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Sulfur emissions, abatement technologies and related costs for Europe in the RAINS model database

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ABSTRACT

This paper describes the part of the Regional Air Pollution Information and Simulation (RAINS) model dealing with the potential and costs for controlling emissions of sulfur dioxide. The paper discusses the selected aggregation level of the emission generating activities and reviews the major options for controlling SO_2 emissions. An algorithm for estimating emission control costs is presented. The cost calculation distinguishes 'general' (i.e., valid for all countries) and 'country-specific' parameters in order to capture characteristic technology- and site-specific factors influencing the actual costs of applying a certain measure under a given condition. The methodology is illustrated by two examples for typical control technologies (wet flue gas desulfurization and the use of low-sulfur gas oil). Finally, the method for constructing emission abatement cost curves showing the relationships between the level of remaining emissions and the associated costs is explained.

The general parameters used in the cost calculations are presented in the main body of the report, while all country-specific parameters are contained in a number of appendices. In addition, these country-specific appendices present the energy scenarios as they are currently implemented in the RAINS model, and the resulting cost curves for SO_2 control related to these energy scenarios.

The appendices are available on the Internet under the URL:
http://www.iiasa.ac.at/~amann/so2review.html

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Sulfur Emissions, Abatement Technologies and Related Costs for Europe in the RAINS Model Database

Janusz Cofala and Sanna Syri

1 Introduction

The RAINS (Regional Acidification INformation and Simulation) model developed at the International Institute for Applied Systems Analysis (IIASA) (Alcamo *et al.*, 1990) is designed as an integrated tool for the assessment of air pollution control strategies in Europe. RAINS calculates the precursor emissions contributing to acidification and eutrophication of natural ecosystems as well as to the formation of tropospheric ozone. It estimates emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and non-methane volatile organic compounds (VOC), calculates their dispersion in the atmosphere and compares the resulting exposure levels with no-damage thresholds for a variety of environmental receptor systems. The optimization analysis enables to identify the cost-minimal allocation of emission controls in order to achieve pre-specified target exposure levels.

RAINS is presently applied as a scenario analysis tool in the context of the international negotiations under the UN/ECE Convention on Long-range Transboundary Air Pollution and for the development of the acidification and ozone strategies of the European Union (EU).

This paper describes data and calculation principles used for the assessment of the future potential and costs for controlling SO_2 emissions in individual countries. Data applied for the NO_x and NH_3 estimates underwent an official review by the Parties to the Convention on Long-range Transboundary Air Pollution in late 1996 (IIASA, 1996). The review of the VOC-related data will be completed in June 1998 (Klimont *et al.*, 1998).

1.1 The General Approach for an Integrated Assessment

The Regional Air Pollution INformation and Simulation (RAINS)-model developed at the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria) provides a consistent framework for the analysis of emission reduction strategies, focusing on acidification, eutrophication and tropospheric ozone. RAINS comprises modules for emission generation (with databases on current and future economic activities, energy consumption levels, fuel characteristics, etc.), for emission control options and costs, for atmospheric dispersion of pollutants and for environmental sensitivities (i.e., databases on critical loads). In order to create a consistent and comprehensive picture of the options for simultaneously addressing the three environmental problems (acidification, eutrophication and tropospheric ozone), the model considers emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC). A detailed description of the RAINS model can be found in Alcamo *et al.*, 1990. A schematic diagram of the RAINS model is displayed in Figure 1.1.

The European implementation of the RAINS model incorporates databases on energy consumption for 40 regions in Europe, distinguishing 22 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010 (Bertok *et al.*, 1993). Emissions of SO_2, NO_x, NH_3 and VOC for 1990 are estimated based on information collected by the CORINAIR'90 inventory of the European Environmental Agency (EEA, 1996) and on national information. Options and costs for controlling emissions of the various substances are represented in the model by considering the characteristic technical and economic features of the most important emission reduction options and technologies. Atmospheric dispersion processes over Europe for sulfur and nitrogen compounds are modeled based on results of the European EMEP model developed at the Norwegian Meteorological Institute (Barret and Sandnes, 1996). For tropospheric ozone, source-receptor relationships between the precursor emissions and the regional ozone concentrations are derived from the EMEP photo-oxidants model (Simpson, 1992, 1993). The RAINS model incorporates databases on critical loads and critical levels compiled at the Coordination Center for Effects (CCE) at the National Institute for Public Health and Environmental Protection (RIVM) in the Netherlands (Posch *et al.*, 1997).

The RAINS model can be operated in the 'scenario analysis' mode, i.e., following the pathways of the emissions from their sources to their environmental impacts. In this case the model provides estimates of regional costs and environmental benefits of alternative emission control strategies. Alternatively, a (linear programming) 'optimization mode' is available for the acidification part to identify cost-optimal allocations of emission reductions in order to achieve specified deposition targets. This mode of the RAINS model was used extensively during the negotiation process of the Second Sulfur Protocol under the Convention on Long-range Transboundary Air Pollution for elaborating effect-based emission control strategies. A non-linear optimization module for tropospheric ozone has been recently completed.

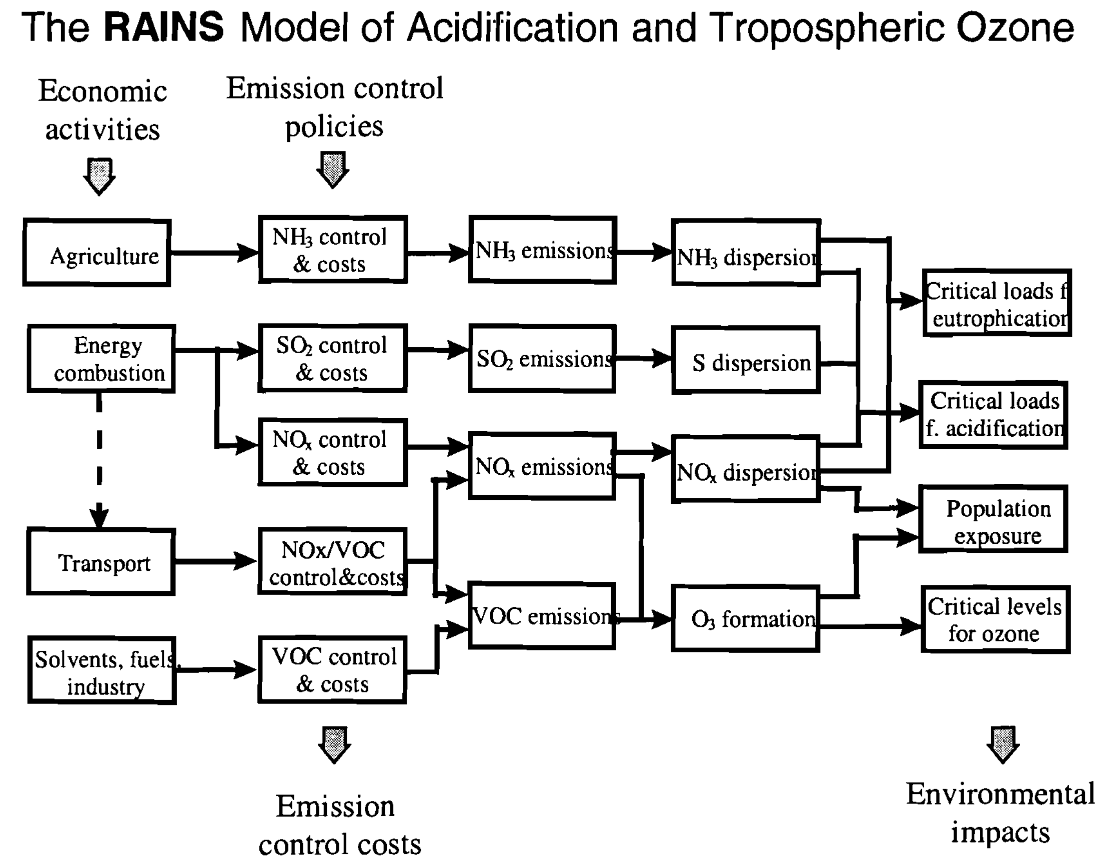

Figure 1.1: Schematic flowchart of the RAINS model framework

1.2 The Objective of Emission Control Costs Estimates in the RAINS Model

To support the development of cost-effective international emission control strategies, the RAINS model aims at a consistent and comparable evaluation of future emission control potentials and costs. Consistency is required for comparing possible emission controls for different countries, different pollutants and different scenarios of economic development in order to ultimately arrive at a cost-effective allocation of measures.

The emission and control costs modules of the RAINS model form a framework for such a consistent international assessment of emission levels and abatement strategies for all European countries. The modules provide a tool for cost evaluation of different future abatement strategies under various energy consumption pathways. They enable the comparison of pollution control costs among countries, which - due to various reasons such as the structure of energy demand or already implemented abatement measures - can be considerably different, and among the pollutants leading to acidification, eutrophication and ground-level ozone.

In practice, the requirement to assess abatement costs for all countries in Europe limits the level of detail that can be maintained in the cost evaluation. In comparison with studies that focus on only one country, data availability and computational constraints require simplifications. Therefore, rather than providing accurate point estimates, e.g., for single power plants, the resulting cost estimates should be considered as indicative, capturing the characteristic differences among countries and pollutants. There are objective factors, such as the structure of the national energy systems, the quality of domestic fuels, the load patterns of power stations, the age structure of installations, the already implemented emission control measures, etc., which cause significant differences in the remaining emission control potential and the associated costs across the European countries.

