN_OC2	Industry: Other combustion, fluidized bed boiler
IN_OC3	Industry: Other combustion, pulverized fuel combustion
IN_OC	Industry: Other combustion
PP_EX_OTH1	Power & district heat plants: Existing plants, other, grate firing
PP_EX_OTH2	Power & district heat plants: Existing plants, other, fluidized bed boiler
PP_EX_OTH3	Power & district heat plants: Existing plants, other, pulverized fuel combustion
PP_EX_OTH	Power & district heat plants: Existing plants, other
PP_EX_WB	Power & district heat plants: Existing plants, wet bottom boiler
PP_NEW1	Power & district heat plants: New plants, grate firing
PP_NEW2	Power & district heat plants: New plants, fluidized bed boiler
PP_NEW3	Power & district heat plants: New plants, pulverized fuel combustion
PP_NEW	Power & district heat plants: New plants
PP_TOTAL	Power & district heat plants (total)
TRA_RD_HD	Heavy duty trucks and buses (exhaust)
TRA_RD_LD2	Motorcycles: 2-stroke; mopeds (also cars) (exhaust)
TRA_RD_M4	Motorcycles: 4-stroke (exhaust)
TRA_RD	Light duty vehicles: cars, motorcycles (electric, renewable)
TRA_RD_LD4	Light duty vehicles: 4-stroke (excluding GDI) (exhaust)
TRA_RDXLD4	Light duty vehicles: gasoline direct injection (GDI) (exhaust)
LEAD_GASOL	Heavy and light duty vehicles: leaded gasoline (exhaust)
TRA_OT	Other transport: Rail (solid fuels), Heating (stationary combustion)
TRA_OT_LD2	Other transport: Off-road; 2-stroke (exhaust)
TRA_OT_CNS	Other transport: Construction machinery (exhaust)
TRA_OT_AGR	Other transport: Agriculture (exhaust)
TRA_OT_RAI	Other transport: Rail (exhaust)
TRA_OT_INW	Other transport: Inland waterways (exhaust)
TRA_OT_AIR	Other transport: Air traffic (LTO)

Abbreviation	Sector
TRA_OT_LB	Other transport: Other off-road; 4-stroke (military, households, etc.)
TRA_OTS_M	Other transport: Ships; medium vessels (exhaust)
TRA_OTS_L	Other transport: Ships; large vessels (exhaust)
TRT_RD_HD	Heavy duty trucks and buses (tyre wear)
TRT_RD_LD2	Motorcycles: 2-stroke; mopeds (also cars) (tyre wear)
TRT_RD_M4	Motorcycles: 4-stroke (tyre wear)
TRT_RD_LD4	Light duty vehicles: 4-stroke (excl. GDI) (tyre wear)
TRT_RDXLD4	Light duty vehicles: Gasoline direct injection (GDI) (tyre wear)
TRB_RD_HD	Heavy duty trucks and buses (brake wear)
TRB_RD_LD2	Motorcycles: 2-stroke; mopeds (also cars) (brake wear)
TRB_RD_M4	Motorcycles: 4-stroke (brake wear)
TRB_RD_LD4	Light duty vehicles: 4-stroke (excl. GDI) (brake wear)
TRB_RDXLD4	Light duty vehicles: Gasoline direct injection (GDI) (brake wear)
TRD_RD_HD	Heavy duty trucks and buses (abrasion)
TRD_RD_LD2	Motorcycles: 2-stroke; mopeds (also cars) (abrasion)
TRD_RD_M4	Motorcycles: 4-stroke (abrasion)
TRD_RD_LD4	Light duty vehicles: 4-stroke (excl. GDI) (abrasion)
TRD_RDXLD4	Light duty vehicles: Gasoline direct injection (GDI) (abrasion)
TRB_OT_RAI	Other transport: Rail (non-exhaust)
PR_PIGI	Industrial Process: Pig iron, blast furnace
PR_PIGI_F	Industrial Process: Pig iron, blast furnace (fugitive)
PR_COKE	Industrial Process: Coke oven
PR_PELL	Industrial Process: Agglomeration plant – pellets
PR_SINT	Industrial Process: Agglomeration plant – sinter
PR_SINT_F	Industrial Process: Agglomeration plant – sinter (fugitive)
PR_HEARTH	Industrial Process: Open hearth furnace
PR_BAOX	Industrial Process: Basic oxygen furnace
PR_EARC	Industrial Process: Electric arc furnace
PR_CAST	Industrial Process: Cast iron (grey iron foundries)
PR_CAST_F	Industrial Process: Cast iron (grey iron foundries) (fugitive)
PR_ALPRIM	Industrial Process: Aluminum production - primary
PR_ALSEC	Industrial Process: Aluminum production - secondary
PR_OT_NFME	Industrial Process: Other non-ferrous metals production - primary and secondary
PR_BRIQ	Industrial Process: Briquettes production
PR_CEM	Industrial Process: Cement production
PR_LIME	Industrial Process: Lime production
PR_CBLACK	Industrial Process: Carbon black production
PR_OTHER	Industrial Process: Production of glass fiber, gypsum, PVC, other
PR_REF	Industrial Process: Petroleum refineries
PR_GLASS	Industrial Process: Glass production (flat, blown, container glass)
PR_FERT	Industrial Process: Fertilizer production
PR_SMIND_F	Industrial Process: Small industrial and business facilities (fugitive)
MINE_BC	Mining: Brown coal
MINE_HC	Mining: Hard coal
MINE_OTH	Mining: Bauxite, copper, iron ore, zinc ore, manganese ore, other
WASTE_FLR	Waste: Flaring in gas and oil industry
WASTE_AGR	Waste: Agricultural waste burning
WASTE_RES	Waste: Open burning of residential waste

