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

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ABSTRACT

This paper describes the module of the Regional Air Pollution Information and Simulation (RAINS) model dealing with the potential and costs for controlling emissions of nitrogen oxides oxides. The paper discusses the selected aggregation level of the emission generating activities and reviews the major options for controlling NO_x emissions. Algorithms for estimating emission control costs for stationary and mobile sources are 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 (combustion modification together with selective catalytic reduction for power plant boilers and catalytic converters for cars). 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 for cost calculation are presented in the main body of the report, while all country-specific parameters are contained in a number of appendices. Furthermore, energy scenarios as they are currently implemented in the RAINS model and the resulting cost curves for NO_x control related to these energy scenarios are presented in these annexes.

The report and all appendices are available on the Internet under the URL:

http://www.iiasa.ac.at/~rains/noxreview.html

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This document builds upon an earlier work on NO_x emission control costs carried out by M. Amann and G. Klaassen (Amann, 1989, 1990; Amann and Klaassen, 1995).

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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 NO_x emissions in individual countries. Its main purpose is to present modeling approach and data for review by the Parties to the Convention on Long-range Transboundary Air Pollution. Since NO_x emission control technologies in the transport sector also reduce the emissions of non-methane volatile organic compounds (VOC), data on these emissions are also included in this paper. Data on SO_2 control strategies and related costs are provided in Cofala and Syri, 1998. VOC-related data are available in Klimont *et al.*, 1998. Data on ammonia emissions were presented for review in the end of 1996. An update is under preparation.

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 (Bertok *et al.*, 1993). The time horizon extends from the year 1990 up to the year 2010. 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.