Since the scope of RAINS is to provide a tool for optimal reduction of negative ecological impacts caused by air pollutants, the cost submodel concentrates only on presenting the direct emission control costs. All indirect costs, such as effects on energy prices, on trade balances, on employment and the benefits induced by reduced damage to ecosystems or materials, are excluded from the evaluation.

2 Aggregation Schemes for the Emission Sources

Precise estimates of emission control potentials and of the associated costs require detailed knowledge about a large number of technical and economic aspects relevant for each individual emission source. In practice, however, much of this detailed information is either difficult to obtain or not available at all on a large scale. Consequently, a Europe-wide assessment must necessarily select a certain level of aggregation on which the analysis can be realistically carried out.

2.1 Sectoral Aggregation of Emission Sources

Various studies developed alternative aggregation schemes for estimating emission control costs. Depending on the overall scope of the assessment, aggregation schemes deal with installations at individual plants (e.g., for cost assessment at a company level), groups of installations with similar technologies (frequently applied in national studies), or choose the macro-economic level of entire economic sectors or even countries. Each of these aggregation schemes is appropriate for a specific purpose, and it is difficult to establish a general superiority of a particular approach.

Obviously there is a clear trade-off between the level of technical detail that can be maintained (and thereby the extent to which specific circumstances of a particular source can be taken into account) and the availability of reliable information for implementing the assessment. In order to arrive at a practical approach for estimating future emission control costs on a continental scale, a compromise between the detailed 'bottom up' and the highly aggregated and/or 'top down' approaches was developed. The major criteria for the aggregation of emission sources are:

- Contribution to total emissions (compared to total European emissions and to emissions for a particular country);
- The possibility to define uniform activity rates (i.e., types of economic activities to which the emission levels can linked) and emission factors;
- The possibility to construct forecasts of future activity levels. Since the emphasis of the cost estimates is on future years, it is crucial that reasonable projections of the activity rates can be constructed or derived;
- Availability and applicability of 'homogeneous' control technologies with similar control efficiencies and costs;
- Availability of relevant data. As far as possible, emission related data should be compatible with the CORINAIR'90/94 emission inventory coordinated by the European Environment Agency.

For SO_2 emissions, the major factors influencing the selected aggregation level are the sectoral disaggregation schemes of the available energy balances (e.g., the energy statistics of UN/ECE, OECD/IEA and EUROSTAT), of the energy projections (e.g., of DG XVII) used as exogenous driver to the RAINS model and of the CORINAIR sector classifications (the SNAP code).

As a common denominator of the sectoral aggregation systems of the most relevant energy statistics, the RAINS model applies the following scheme for grouping emission generating activities into sectors of economic activities:

- centralized power plants and district heating (PP),
- fuel conversion other than power plants (CON),
- domestic, commercial and agricultural use (DOM),
- transportation (TRA),
- industrial (IN),
- non-energy use - feedstocks (NONEN) and
- other emission sources (OTHER), including all remaining sectors of minor importance.

Unfortunately, this basic aggregation system ignores a number of factors highly relevant for emission generation, such as emission factors, applicability and effectiveness of control technologies, etc.. Consequently, these primary sectors are further disaggregated in the RAINS model into sub-sectors.

The relations between CORINAIR'90 categories and the RAINS sectors are shown in Table 2.1 and Table 2.2. Due to the differences in the format of the energy statistics and CORINAIR, a direct and full comparison of RAINS estimates with CORINAIR'90 data is only possible at a more aggregated level.

The **power plant** sector includes the centralized production of electricity and district heat. It is further subdivided into new power plants (PP_NEW) and existing plants (PP_EX). Existing plants refer to all sources that came on line before or in 1990. In addition, existing plants are further subdivided into wet bottom boilers (PP_EX_WB) and other types of boilers (PP_EX_OTH)[1], because the emission factors for NO_x show significant differences.

The **fuel conversion** sector includes refineries, coke and briquettes production plants, coal gasification plants etc, but does not include the power stations and district heating plants. Energy consumption for fuel conversion as recorded under combustion in the conversion sector (CON_COMB) includes only the energy consumed in the fuel conversion process and not the energy content of the input materials and final fuel products. The losses during transmission and distribution of the final product are

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[1] The reason for that sub-division is the difference in NO_x emission factors. For calculating sulfur emissions such a sub-division is not necessary.

reported under (CON_LOSS), encompassing the own-use of electricity and heat by the fuel conversion sector and by the industrial auto-producers. Also the own-use of electricity and heat by power plants and district heating plants as well as losses during the transmission and distribution of electricity and district heat are included in this category.

Table 2.1: RAINS sectors of the SO_2/NO_x modules for stationary sources and their relation to the main activity groups of the CORINAIR'90 inventory

RAINS sectors		CORINAIR
Primary	**Secondary**	**SNAP code**
Power plants and district heating plants (PP)	New boilers (PP_NEW) Existing boilers, wet bottom (PP_EX_WB) Existing boilers, dry bottom (PP_EX_OTH)	01
Fuel production and conversion (other than power plants) (CON)	Combustion (CON_COMB) Losses (CON_LOSS)	05
Domestic (DOM)	Residential, commercial, institutional, agriculture	02
Industry (IN)	Combustion in boilers, gas turbines and stationary engines (IN_BO)	0301
	Other combustion (IN_OC)	03 excl. 0301[2]
	Process emissions (IN_PR)[3]	04
Non-energy use of fuels (NONEN)	Use of fuels for non-energy purposes (feedstocks, lubricants, asphalt)	
Other emissions (OTHER)	Other sources (air LTO cycle, waste treatment and disposal)	0805

[2] Excluding processes with and without contact treated separately as process emissions.

[3] Emissions are not directly attributed to fuel consumption.

Table 2.2: Sectors in the RAINS module for mobile sources and their relation to the CORINAIR'90 SNAP codes

RAINS sector		CORINAIR
Primary	**Secondary**	**SNAP code**
Road transport (TRA_RD)	Heavy duty vehicles (trucks, buses and others) (TRA_RD_HD)	0703
	Light duty vehicles, four-stroke (cars, light commercial vehicles, motorcycles) (TRA_LD_LD4)	0701,02,04,05
	Light duty vehicles, two-stroke (cars, motorcycles) (TRA_RD_LD2)	0701,02,04,05
Off-road (TRA_OT)	Machinery with two-stroke engines (TRA_OT_LD2)	0801
	Other machinery and land-based sources (four stroke) (TRA_OT_LB)	0801,02,05
Ships (TRA_OTS)	Medium vessels (TRA_OTS_M)	0803,0804
	Large vessels (TRA_OTS_L)	0803,0804

For **industrial** energy use, the RAINS database distinguishes between energy combustion in industrial boilers for the auto-production of electricity and heat (IN_BO) and fuel combustion in other industrial furnaces (IN_OC). This distinction has been introduced in order to assure future comparability with fuel consumption data provided in the CORINAIR 1994 inventory (EEA, 1996). However, the CORINAIR inventory for 1990 did not include full information on energy consumption by boiler/furnace category. Also the available energy statistics and forecasts do not always enable a split of industrial combustion between boilers and furnaces. In such a case, all industrial fuel combustion is reported as IN_OC. In the latest version of CORINAIR (CORINAIR'94) full details on fuel consumption should become available. Thus, it will be possible to tune the industrial energy consumption to the more detailed structures soon.

Furthermore, RAINS also includes the so-called '**process emissions**' in the industrial sector, i.e., emissions that can not be directly linked to energy consumption. Industrial processes included in RAINS are

- oil refineries (IN_PR_REF),
- coke plants (IN_PR_COKE),
- sinter plants (IN_PR_SINT),
- pig iron - blast furnaces (IN_PR_PIGI),
- non-ferrous metal smelters (IN_PR_NFME),
- sulfuric acid plants (IN_PR_SUAC),
- nitric acid plants (IN_PR_NIAC),
- cement and lime plants (IN_PR_CELI), and
- pulp mills (IN_PR_PULP).

Other production processes distinguished in the CORINAIR inventory are covered by sector IN_OC.

The **non-energy** (NONEN) use of fuels includes the consumption of lubricants, the heavy oil fractions like asphalt for road construction and fuel used as chemical feedstock. It is assumed that the use of non-energy products does not cause any emissions of sulfur dioxide.

The **transport** sector is divided into road transport (TRA_RD) and off-road transport (TRA_OT). The latter category is subdivided further into land-based transport (rail, inland waterways, off-road machinery and agricultural tractors) and the so-called national sea traffic (TRA_OTS), which includes emissions from ships operating in the coastal zone or between ports located in the same country.

Since only a small fraction of emissions caused by air transport (i.e., the emissions generated during landing, taxi and take-off - LTO) is accounted for in national emission inventories, fuel use by aircrafts is not included in the RAINS database. Emissions originating from airports (LTO only) are assessed separately and put together with other sources like waste treatment and disposal to the sector called OTHER. RAINS does not consider control options for the emissions from the latter sector.

2.2 Aggregation of Fuel Categories

The emission sources grouped into the economic sectors listed above are further subdivided according to the type of fuel. The fuel categories distinguished in RAINS are shown in Table 2.3. RAINS considers the major energy flows for 17 categories of fuels[4]. For solid fuels (hard coal, lignite) the model offers an opportunity to distinguish - within each sector - different quality parameters (grades) such as calorific value, sulfur content or sulfur retained in ash. This increases the accuracy of estimates of emissions and emission control costs. However, if for a specific country, only the average fuel quality parameter is known, only one category is used.