Abbreviation	Sector
STH_COAL	Storage and handling: Coal
STH_FEORE	Storage and handling: Iron ore
STH_NPK	Storage and handling: N,P,K fertilizers
STH_OTH_IN	Storage and handling: Other industrial products (cement, bauxite, coke
STH_AGR	Storage and handling: Agricultural products (crops)
AGR_POULT	Agriculture: Livestock - poultry
AGR_PIG	Agriculture: Livestock - pigs
AGR_COWS	Agriculture: Livestock - dairy cattle
AGR_BEEF	Agriculture: Livestock - other cattle
AGR_OTANI	Agriculture: Livestock - other animals (sheep, horses)
AGR_ARABLE	Agriculture: Ploughing, tilling, harvesting
AGR_OTHER	Agriculture: Other (activity as emissions in kt)
CONSTRUCT	Construction activities
RES_BBQ	Residential: Meat frying, food preparation, BBQ
RES_CIGAR	Residential: Cigarette smoking
RES_FIREW	Residential: Fireworks
OTHER	Other: (activity given as emissions in kt)
NONEN	Non-energy use of fuels

Annex 5: Explanation of abbreviations used in RAINS for control technologies

Abbreviation	Technology
NOC	No Control
NSC	Stock not suitable for control
ESP1	Electrostatic precipitator: 1 field - power plants
ESP2	Electrostatic precipitator: 2 fields - power plants
ESP3P	Electrostatic precipitator: more than 2 fields - power plant
FF	Fabric filters - power plants
CYC	Cyclone - power plants
WSCRB	Wet scrubber - power plants
IN_ESP1	Electrostatic precipitator: 1 field - industrial combustion
IN_ESP2	Electrostatic precipitator: 2 fields - industrial combustion
IN_ESP3P	Electrostatic precipitator: more than 2 fields - industrial combustion
IN_FF	Fabric filters - industrial combustion
IN_CYC	Cyclone - industrial combustion
IN_WSCRB	Wet scrubber – industrial combustion
PR_ESP1	Electrostatic precipitator: 1 field - industrial processes
PR_ESP2	Electrostatic precipitator: 2 fields - industrial processes
PR_ESP3P	Electrostatic precipitator: more than 2 fields - industrial processes
PR_WESP	Wet electrostatic precipitator: industrial processes
PR_FF	Fabric filters - industrial processes
PR_CYC	Cyclone - industrial processes
PR_WSCRB	Wet scrubber – industrial processes
GHIND	Good housekeeping: industrial oil boilers
PRF_GP1	Good practice: industrial processes - stage 1 (fugitive)
PRF_GP2	Good practice: industrial processes - stage 2 (fugitive)
FP_CAT	Fireplaces, catalytic insert
FP_ENC	Fireplaces, non-catalytic insert
WOOD1	New domestic stoves (wood): non-catalytic
WOOD2	New domestic stoves (wood): catalytic
COAL1	New domestic stoves (coal): stage 1
COAL2	New domestic stoves (coal): stage 2
NB_COAL	New domestic boilers: (coal)
MB_PELL	New medium (automatic) size boilers: (wood chips, pellets)
MB_PLBAG	New medium size boilers: (wood chips, pellets) with end-of-pipe abatement
MB_CYC	Cyclone for medium boilers in domestic sectors
MB_BAG	Baghouse for medium (automatic) boilers in domestic sector
GHDOM	Good housekeeping: domestic oil boilers
MDEUI	EURO I -1992/94, diesel light duty and passenger cars
MDEUII	EURO II -1996, diesel light duty and passenger cars
MDEUIII	EURO III -2000, diesel light duty and passenger cars
MDEUIV	EURO IV -2005, diesel light duty and passenger cars
MDEUV	EURO V -diesel light duty and passenger cars, post-2005 St.1
MDEUVI	EURO VI -diesel light duty and passenger cars - post 2005, St.2
CAGEUI	Construction and agriculture - off-road -1998, as EUROI for HDV
CAGEUII	Construction and agriculture - off-road -2000/02, as EUROII for HDV