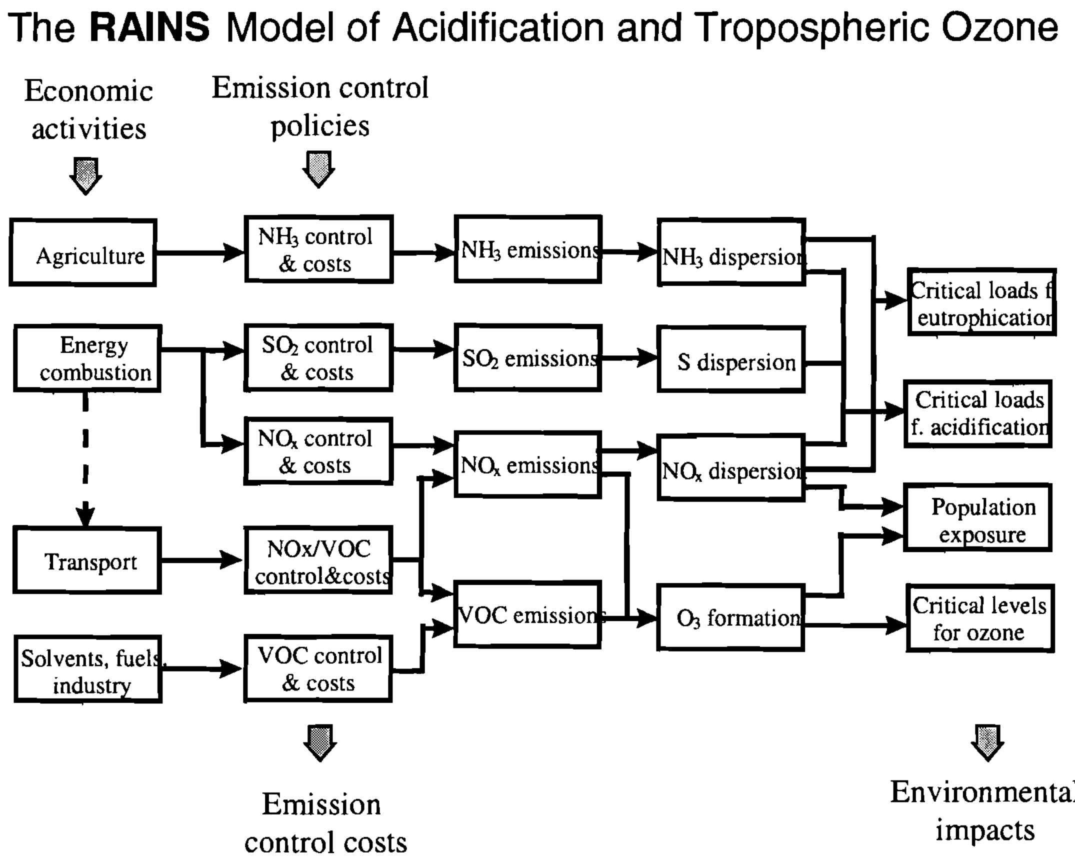

Figure 1.1: Schematic flowchart of the RAINS model framework

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 to identify optimized approaches to reduce negative ecological impacts caused by air pollutants, the cost submodel only concentrates 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 Nitrogen Oxides Emission Mechanisms

Anthropogenic NO_x emissions originate mostly from energy combustion in stationary and mobile sources. Emissions from industrial processes (not associated with fuel combustion, e.g., the production of nitric acid) have only minor importance in Europe (EEA, 1996). Two chemical reactions appear as the most important formation mechanisms for nitrogen oxides during combustion of fossil fuels:

Fuel NO_x. During combustion the nitrogen chemically associated with the fuel (as apart from the molecular nitrogen which is part, e.g., of natural gas) converts to amines and cyanids, which then together combine with oxygen to form nitrogen oxides. This 'fuel NO_x ' formation is a function of the fuel's nitrogen content as well as of the burner type and firing mode that is used. Fuel nitrogen contents typically vary for coal between 0.5 and 2.0 percent (by weight), and are less than 1 percent for oil. In natural gas the nitrogen content is negligible. Because of the simultaneous reverse reaction (i.e. formation of nitrogen from nitrogen oxides), typically only between 5 and 25 percent of the total fuel nitrogen is converted to NO_x.

Thermal NO_x. The thermal NO_x generation is due to the mechanism discovered by Zeldovich, in which nitrogen and oxygen from the air combine to form NO_x under high temperature:

$$N_2 + O_2 \rightarrow 2NO$$
$$N + O_2 \rightarrow NO + O$$

This formation process usually becomes important at temperatures above 1400 degrees C (Rentz *et al.*, 1987), a temperature which is generally exceeded in most combustion processes. At higher temperatures, thermal NO_x generation increases exponentially. It depends also on the residence time of combustion air in the combustion chamber and the availability of excess air.

The largest fraction of nitrogen oxides emissions are emitted as NO (monoxide) and are oxidized in the atmosphere to NO_2 (dioxide). Recently higher attention has also been drawn to the generation of N_2O because of its contribution to the global greenhouse effect. For purposes of bookkeeping for emission estimates, however, all species of nitrogen oxides are usually converted to NO_2.

3 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.

3.1 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 and NO_x 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 categories and the RAINS sectors are shown in Table 3-1 and Table 3-2. 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), 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 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 3-1: RAINS sectors of the SO_2/NO_x modules for stationary sources and their relation to the main activity groups of the CORINAIR inventory

RAINS sector Primary	 Secondary	CORINAIR SNAP97 code
Power plants and district heating plants (PP)	- New boilers (PP_NEW) - Existing boilers, dry bottom (PP_EX_OTH) - Existing boilers, wet bottom (PP_EX_WB)	0101, 0102
Fuel production and conversion (other than power plants) (CON)	- Combustion (CON_COMB) - Losses (CON_LOSS)	0103, 0104, 0105, 05
Domestic (DOM)	- Residential, commercial, institutional, agriculture	02
Industry (IN)	- Combustion in boilers, gas turbines and stationary engines (IN_BO) - Other combustion (IN_OC) - Process emissions (IN_PR)[2]	0301 03 exc. 0301[1] 04
Non-energy use of fuels (NONEN)	- Use of fuels for non-energy purposes (feedstocks, lubricants, asphalt)	
Other emissions (OTHER)	- Other sources: (air traffic LTO cycles, waste treatment and disposal, agriculture)	080501, 080502, 09, 10

[1] Also processes with contact from SNAP code 0303 that are treated separately as process emissions are excluded.