[4] The abbreviation 'No fuel use' (NOF) is used for process emissions.

Table 2.3: Fuel categories in RAINS

Fuel type	Abbreviation
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
Other solid-low S (biomass, waste, wood)	OS1
Other solid-high S (incl. high S waste)	OS2
Heavy fuel oil	HF
Medium distillates (diesel, light fuel oil)	MD
Light fractions (gasoline, kerosene, naphtha, LPG)	LF
Natural gas (incl. other gases)	GAS
Renewable (solar, wind, small hydro)	REN
Hydro	HYD
Nuclear	NUC
Electricity	ELE
Heat (steam, hot water)	HT
No Fuel use	NOF

2.3 Spatial Aggregation of the Emission Sources

The basic spatial resolution of the RAINS emission and cost module is the country-level. Calculations are performed for 36 European countries and four sea regions within the EMEP modeling domain[5]. In addition, for Russia (because of the large geographical area) and for Germany (because of the implementation differences in the base year 1990) further divisions into sub-national regions are made. The countries/regions and their codes used by RAINS are shown in Appendix 1.

[5] EMEP stands for Cooperative Program for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe.

3 Energy Scenarios Stored in the RAINS Database

The RAINS model estimates future SO_2 emissions based on scenarios of national energy consumption and on assumptions about applied emission controls (e.g., the current legislation). The database contains entries for the year 1990 (base year), 1995, 2000, 2005 and 2010.

The present RAINS implementation comprises a number of alternative energy projections, which can be used to assess the likely range of future SO_2 emissions under a variety of alternative energy developments.

The so-called **'Official Energy Pathway'** (OEP) is available for all European countries. The OEP scenario is a collection of projections of future energy consumption reported by the governments of individual countries to the UN/ECE Energy Database (UN/ECE, 1996). Where necessary, missing forecast data have been constructed by IIASA based on a simple energy projection model.

In addition, for the EU countries several scenarios developed for the European Commission (DGXVII) are also stored in RAINS. These are:

- The **'Conventional Wisdom'** (CW) energy scenario of DG-XVII. Data are extracted from the 'Energy 2020' Study (DG-XVII, 1996).
- The **'Low CO_2'** scenario that demonstrates the effects of measures aimed at reducing emissions of carbon dioxide to the atmosphere (Capros *et al.*, 1996)
- The **'Business as Usual'** (BAU) scenario (Capros *et al.*, 1997). This scenario can be regarded as an update of the 'Conventional Wisdom' scenario.
- The **'Energy Efficiency'** (EE) scenario (Gusbin *et al.*, 1997). This scenario is a modification of the BAU scenario. Data is available for Belgium, France and Spain.
- For Austria, Denmark, Finland, the Netherlands, Sweden (provisional), and the United Kingdom the updates of their national scenarios are available. These scenarios are called further **'National Pathways'** (NP). In addition, the national energy projections from Greece and Ireland are currently under implementation.

The energy scenarios used in the recent analyses of control strategies of acidification and ground-level ozone prepared for the UN/ECE and for the EU are shown in Appendix 2. For the non-EU countries the OEP scenario was used. For the EU countries the BAU scenario was the basis for simulations. If for a given country the National Pathway (NP) was available, then the NP scenario was used instead of the BAU.

4 Emission Calculation

The RAINS model calculates present and future sectoral emissions as a product of activity level (e.g., fuel consumption) and an emission factor:

$$S_i(t) = \sum_j \sum_k act_{i,j}(t) * ef_{i,j} * af_{i,j,k}(t) * (1 - \eta_{j,k})$$

with

$S_i(t)$	SO_2 emissions in country i in time step t
$act_{i,j}(t)$	activity level of sector j in time step t
$ef_{i,j}$	(unabated) emission factor per unit of activity for country i and sector j
$\eta_{j,k}$	sulfur removal efficiency of technology k in sector j
$af_{i,j,k}(t)$	application factor of technology k in country i for sector j in time step t.

The country- and sector-specific emission factor $ef_{i,j}$ is calculated taking into account the most important fuel characteristics:

$$ef_{i,j} = 2 * \frac{sc_{i,j,l}}{hv_{i,j,l}} * (1 - sr_{i,j,l})$$

with

$sc_{i,j,l}$	sulfur content (per weight) of fuel l used in sector j in country i
$hv_{i,j,l}$	heat value of fuel l used in sector j in country i
$sr_{i,j,l}$	sulfur retention in ash (fraction) of fuel l used in sector j in country i.

It is important to mention that the unabated emission factor reflects the hypothetical situation if no control measures were applied and is derived from information of the CORINAIR'90 inventory (if, in a particular situation, in the year 1990 emission controls were applied, they are reflected in the application factor *af*). Any change in emission factors over time (e.g., caused by a changed sulfur content) is interpreted as an emission control measure and reflected via a modified application factor *f* of a control technology k with the efficiency η (e.g., by assuming the use of low-sulfur fuels). This approach implies that all changes in fuel quality, even those occurring 'autonomously' due to other reasons, are credited as emission abatement efforts with costs attributed to them.

The fuel quality parameters and the resulting unabated emission factors are presented in Appendix 3.

For industrial process emissions not related to energy use, activity levels (industrial production data) are extracted either from the CORINAIR'90 inventory (if available for a given country) or from international industrial statistics (UN, 1995, 1996). Due to the lack of detailed forecasts of future activity levels, the projections up to the year 2010 are based on trend extrapolation. For the majority of countries the assumption was made that activity levels will only change marginally compared with 1990. Emission factors and activity levels for process emissions are shown in Appendix 4.

5 Options for Reducing SO_2 Emissions

In principle, there is a variety of options to reduce SO_2 emissions from energy combustion, i.a., through

- changes in the energy system leading to lower consumption of sulfur containing fuels (by energy conservation or fuel substitution),
- the use of low-sulfur fuels,
- fuel desulfurization,
- combustion modification (e.g., by adding of sorbent to the furnace) and
- treatment of the flue gases.

Measures influencing the energy consumption structure, such as energy conservation and fuel substitution, affect often not only SO_2 emissions, but at the same time a wide variety of other environmental (e.g., greenhouse gas emissions), economic (trade balances, etc.) and political (energy supply security, etc.) aspects. A full assessment of the costs and benefits of these measures can only be accomplished by a detailed analysis of the technical potential for restructuring the energy systems and of the resulting macro-economic impacts. Clearly, such a comprehensive assessment is beyond the scope of the RAINS model as it is presently implemented, and national energy and/or economic models are more suited for this task[6]. Consequently, the RAINS model refrains from attempting a necessarily incomplete economic analysis and restricts itself to simulating the environmental impacts of structural changes of energy systems.

The economic assessment in RAINS concentrates on the technical emission control options, which do not imply structural changes of the energy system. In the literature several dozens of technologies for reducing SO_2 emissions are documented (Rentz *et al.*, 1996; Takeshita, 1995). Obviously, a continental scale analysis on an aggregated level cannot determine for each individual emission source the most appropriate choice of technology, nor does it appear as reasonable to explicitly consider each single technology variant for the envisaged large-scale assessment. As a practical approach, the large number of available technologies were grouped into five categories, taking their major technical (e.g., sulfur removal efficiencies) and economic properties (e.g., investments/operating costs) as selection criteria. The following five broad groups of technical emission control options are distinguished:

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[6] In the past, the results of such an exercise performed by Rentz *et al.* (1994) have been introduced into the RAINS model.

- The use of low-sulfur fuels, including fuel desulfurization;
- In-furnace control of SO_2 emissions (e.g., through limestone injection or with several types of fluidized bed combustion);
- Conventional wet flue gas desulfurization processes;
- Advanced, high efficiency methods for capturing sulfur from the flue gas;
- Measures to control process emissions.

The technical and economic properties of each of these major categories are represented by the characteristic features of the most widespread representative technology.

For low-sulfur fuels, a distinction is made between low-sulfur coal and coke, low-sulfur heavy fuel oil and low-sulfur gas oil with the characteristic cost differentials of these options. These alternatives may be used to substitute fuels of the same category having higher (unabated) sulfur content and do not require major investments at the plant site. As mentioned above, however, inter-fuel substitution (e.g., replacement of coal by gas) is not considered RAINS.

Add-on and integrated controls (i.e., desulfurization during combustion or purification of the flue gases) require measures at the plant site. Three typical techniques with different cost characteristics and removal rates have been selected to represent the wide spectrum of control technologies with different cost efficiencies (Amann, 1990):

- In-furnace control techniques (fluidized bed combustion, limestone injection) with typical removal efficiencies between 40 and 80 percent and relatively low cost investment costs;
- Wet flue gas desulfurization (WFGD) with typical sulfur removal rates between 85 and 95 percent at moderate costs;
- Advanced high-efficiency processes with emission reductions of up to 99 percent and relatively high costs.

Measures to control process emissions are process-specific and depend critically on the type of technology and equipment used. Due to the poor availability of data related to industrial process emissions, a more aggregated approach distinguishing three generic stages of control with different efficiencies and different costs was adopted to reflect the overall potential for removing emissions from these sources.

Table 5.1 presents the SO_2 control technologies considered in the RAINS model together with their sulfur removal efficiencies. Brief characteristics of the individual options are presented in the following sections.