Abbreviation	Technology
CAGEUIII	Construction and agriculture - off-road; as EUROIII for HDV
CAGEUIV	Construction and agriculture - off-road; as EUROIV for HDV
CAGEUV	Construction and agriculture - off-road; as EUROV for HDV
CAGEUVI	Construction and agriculture - off-road; as EUROVI for HDV
TIWEUI	Rail and inland waterways - off-road -1998, as EUROI for HDV
TIWEUII	Rail and inland waterways - off-road -2000/02, as EUROII for HDV
TIWEUIII	Rail and inland waterways - off-road; as EUROIII for HDV
TIWEUIV	Rail and inland waterways - off-road; as EUROIV for HDV
TIWEUV	Rail and inland waterways - off-road; as EUROV for HDV
TIWEUVI	Rail and inland waterways - off-road; as EUROVI for HDV
HDEUI	EURO I - 1992, heavy duty diesel vehicles
HDEUII	EURO II - 1996, heavy duty diesel vehicles
HDEUIII	EURO III - 2000, heavy duty diesel vehicles
HDEUIV	EURO IV - 2005, heavy duty diesel vehicles
HDEUV	EURO V - 2008, heavy duty diesel vehicles
HDEUVI	EURO VI, heavy duty diesel vehicles, post-2008
LFGDIII	EURO III, gasoline direct injection engines
LFGDIV	EURO IV, gasoline direct injection engines
LFGDV	EURO V, gasoline direct injection engines
LFGDVI	EURO VI, gasoline direct injection engines
LFEUI	EURO I, light duty, spark ignition engines: 4-stroke, not DI
LFEUII	EURO II, light duty, spark ignition engines: 4-stroke, not DI
LFEUIII	EURO III, light duty, spark ignition engines: 4-stroke, not DI
LFEUIV	EURO IV, light duty, spark ignition engines: 4-stroke, not DI
LFEUV	EURO V, light duty, spark ignition engines: 4-stroke, not DI
LFEUVI	EURO VI, light duty, spark ignition engines: 4-stroke, not DI
MMO2I	Motorcycles and mopeds, 2-stroke, stage 1
MMO2II	Motorcycles and mopeds, 2-stroke, stage 2
MMO2III	Motorcycles and mopeds, 2-stroke, stage 3
MOT4I	Motorcycles, 4-stroke, stage 1
MOT4II	Motorcycles, 4-stroke, stage 2
MOT4III	Motorcycles, 4-stroke, stage 3
HDSEI	Heavy duty vehicles, spark ignition engines, stage 1
HDSEII	Heavy duty vehicles, spark ignition engines, stage 2
HDSEIII	Heavy duty vehicles, spark ignition engines, stage 3
STMCM	Combustion modification: ships (medium vessels)
STLHCM	Combustion modification: ships (large vessels-fuel oil)
STLMCM	Combustion modification: ships (large vessels-diesel)
STH_GP	Good practice: storage and handling
FEED_MOD	Feed modification (all livestock)
HAY_SIL	Hay-silage for cattle
FREE	Free range poultry
ALTER	Low-till farming, alternative cereal harvesting
AGR1	A generic option for 'other animals' - good practice
FLR_GP	Good practice in oil and gas industry - flaring
BAN	Ban on open burning of agricultural or residential waste
MINE_GP	Good practice in mining industry
SPRAY	Spraying water at construction places

Abbreviation	Technology
FILTER	Filters in households (kitchen)
RESP1	Generic, e.g. street washing