5.1 Combustion Modification

Typical means of sulfur emission reduction by combustion modification are the addition of limestone into conventional boilers and the fluidized bed combustion. SO_2 can be captured during combustion if a SO_2 sorbent such as limestone ($CaCO_3$) or dolomite ($CaCO_3$*$MgCO_3$) is present. SO_2 sorbent can be added to the coal pellets fired in stoker boilers or injected into pulverized coal-fired boilers.

The most common process currently in use, the limestone injection into pulverized coal-fired boilers, was selected to represent the cost-efficiency ratio of these techniques. This technology achieves emission reduction rates from 50 to 60 percent at moderate investments, making it an attractive option for countries facing economic difficulties or for power plants that are designed to operate at peak load. Due to the high sorbent/sulfur ratio necessary to achieve sufficient emission reduction rates, this technology also produces large amounts of waste material. Most countries face increasing difficulties with waste disposal, and the costs are expected to increase in the future.

Also the fluidized bed combustion (FBC) falls into the 'Combustion Modification' category. In fluidized bed boilers it is possible to simultaneously remove SO_2 and NO_x with relatively high efficiencies. The conditions (temperature, particle residence time in boiler) are very favorable for the sorbent – SO_2 reaction. There are, however, methodological difficulties to apportion the extra costs of the FBC technology (on top of conventional boilers) to the removal of SO_2 and NO_x abatement. In order to avoid the otherwise necessary methodological complications, it has been decided not to treat FBC as a separate option in the RAINS model and to subsume it under the other categories. Since control efficiencies and costs of modern FBC boilers are comparable with the combined costs of wet flue gas desulfurization for SO_2 and selective catalytic reduction (SCR) for NO_x removal (OECD, 1993), this simplification does not introduce major errors when estimating emission control potentials and costs.

Table 5.1 Main groups of SO_2 emission control technologies considered in RAINS

Technology name	Applicable to	RAINS abbreviation	Removal efficiency, %
Low-sulfur coal (0.6 %S)	All sectors	LSCO	(*)
Low-sulfur coke (0.6 % S)	All sectors	LSCK	(*)
Low-sulfur heavy fuel oil (0.6 %S)	All sectors	LSHF	(*)
Low-sulfur gas oil - stage 1 (0.2% S)	All sectors	LSMD1	(*)
Low-sulfur gas oil - stage 2 (0.045% S)	All sectors	LSMD2	(*)
Low-sulfur gas oil - stage 3 (0.003% S)	Road transport	LSMD3	(*)
Limestone injection	Industry, power plants	LINJ	50
Industry, Wet FGD (flue gas desulfurization)	Industry	IWFGD	85
Power plants, Wet FGD, already retrofitted	Power plants	PRWFGD	90
Power plants, Wet FGD	Power plants	PWFGD	95
High efficiency FGD	Power plants, refineries	RFGD	98
Process emissions – Stage 1 control	Process sources	SO2PR1	50
Process emissions – Stage 2 control	Process sources	SO2PR2	70
Process emissions – Stage 3 control	Process sources	SO2PR3	80

(*) The control efficiency depends on the initial sulfur content of the fuel to be replaced.

5.2 Conventional Wet Flue Gas Desulfurization Processes

Wet limestone flue gas desulfurization (WFGD) is the most commonly used flue gas desulfurization technique in Europe. In the early 1990s about 50.000 MW_{el} of coal fired power plants were equipped with flue gas desulfurization, of which more than 80 percent were wet scrubbers (Vernon and Soud, 1990). This technology produces gypsum as a by-product, which can be further used for a variety of industrial applications. WFGD processes have been installed in power plants, waste incineration plants and to some industrial heating plants. Early installations of WFGD processes were designed for sulfur removal efficiencies between 85 and 90 percent, while the latest installations reach up to 95 percent sulfur removal.

5.3 High-efficiency Flue Gas Desulfurization

In order to mark the upper end of available SO_2 removal options, RAINS also considers high-efficiency processes while taking into account the increased costs of these options. There are several technical approaches to achieve sulfur removal rates up to 99 percent, e.g., specially designed wet FGD processes or the Wellman-Lord technology. RAINS uses the Wellman-Lord process to derive the typical economic and technical properties representative for such high-efficiency desulfurization techniques.

This regenerative desulfurization method produces instead of waste material SO_2 rich gas (about 97% SO_2) that can be used as raw input to chemical industry to produce sulfuric acid or even elementary sulfur. Caustic soda (NaOH) is used as a sorbent. Spent absorber liquid is regenerated so that the losses of the sorbent are small. The desulfurization process is based on converting SO_2 to sodium sulfates. Typical reduction efficiencies achieved have been more than 97 %. (Rentz *et al.*, 1996).

5.4 Low-sulfur Fuels and Fuel Desulfurization

Unlike the options depending on the implementation of add-on controls, the use of low-sulfur fuels does not require direct investments at the plant site. Low-sulfur fuels could be either supplied from naturally occurring fuel qualities with lower sulfur content or by desulfurization of high sulfur fuels.

Since a detailed simulation of the international markets for low-sulfur fuels and of the installed desulfurization capacities, e.g., in refineries is outside the scope of the RAINS model, the economic assessment is limited to the use of price differentials between high- and low-sulfur fuels.

Although there are coal qualities with lower sulfur content available on the world market, the conservative assumption is made that only coal with 0.6 percent sulfur will be available at sufficient quantities so that the demand could be satisfied even if the utilization of this type of coal became a major long-term option for Europe.

Desulfurization affects various oil products in different ways. The light fraction products (gasoline, jet fuel) contain a negligible amount of sulfur. For middle distillates (gas oil, diesel), three desulfurization stages are distinguished:

- A 'low-cost' desulfurization down to a sulfur content of 0.2 percent;
- A second step with higher costs to fulfil a 0.05 % limit on the sulfur content to comply with the EU regulation on the sulfur content of gas oil for mobile sources (Johnson and Corcelle, 1995) and the provisions of the Second Sulfur Protocol to the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1994). Experience shows that, in order to fully comply with a 0.05 % limit, the market average will be at about 0.045 %. For stationary sources, the current limit of EU

and UN/ECE regulations is 0.2 percent. However, there are countries (e.g., Austria, Sweden), where stricter limits are in force. Thus, in order to be able to model the situation in these countries and to provide the possibility for further emission reductions in other countries, the 0.05 percent sulfur option is available for all sectors.

- In addition, because of the recent EU proposal for the tighter 50 ppm standard on the sulfur content of diesel fuel (OJ 97/C 351/01, 1997), a third stage reduction down to 30 ppm (0.003 % S, market average) has been introduced for road vehicles.

The desulfurization of heavy fuel oil is considered to be economically competitive only down to a sulfur content of 0.6 percent. This sulfur content can be achieved either through refining North Sea crudes, or by desulfurization at the refinery. For both cases the desulfurization costs occurring in the refining process are applied.

5.5 Control of Process Emissions

Industrial activities emitting sulfur oxides can be divided into combustion processes and processes where emissions cannot be directly linked to energy use. The latter are the processes that release sulfur contained in raw material (e.g., iron ores) or processes that absorb sulfur due to composition of materials produced (e.g., cement production).

RAINS uses emission factors to estimate emissions from the industrial activities in oil refineries, coke plants, sinter plants, pig iron - blast furnaces, non-ferrous metal smelters, sulfuric acid plants, nitric acid plants, cement and lime plants and pulp mills. In order to accurately calculate the energy- and non-energy related emissions from these processes, RAINS defines the emission factors for these processes as the difference between the actual emissions per ton of production and the hypothetical emissions that would result from fuel use only.

However, there are two exceptions to this rule. The first one relates to cement and lime production, where total emissions per ton of product are used to calculate the emissions. This is because the retention of sulfur in the material during cement and lime production is so high (more than 80 percent) that it the standard approach outlined above would require negative process emission factors. To avoid computational difficulties caused by negative emission factors, total emissions are included in the process emission factor. In order to avoid double counting, fuel consumption by cement and lime industry is subtracted from industrial fuel use before performing emissions calculations.

The second exception is the production of pig iron in blast furnaces. In this process a large proportion of sulfur originating from the fuel (coke) is retained in slag. In order to take this effect into account, a high retention of sulfur (more than 90 percent) for industrial use of coke is assumed in the model.

The available measures for reducing emissions from process sources are strongly related to the main production technology. They are site-specific and depend, inter alia on the quality of raw materials used and on many other factors. Therefore, it is difficult to develop generally valid technological characteristics of control technologies at the same degree of detail as for fuel-related emissions. Thus, for estimating emission control potentials and costs, the emissions from all processes are combined into one group, to which three stages of control can then be applied. Without defining specific emission control technologies, these three stages are represented by typical removal efficiencies with increasing marginal costs of reduction. Date are based on Dutch sources (Van Oostvorn, 1984; VROM, 1987) and consultations with experts from the German Environmental Protection Agency (UBA).

6 Cost Evaluation Methodology

This section introduces the methodology for calculating abatement costs in the RAINS-SO_2 module. The approach is in line with the methodologies currently applied in RAINS for the calculations of NO_x, VOC and ammonia emissions (Klaassen, 1991; Klimont *et al.*, 1998).

The basic intention of the cost evaluation is to identify the values to society of the resources diverted in order to reduce SO_2 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 resource allocation. Any taxes added to production costs are similarly ignored as transfers.

The central assumption for the cost evaluation of the RAINS model is the existence of a free market for desulfurization equipment throughout Europe accessible for all Parties at the same conditions. This means that a given technical equipment is available to all countries at the same costs, and that cost differences are related solely to objective technical factors requiring different design of the equipment. There are, however, a number of country- and site-specific circumstances, which make the actual sulfur removal with a given technology cheaper of more expensive. Due to variations in average boiler sizes, capacity utilization rates, sulfur contents of the fuels used etc., costs on a unit basis (i.e, per ton of SO_2 emissions removed) differ notably among countries. The RAINS cost calculation routine is designed to capture these differences in a systematic way.

The cost assessment in RAINS distinguishes cases where investments are required at the plant site (add-on controls) and for which the full average annual life-cycle costs are calculated, and applies a simplified treatment for low-sulfur fuels, where the costs for necessary (centralized) infrastructure are converted into price differentials.

6.1 Methodology for Add-on Controls

RAINS calculates in a first step the average annual costs, taking into account the normal *technical* lifetime of the installations, using the common costing methodology proposed by the relevant expert groups of the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1988). In doing so, expenditures are differentiated into

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

In a second step, potential unit costs are calculated by relating the annual costs to the abated emissions.

The approach considers some of the parameters as country- specific while others are common for all the countries. Country-specific parameters include the average size of installations in a given sector/class, prices for labor and electricity, prices of material. Common parameters include the interest rate and technology-specific data, e.g., removal efficiencies, investments, maintenance costs, specific demand for labor, energy, and materials.

6.1.1 Investments

The investments include the expenditure accumulated until the start-up of an installation, such as delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement and capital. The model uses **investment functions** where these cost components are aggregated into one function. Investments in flue gas desulfurization depend on the boiler size *bs* and the (fuel specific) flue gas volume *v* treated. The form of the function is described by its coefficients ci^f and ci^v. The coefficients *ci* are valid for hard coal fired boilers. Thus the coefficient *v* is used to account for different flue gas volumes to be handled when other fuel is used. The coefficients *ci* are given separately for three capacity classes: less than 20 MW_{th}, from 20 to 300 MW_{th} and above 300 MW_{th}. Additional investments in case of a retrofit of existing boilers/furnaces are taken into account by a retrofit cost factor *r*. The shape of investment function is given by Equation 1:

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

where

ci^f, ci^v	coefficients of the investment function
bs_i	boiler size
v	relative flue gas volume
r	retrofit factor.

The investments can be **annualized** over the technical lifetime of the plant *lt* by using the real interest rate *q* (as %/100):

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \qquad (2)$$

6.1.2 Operating costs

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

$$OM^{fix} = I * f \qquad (3)$$

The **variable operating costs** OM^{var} related to the actual operation of the plant take into account:

- additional labor demand
- increased energy demand for operating the device (e.g., for the fans and pumps),
- sorbent material demand (e.g., limestone),
- byproducts/waste disposal[7].

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

$$OM^{var} = (\lambda^l c^l / pf + \lambda^e c^e) + ef * \eta * (\lambda^s c^s + \lambda^d c^d), \qquad (4)$$

$$ef = 2 * \frac{sc}{hv} * (1 - sr)$$

where

η removal efficiency,

λ^l labor demand,

[7] In cases where a by-product has a market value (e.g., sulfur produced by regenerative FGD), the byproduct disposal costs are negative.

λ^e additional energy demand,

λ^s sorbents demand,

λ^d demand for waste disposal,

c^l labor cost,

c^e electricity price,

c^s sorbent cost,

c^d byproduct/waste disposal cost,

pf load factor (annual operating hours at full load)

ef unabated emission factor,

sc sulfur contents,

hv lower heat value and

sr sulfur retention in ash.

6.1.3 **Unit Reduction Costs**

6.1.3.1 Unit Costs per PJ

Based on the above-mentioned cost items, the unit costs for the removal of SO_2 emissions can be calculated. In Equation 5 all 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):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} \tag{5}$$

6.1.3.2 Unit Costs per Ton SO_2 Removed

Although the cost coefficient c_{PJ} is useful for the calculation of the effects of controls on the prices of output fuels (e.g., electricity or heat), the cost efficiency of different control options can only be evaluated by relating the abatement costs to the amount of reduced SO_2 emissions. For this purpose Equation 6 is used:

$$c_{SO_2} = c_{PJ} / (ef * \eta) \tag{6}$$

6.1.4 Marginal Reduction Costs

Another way to evaluate costs of emission reductions follows the concept of marginal costs. 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. RAINS uses the concept of marginal costs for ranking the available abatement options according to their cost effectiveness into so-called 'national cost curves'. (National cost curves are described in Section 9.2).

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

$$mc_m = \frac{c_m \eta_m - c_{m-1}\eta_{m-1}}{\eta_m - \eta_{m-1}}$$

with

c_m	unit costs for option m and
η_m	removal efficiency of option m.

6.2 Costs of Low-sulfur Fuels

Instead of performing for internationally traded low-sulfur fuels the full calculation of capacity-related costs, which would include, i.a., a detailed bookkeeping of international refinery capacities, RAINS restricts itself to the use of price differentials for the different fuel qualities. Since for some fuels (e.g., gas oil) several stages of fuel desulfurization are considered , the (cumulative) costs for stage i control is calculated from Equation 7:

$$c_{PJi} = c_{PJ(i-1)} + c_{PJi\%} * (s_{i-1} - s_i) \qquad (7)$$

with

s_i	sulfur content for stage i reduction,
c_{pji}	cost per PJ for stage i reduction,
$c_{pji\%}$	cost per PJ and percent of sulfur reduced for stage i reduction.

The cost coefficient $c_{pji\%}$ is derived from literature (see Section 7.3) or from external calculations following the procedure outlined for add-on technologies and is applied uniformly for all countries. For stage 1 control Equation 7 is reduced to:

$$c_{PJ1} = c_{PJ1\%} * (s_0 - s_1) \qquad (8)$$

where:

s_0 original (unabated) sulfur content.

Similarly as for add-on controls, the unit cost per ton of SO_2 removed can be calculated from Equation 6.

7 Data Sources and Parameter Values Used

The databases on emission control costs have been compiled from documented operating experience provided in a number of national and international studies. Main references are the proceedings presented at the various UN/ECE Seminars on Emission Control Technologies (e.g, UN/ECE, 1996b, etc.), the Technical Annexes to the SO_2 Protocols and other documentation prepared for these purpose (e.g., CEC, 1996; Rentz *et al.*, 1987, 1996; Schärer, 1993; OECD, 1993; Takeshita, 1995). Country-specific information has been extracted from relevant national and international statistics (e.g., ILO, 1995; IMF, 1995; UN/ECE, 1995; UN/ECE, 1996). The basic input data for SO_2 control technologies used in RAINS have been reviewed in the process of the negotiations for the *Second Sulfur Protocol* of the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1994) and have been recently updated to take into account latest operating experience. All costs are given in constant 1990 ECU.

7.1 Add-on Technologies

For add-on control options data distinguish technology-specific and country-specific parameters. The technology-specific parameters are common for all countries in Europe. Names and units of technology-specific parameters are presented in Table 7.1. The values of the coefficients of the investment functions for individual technologies are given in Table 7.2. The coefficients are estimated separately for three capacity classes. Values of the other common parameters used in the calculation of emission control costs in RAINS are listed in Table 7.3 and Table 7.4.

Table 7.1: Names and units of technology-specific parameters for the cost calculation of add-on control technologies

Symbol	Item	Unit
I	Investment function	ECU/kW_{th}
ci^f	Intercept of the investment function	ECU/kW_{th}
ci^v	Slope of the investment function	10^3 ECU
v	Flue gas volume (relative to that of hard coal)	-
r	Retrofit cost factor	%/100
η	Sulfur removal efficiency	%/100
f	Maintenance costs and overheads	%/100/year
λ^e	Specific demand for electricity	kWh/GJ_{th}
λ^l	Specific demand for labor	$man\text{-}year/MW_{th}$
λ^s, λ^d	Specific demand for sorbents and byproducts/waste disposal	ton/t SO_2 removed

Table 7.2: Coefficients of the investment function for add-on control technologies

Technology/coefficient		Capacity class (MW_{th})		
		<20	20-300	>300
Limestone injection	ci^f, ECU/kW_{th}	53	26	18
	ci^v, 10^3 ECU	0	527	3000
Wet FGD	ci^f, ECU/kW_{th}	80	68	36
	ci^v, 10^3 ECU	0	243	10000
Advanced FGD	ci^f, ECU/kW_{th}	308	150	94
	ci^v, 10^3 ECU	0	3159	19900

Table 7.3: Relative flue gas volume v for different fuel categories used in RAINS (hard coal=1)

Item	**Value**
Brown coal	1.2
Hard coal	1.0
Other solid fuels	1.0
Heavy fuel oil and gas	0.9

Table 7.4: Other technology-specific parameters for add-on control technologies

Parameter	**Unit**	**Limestone injection**	**Wet FGD**	**Advanced FGD**
Removal efficiency η	%	50	95	98
Retrofit coefficient r	%/100	0.3	0.3	0.3
Fixed O+M cost f	%/100/yr	0.04	0.04	0.04
Labor demand λ^l	man-yr/GW_{th}	10.8	10.8	25.2
Electricity demand λ^e	GWh/PJ fuel inp.	0.5	1	2.2
Sorbent demand λ^s	t/tSO_2	4.68	1.56	0.01
Byproducts λ^d	t/tSO_2	7.8	2.6	0.5

Table 7.5 shows a list of country-specific parameters used in emissions and control costs calculations in the EMCO-S module of RAINS. The most essential country-specific parameters with largest influence on reduction costs are

- fuel characteristics (sulfur contents, heat values and the sulfur retention in ash),
- load factors (i.e., annual average operating hours at full load),
- the average boiler sizes for each fuel/sector combination, and
- prices for local inputs.

Actual values of country-specific parameters are extracted from relevant national and international sources. For the power plant sector the information on fuel quality, installed capacities and capacity factors is taken from the IEA Coal Research database (Maude *et al.*, 1994) and from detailed international energy statistics (e.g., UN/ECE, 1995).

Labor costs used in the calculations for the EU countries, for Norway and for Switzerland are extracted from ILO statistics (ILO, 1995). Since for central and east

European countries with economies in transition reliable data is not available, the labor costs were estimated based on per capita GDP (IMF, 1995). It has been assumed that the ratio between wage level and per capita GDP in each country is the same as the average of the 'cohesion' group of EU countries (Greece, Ireland, Portugal and Spain). Actual values of the country-specific parameters are shown in Appendix 3.

In principle, the structure of RAINS enables the use of different real interest rates for different countries, possibly to reflect international differences in capital availability. However, following the advice of the UN/ECE Task Force on Economic Aspects of Abatement Strategies, a uniform real interest rate of four percent is presently used for all countries.

In calculating costs, uniform assumptions are made about the technical lifetime of control equipment for stationary sources (20 years remaining lifetime for existing power plants (retrofits) and for boilers/furnaces in industry, 30 years for new power plants). It should be mentioned, however, that the actual replacement schedule for existing plants is a matter defined in the energy scenario, which is an exogenous input to the RAINS model.

Table 7.5: Country-specific parameters for calculating costs of add-on technologies

Symbol	**Item**	**Unit**
sc	Sulfur content	%/100
hv	Heat value (lower)	GJ/t
sr	Sulfur retained in ash	%/100
ef	Unabated emission factor	ktonSO_2/PJ
bs	Average boiler size	MW_{th}
pf	Capacity utilization	hours/year
c^e	Electricity price	ECU/kWh
c^l	Wages	ECU/man-year
c^s	Sorbent cost	ECU/ton
c^d	Byproducts/waste disposal cost	ECU/ton
lt	Control equipment lifetime	years
q	Real interest rate	%/100

7.2 Costs for Process Emissions Control

As explained in Section 3, abatement of process emissions is treated in RAINS in a simplified way. RAINS distinguishes three stages for controlling the process emissions. The assumed reduction efficiencies and related costs, equal all over Europe, are given in Table 7.6. They were estimated based on Dutch sources (van Ostvoorn, 1984; VROM, 1987) and consultations with experts from the German Environmental Protection Agency (UBA).

Table 7.6: Process emission reductions and related costs in RAINS.

Measure	RAINS code	Reduction efficiency	Reduction costs ECU/ton SO_2
Stage 1 control	SO2PR1	50 %	350
Stage 2 control	SO2PR2	70 %	407
Stage 3 control	SO2PR3	80 %	513

7.3 Costs of Low-sulfur Fuels and Fuel Desulfurization

For the reasons explained above, the costs for low-sulfur fuels are represented in the model by price differentials between high-and low-sulfur alternatives.

For coal, the costs related to this option are derived from several analyses of the long-term price differences on the world market (OECD, 1987; Amann, 1990; Pototschnik, 1994).

The costs of low-sulfur heavy fuel oil are based on a study done by CONCAWE (CONCAWE, 1993). The price differentials presented in that study were adapted to maintain internal consistency with the interest rate of four percent used in RAINS.

Estimates of costs of low-sulfur medium distillates (gas oil) are based on Dutch experience (Kroon, 1992). The price differential for the low-cost desulfurization (down to 0.2 percent sulfur) is estimated at a level of 1/3 of that for the high-cost option (down to 0.05 percent sulfur). Cost of the Stage III reduction of diesel oil down to a market average of 30 ppm (0.003 percent S) are based on the findings of the Auto-Oil project (EC, 1996, Touche & Ross, 1995) and on information available with the European Commission, DG-XI, (Mackowski, 1998). The resulting cost data are shown in Table 7.7.

It should be stressed that data on costs of low-sulfur fuels are highly uncertain. In particular, in many countries the situation is such that there is little difference in prices charged for the low-sulfur alternatives. However, such a situation is usually considered as a short-term phenomenon caused by the current state of environmental regulations in these countries. It can be expected that, when stricter SO_2 limits come into force, the demand for low-sulfur coal and heavy fuel oil will increase and that the price differentials will go up (Passant *et al.,* 1998).

Table 7.7: Options for low-sulfur fuels considered in RAINS and their costs

Fuel type	**Price difference (million ECU/PJ/%S[8])**	**Cost per ton of SO_2 removed[9] (ECU/t SO_2)**
Hard coal (HC), 0.6%	0.28	370
Derived coal (coke - DC), 0.6 %	0.28	370
Heavy fuel oil, 0.6% S	0.20	410
Gasoil		
- reduction to 0.2 %S	0.68	1440
- reduction from 0.2% S to 0.045% S	2.04	4330
- reduction from 0.045% S to 0.003% S	6.69	14200

[8] Percent S reduced compared to original fuel.

[9] Since this cost depends on heating value of fuel, values given in the table are indicative.

8 Example Cost Calculations

This section presents two examples that illustrate the costing methodology used in RAINS. The first case shows how the costs are calculated for add-on control technologies. Parameters used in the example are for an existing brown coal fired power plant. The second example demonstrates the method for low-sulfur gas oil.

8.1 Costs of Wet Limestone FGD for an Existing Brown Coal Fired Plant

I. Values of the input parameters:

Boiler size	550 MW_{th}
Fuel type	brown coal (BC1)
Sulfur content	1.39 % S (weight)
Sulfur retained in ash	22%
Heat value	11.3 GJ/ton
Emission factor	1920 ton SO_2/PJ
Removal efficiency	95 %
Relative flue gas volume	1.2
Retrofit cost factor	0.3
Capacity utilization	5200 hours/year
Lifetime	20 years
Real interest rate	4%
Parameters of the investment function:	
ci^f	36 ECU/kW_{th}
ci^v	10000 kECU
Labor demand	10.8 man-years/GW_{th}
Labor cost	10000 ECU/man-year
Electricity price	0.04 ECU/kWh
Additional energy demand	1.0 GWh/PJ fuel input
Sorbent (limestone) demand	1.56 t/t SO_2
Sorbent cost	18 ECU/ton
Amount of by-product (gypsum)	2.60 t/t SO_2
Disposal cost	0 ECU/t[10]

[10] It is assumed that gypsum produced is further utilized. Thus disposal costs are assumed to be equal to zero.

II. Investment-related costs:

a. Investments:

$$(36+\frac{10000}{550})*1.2*1.3 = 84.4\ ECU/kW_{th}$$

b. Annualized capital costs:

$$0.074*\text{ investment} = 6.25\text{ ECU/kW}_{th}$$

c. Fixed operating costs:

$$4\ \%\text{ of investment} = 3.38\text{ ECU/kW}_{th}$$

III. Variable costs:

a. Labor

$$\frac{10.8*10000}{5200*3600*10^{-6}} = 5.8*10^{3}\ ECU/PJ$$

b. Electricity:

$$1.0*0.040*10^{6} = 40*10^{3}\ ECU/PJ$$

c. Sorbents and waste disposal:

$$1920*0.95*(18*1.56+0*2.6) = 51.2*10^{3}\text{ ECU/PJ}$$

d: Subtotal (a to c):

$$97.0*10^{3}\text{ ECU/PJ}$$

IV. Costs per unit energy input:

$$\frac{(6.25+3.38)}{3600*10^{-12}*5200}+97.0*10^{3} = 611.4*10^{3}\ ECU/PJ$$

V. Costs per ton SO_2 abated:

$$\frac{611.4*10^{3}}{1920*0.95} = 335\ ECU/t\ SO_2$$

8.2 Cost of Stage 2 Low-sulfur Gas Oil

I. Parameter values:

Initial sulfur content s_0	0.5 % S
Sulfur content of stage 1 control	0.2 % S
Sulfur content of stage 2 control	0.045 % S
Removal efficiency for stage 2	91 %
Unit cost of stage 1 control	$0.68*10^6$ ECU/PJ%S
Unit cost of stage 2 control	$2.04*10^6$ ECU/PJ%S
Heating value of gas oil	43.0 GJ/t
Unabated emission factor:	233 t SO_2/PJ

II. Cost per unit energy input:

For stage 1:

$$0.68*(0.5 - 0.2)*10^6 = 204*10^3 \text{ ECU/PJ}$$

For stage 2 (cumulative):

$$204*10^3+2.04*(0.5 - 0.2)*10^6= 520*10^3 \text{ ECU/PJ}$$

III. Costs per ton SO_2 abated:

$$520*10^3/(233*91/100) = 2452 \text{ ECU/t } SO_2$$

9 Control Strategies and Cost Curves

9.1 Scenario Construction in RAINS:

9.1.1 Control Strategy Tables

A central objective of the RAINS model is the simulation of the environmental impacts of alternative emission control strategies. In this context, an emission control strategy can be considered as a set of assumptions (for a particular year) about the application of specific emission control measures to certain fractions of the emission sources in the various economic sectors considered in RAINS.

Expressed in technical terms, a control strategy describes which of the emission control options listed in Table 5.1 is assumed for a given fuel/sector combination and specifies to what percent of the total capacity (percent of fuel use) it will be applied.

Table 9.1 provides an example of a RAINS control strategy table. Apart from the abbreviations for individual sectors and technologies, which are explained in the earlier tables of this report, two additional abbreviations (NSC and NOC) are introduced in the 'Technology' column:

- It occurs that in some sectors the applicability of individual emission control options might be limited due to the specific age- or size-distribution of the existing capacities. In order to take such a limited applicability into account, a 'pseudo-technology' called 'stock not suitable for control' (NSC) is used when designing the control strategy. In the further model calculations, this 'pseudo-technology' prohibits the application of other (real) emission control options to the specified fraction of fuel consumption.
- 'No control' (NOC) is used to mark the percentage of capacities that remain uncontrolled in a given scenario. However, these shares of capacities/fuel consumption are taken into account when constructing the cost curve to determine the cost-optimal controls on top of existing controls assumed in a given scenario.

For reasons of simplicity, Table 9.1 includes only controls for two fuel/sector combinations, i.e., for existing hard coal fired power plants and for the use of diesel oil (medium distillates) in road transport. RAINS enables to create more than 200 fuel/sector/control technology combinations. As an illustration, the example of a control strategy file assumes that in 1990 30 percent of capacities in existing hard coal fired power plants were already retrofitted with FGD technology (PRWFGD). Another 30 percent was controlled through the use of low-sulfur coal (LSCO). For 2010, the strategy assumes that additional 40 percent will be equipped with FGD controls (PWFGD). The share of uncontrolled capacities decreases to 30 percent, of which 10 percent is not suitable for control (NSC).

Table 9.1: A control strategy file (an example)

Fuel	Sector	Technology	Percent capacities controlled in 1990	1995	2000	2005	2010
HC1	PP_EX_OTH	NOC	30	30	30	30	20
HC1	PP_EX_OTH	NSC	10	10	10	10	10
HC1	PP_EX_OTH	LSCO	30	30	20	10	0
HC1	PP_EX_OTH	PRWFGD	30	30	30	30	30
HC1	PP_EX_OTH	PWFGD	0	0	10	20	40
MD	TRA_RD	NOC	0	0	0	0	0
MD	TRA_RD	NSC	0	0	0	0	0
MD	TRA_RD	LSMD1	0	80	0	0	0
MD	TRA_RD	LSMD2	0	0	100	80	0
MD	TRA_RD	LSMD3	0	0	0	20	100

The second part of Table 9.1 explains the control strategy for diesel oil in road transport. Assume that the initial (unabated) sulfur content of diesel oil is 0.5 percent. The strategy implies that in 1995 the average sulfur content was reduced to (0.2*0.5 % + 0.8*0.2 %) = 0.26 %. In 2005 the average S content will be (0.8*0.045 %+0.2*0.003 %) = 0.0366 %. Finally, in 2010 only diesel oil with S content of 0.003 % S will be used in road transport.

9.1.2 The Current Legislation Scenario

Control strategies are used to simulate the specific sets of legislation on emission controls valid for a given country or for groups of countries. The RAINS model allows to combine such emission control strategies with a selected energy pathway to form a so-called 'emission scenario', for which the environmental impacts can then be explored.

A special example of an emission scenario may be the 'Current legislation' scenario, which describes for each country the expected temporal penetration of the various emission control measures prescribed for individual sectors by the applicable national and international legislation. The latest versions of the 'Control Strategy Files' used for the calculations for the EU and UN/ECE are presented in Appendix 5. The following paragraphs describe the main pieces of national and international legislation taken into account when constructing these files.

For SO_2, the starting point for the analysis is a detailed inventory of regulations on emission controls, taking into account the legislation in the individual European countries, the relevant Directives of the European Union (in particular the Large Combustion Plant Directive - LCPD (OJ, 1988) and the directives on sulfur content of liquid fuels (gas oil - Johnson & Corcelle (1995), heavy fuel oil - COM(97)88, 1997)), as well as the obligatory clauses dealing with emission standards from the protocols under the Convention on Long-range Transboundary Air Pollution. For instance, the Second Sulfur Protocol (UN/ECE, 1994) requires emission control according to 'Best Available Technology' (BAT) for new plants. It also requires the reduction of the sulfur content in gas oil for stationary sources to 0.2 percent and to 0.05 percent if used as diesel fuel for road vehicles.

An inventory of national and international emission standards in Europe has been compiled by Bouscaren & Boucherau (1996). In addition, information on power plant emission standards has been taken from the UN/ECE compilation on strategies and policies (UN/ECE, 1995b), the survey of the IEA Coal Research (McConville, 1997). and from the environmental standards database developed by the Central European University (CEU, 1996).

Table 9.2: Measures assumed for the 'Current Legislation' (CLE) scenario for SO_2 emissions in EU countries

Stationary and mobile sources:

- Emission standards for new plant from the Large Combustion Plant Directive - LCPD (OJ, 1988) and from the Second Sulfur Protocol (UN/ECE, 1994a)
- Limits on sulfur content of gas oil for stationary and mobile sources and for heavy fuel oil as in the appropriate directives (- compare Johnson & Corcelle, 1995, COM(97)88, 1997)
- National emission standards on stationary sources if stricter than the international standards. Control measures for stationary sources included in the CLE scenario for individual countries of the EU are shown in Table 9.4.

Table 9.3: Measures assumed for the 'Current Legislation' (CLE) scenario for SO_2 emissions in the non-EU countries

Stationary and mobile sources:
Signatories of the Second Sulfur Protocol (Bulgaria, Croatia, Czech Republic, Hungary, Norway, Poland, Russian Federation, Slovak Republic, Slovenia, Switzerland, Ukraine) - New plant emission standards and limits on the sulfur content of gas oil for stationary and mobile sources as in the Protocol.
Czech Republic, Croatia, Norway, Poland, Slovak Republic, Slovenia, Switzerland, Romania, F. Yugoslavia - national emission standards on existing and new plant
Other countries in Central and Eastern Europe – No control

Table 9.4: SO_2 abatement technologies for the power plant and industrial sources assumed in the 'Current Legislation' (CLE) scenario for the EU countries

Country Capacity class, MW_{th}	New plants Coal	 Oil	Existing plants Coal	 Oil
Austria				
10 - 50	FGD	LSHF	LSCO	LSHF
50 - 300	FGD	FGD	FGD/LSCO(1)	LSHF
> 300	FGD	FGD	FGD	FGD
Industrial processes:	Stage 3		Stage 3	
Belgium (6)				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	LSCO	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	FGD	LSCO	FGD
>500 >500	FGD	FGD	LSCO	FGD
Industrial processes:	Stage 1		Stage 1	
Denmark(6):				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	LSCO	LSHF
100 - 500 300 - 500	FGD	FGD	FGD	FGD
>500 >500	FGD	FGD	FGD	FGD
Industrial processes:	Stage 1		Stage 1	
Finland(6):				
50 - 200	FGD	FGD	FGD	FGD
>200	FGD	FGD	FGD	FGD
Industrial processes:	Stage 1		Stage 1	
France:				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	FGD	-	LSHF
>500 >500	FGD	FGD	-	LSHF
Industrial processes:	-		-	
Germany(6):				
50 - 100	LSCO	LSHF	LSCO	LSHF
100 - 300	FGD	FGD	FGD	FGD
> 300	FGD	FGD	FGD	FGD
Industrial processes:	Stage 2		Stage 2	
Greece:				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	LSHF	-	LSHF
>500 >500	FGD	FGD	-	LSHF
Industrial processes:	-		-	
Ireland(6)				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	LSCO	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	FGD	LSCO	LSHF
>500 >500	FGD	FGD	LSCO	LSHF
Industrial processes:	-		-	

Table 9.4: SO_2 abatement technologies for the power plant and industrial sources assumed in the 'Current Legislation' (CLE) scenario for the EU countries, continued

Country Capacity class, MW_{th}	New plants Coal	 Oil	Existing plants Coal	 Oil
Italy:				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	LSHF	-	LSHF
>500 >500	FGD	FGD	FGD	LSHF
Industrial processes:	Stage 1		Stage 1	-
Luxembourg(6):				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	FGD	-	FGD
>500 >500	FGD	FGD	-	FGD
Industrial processes:	-		-	
Netherlands:				
<300(3)	FGD	FGD	LSCO/FGD	LSHF/FGD
>300	FGD	FGD	FGD	FGD
Industrial processes:	Stage 1		Stage 1	
Portugal:				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	LSHF	-	LSHF
>500 >500	FGD	FGD	-	LSHF
Industrial processes:	-		-	
Spain:				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	-	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	LSHF	-	LSHF
>500 >500	FGD	FGD	-	LSHF
Industrial processes:	-		-	
Sweden:				
<50	FGD (4)	FGD (5)	FGD (4)	FGD (5)
>50	FGD	FGD	FGD	FGD
Industrial processes:	Stage 2		Stage 2	
UK(6):				
Coal Oil				
50 - 100 50 - 300	LSCO	LSHF	LSCO	LSHF
100 - 500 300 - 500	LSCO/FGD(2)	FGD	LSCO	LSHF
>500 >500	FGD	FGD	FGD	FGD
Industrial processes:	-		-	

(1) Lignite/hard coal
(2) Below 300 MW_{th}/above 300 MW_{th}
(3) Includes also sources below 50 MW_{th}
(4) Requires at least 70 % desulfurization when low-sulfur coal (0.8 % S) is used
(5) Requires at least 50 % desulfurization when low-sulfur fuel oil (0.8 % S) is used
(6) Emissions determined by the national emission ceiling from the Second Sulfur Protocol

Explanations of abbreviations:

FGD - Flue gas desulfurization
LSCO - Low-sulfur coal
LSHF - Low-sulfur heavy fuel oil
Stage 1,2,3 - Abatement technologies for process emissions

9.2 Cost Curves for Controlling SO_2 Emissions

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 protection levels for vegetation, natural ecosystems or human health).

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 the fuel 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 the 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 SO_2 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 considered country.

After ranking the remaining 'cost-efficient' emission control options, the RAINS model 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[11].

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[11] The algorithm for calculating marginal abatement costs can be explained using the following example:

Assume a fuel type "F" is used in sector "S", and control technologies applicable to this fuel-sector combination ("F-S") are "CT1", "CT2" and "CT3". The total amount of pollutant emitted by this "F-S" fuel-sector combination, is 4 kt. Assume the technology "CT1" reduces emissions by 50% (i.e., 2 kt), "CT2" reduces emissions by 70% (2.8 kt), and "CT3" reduces sulfur dioxide emissions by 80% (3.2 kt). Further, assume the unit costs (ECU/ton) to reduce emissions using the three control technologies "CT1", "CT2" and "CT3" are ECU 700, ECU 814 and ECU 1025, respectively. Then the marginal costs for the first fuel-sector-control technology type "F-S-CT1" is equal to the unit cost, i.e., 700 ECU/ton. If the "CT2" type control technology is later applied to the same fuel-sector combination, then the marginal cost for fuel-sector-control technology type "F-S-CT2" is (814 ECU/ton * 2.8 kt) minus (700 ECU/ton * 2.0 kt) divided by extra amount of pollutant removed (0.8 kt) which is equal to 1099 ECU/ton. The marginal cost for the "F-S-CT3" combination is 2502 ECU/ton.

The cost curve can be displayed in RAINS in tabular or graphical form. Examples are presented in Table 9.5 and in Figure 9.1.

The cost curve concerns a selected country (or region of a country), emission scenario and year. The table includes columns listing fuel, economic sector, control technology (F-S-T) combinations, unit costs (in ECU/ton pollutant removed), marginal costs (in ECU/ton pollutant removed), actual amount of pollutant removed (kt), remaining emissions (i.e., maximum emission less cumulative emissions removed, in kt), and total cumulative control costs in million ECU/year.

The cost curve displayed in Table 9.5 is constructed with the 'No control' situation as a starting point. This means that this table ranks all available options for emission control according to their cost-effectiveness, but does not distinguish whether a specific options is already part of, e.g., the current legislation. As an alternative, costs curves could also be constructed starting from the 'Current legislation' situation. Such curves exclude all measures, which are already adopted by the current legislation, and consider only the remaining potential for emission controls.

Table 9.5: SO_2 abatement cost curve in tabular form (an example)

Fuel Sector Techn.	Unit cost ECU/t SO2	Marginal cost ECU/t SO2	SO2 removed 1000t/a	Remaining SO2 1000t/a	Total cost Mio ECU/a
Initial emissions			0	1725	0
NOF IN_PR SO2PR1	350	350	122	1603	43
HC1 DOM LSCO	382	382	3	1599	44
HC1 PP_EX_OTH LSCO	401	401	21	1578	53
HC1 PP_EX_WB LSCO	401	401	29	1549	64
HC1 PP_NEW LSCO	401	401	60	1489	88
HC1 IN_OC LSCO	401	401	10	1478	93
HC1 CON_COMB LSCO	401	401	8	1470	96
BC1 PP_NEW PWFGD	402	402	453	1017	278
HF IN_OC LSHF	402	402	77	940	309
HF CON_COMB LSHF	402	402	57	884	331
HF PP_NEW LSHF	402	402	24	859	341
HF PP_EX_OTH LSHF	402	402	19	840	349
HF DOM LSHF	417	417	1	839	349
DC DOM LSCK	448	448	8	832	353
NOF IN_PR SO2PR2	407	550	49	783	379
HC1 PP_NEW PWFGD	544	648	83	700	433
NOF IN_PR SO2PR3	513	1255	24	676	464
HC1 PP_EX_OTH PWFGD	917	1292	29	646	501
HC1 PP_EX_WB PWFGD	917	1292	40	606	554
MD TRA_RD LSMD1	1446	1446	21	585	584
MD PP_EX_OTH LSMD1	1446	1446	0	585	584
MD IN_OC LSMD1	1446	1446	3	582	589
MD DOM LSMD1	1446	1446	26	556	626
MD CON_COMB LSMD1	1446	1446	1	555	627
MD PP_NEW LSMD1	1446	1446	0	555	627
MD TRA_OT LSMD1	1446	1446	3	552	631
HC1 CON_COMB IWFGD	1030	1510	10	542	647
HC1 IN_OC IWFGD	1203	1554	23	518	683
BC1 IN_OC IWFGD	1568	1568	19	500	713
HF CON_COMB IWFGD	622	1650	12	487	733
HF IN_OC IWFGD	831	1833	33	454	794
OS2 PP_NEW LINJ	3715	3715	2	453	800
OS2 PP_NEW PWFGD	3902	4110	2	451	807
MD CON_COMB LSMD2	3632	4337	3	448	819
MD DOM LSMD2	3632	4337	79	369	1163
MD TRA_OT LSMD2	3632	4337	9	360	1202
MD IN_OC LSMD2	3632	4337	10	350	1245
MD PP_NEW LSMD2	3632	4337	1	349	1247
MD TRA_RD LSMD2	3632	4337	65	285	1528
MD PP_EX_OTH LSMD2	3632	4337	1	284	1530
HF CON_COMB RFGD	1261	5438	10	274	1587
OS2 PP_EX_OTH LINJ	5545	5545	1	273	1592
OS2 PP_EX_OTH PWFGD	6125	6770	1	272	1597
HF PP_NEW PWFGD	2732	7708	11	261	1685
BC1 PP_NEW RFGD	788	13021	14	246	1871
HF PP_EX_OTH PWFGD	4519	13310	9	238	1989
MD TRA_OT LSMD3	5432	14222	2	235	2024
MD TRA_RD LSMD3	5432	14222	18	218	2273
HC1 PP_NEW RFGD	1120	19347	5	213	2360
HF PP_NEW RFGD	6284	118748	1	212	2494

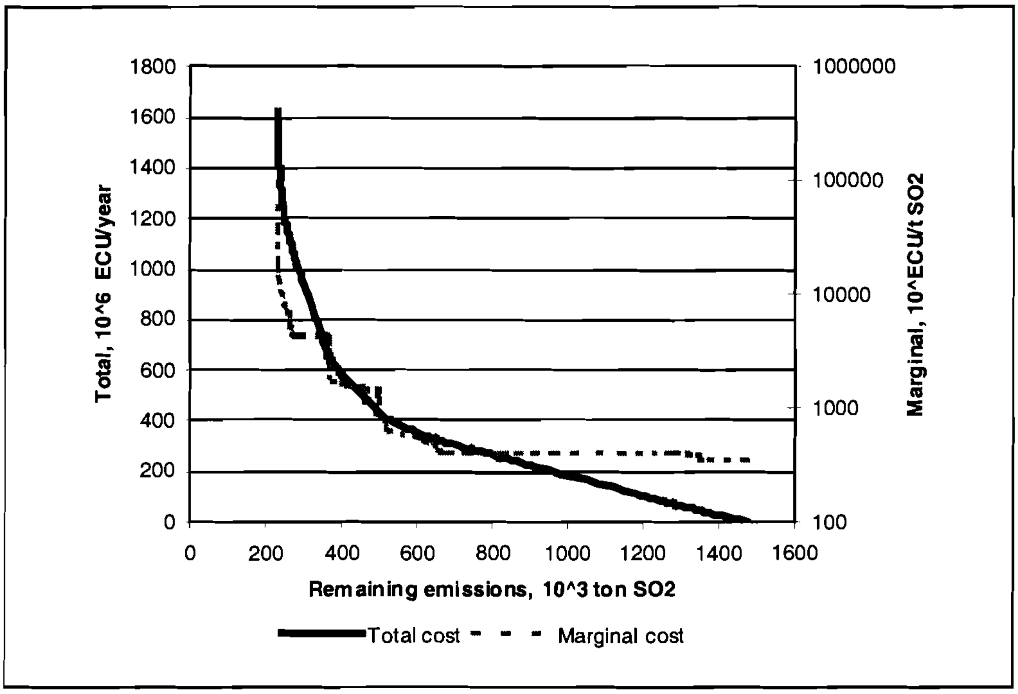

Figure 9.1: SO_2 abatement cost curve in graphical format (an example)

As mentioned above, RAINS creates cost curves only for the emission control potential available after the implementation of a selected initial set of control measures. Thus, in order to obtain total costs of emission reduction in a country, the costs of measures that are predetermined in a given scenario must be added to the values read from the cost curve.

The potential for remaining measures considers investments already made for emission control and excludes early scrapping - or further improvements - at such installations. However, if in a particular sector emissions are initially controlled by low-sulfur fuels, the cost curves assume that it is possible to switch back to fuels with the original sulfur content and to apply add-on control technologies (e.g., flue gas desulfurization).

Cost curves for individual countries are presented in Appendix 6.

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