[2] Emissions are not directly attributed to fuel consumption. Production processes covered: oil refineries, coke, sinter, pig iron, non-ferrous metals (zinc, lead and copper), cement, lime, sulfuric acid, nitric acid, pulp mills. Other processes are covered in 'Industry-Other combustion'.

Table 3-2: Sectors in the RAINS NO_x module for mobile sources and their relation to the CORINAIR codes

RAINS sector Primary	 Secondary	CORINAIR SNAP97 code
Road transport (TRA_RD)	-Heavy duty vehicles (trucks, buses and others) (TRA_RD_HD)	0703
	- Light duty vehicles, four-stroke (cars, vans, motorcycles) (TRA_RD_LD4) - Light duty vehicles, two-stroke (cars, motorcycles) (TRA_RD_LD2)	0701,02,04,05
Off-road (TRA_OT)	- Other mobile sources and machinery with two-stroke engines (TRA_OT_LD2) - Other land-based mobile sources and machinery with four-stroke engines (TRA_OT_LB)	03, 08 exc. 0804 and 0805
Maritime activities (TRA_OTS)	- Medium vessels (TRA_OTS_M) - Large vessels (TRA_OTS_L)	080402, 080403

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. Additionally, the land-based vehicles are subdivided into heavy duty and light duty as well as into four-stroke and two-stroke engines.

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.

3.2 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 3-3. RAINS considers the major energy flows for 17 categories of fuels[3]. 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.

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

Table 3-3: 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

3.3 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[4]. 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.

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

4 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, 1996a). 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 and Kokkolakis, 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, Belgium, Denmark, Finland, Germany, Greece, Ireland, the Netherlands, Sweden and the United Kingdom the updates of their national scenarios are available. These scenarios are called further **'National Pathways'** (NP).

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.

5 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:

$$N_i(t) = \sum_j \sum_k act_{i,j}(t) * ef_{i,j} * (1 - \eta_{j,k} * af_{i,j,k}(t)) \qquad (5.1)$$

$N_i(t)$	NO_x 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
$\eta_{j,k}$	NO_x 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 application factor for a given technology has to be always lower than the so-called applicability, i.e., the maximum potential of implementation of a given technology in a given sector and given year. The applicability can be limited by two factors:

- The unit size of boiler/furnace may be to small for installation of expensive and technically complicated emission control measures (e.g., installation of the SCR technology for small boilers in the residential/commercial sector)
- For sectors where retrofit of existing capital stock with control measures is not possible (e.g., vehicles in transport) the applicability of control technologies is limited to new vehicles.

The assumptions about the applicabilities of individual technologies to the sectors distinguished in RAINS are described in Section 10.

The emission factors $ef_{i,j}$ are country- and sector-specific. 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.* for the base year (1990). Any change in emission factors over time (e.g., caused by an autonomous improvement in the performance of a boiler/furnace) is interpreted as an emission control measure and reflected via a modified application factor *af* of a control technology *k* with the efficiency η. This approach implies that all changes in unit emissions, even those occurring 'autonomously' due to other reasons, are credited as emission abatement efforts with costs attributed to them. Unabated NO_x emission factors for all sectors and VOC emission factors for transport sources 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.

6 Options for Reducing NO_x Emissions

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

- changes in the energy system leading to lower consumption of fuels (by energy conservation or fuel substitution),
- combustion modification and
- treatment of the flue gases.

Measures influencing the energy consumption structure, such as energy conservation and fuel substitution, affect not only NO_x emissions, but at the same time a wide variety of other environmental (e.g., greenhouse gas emissions), economic (e.g., trade balances) and political (e.g., energy supply security) 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. National energy-environment and/or economic models are more suited for this task[5]. Consequently, the RAINS model refrains from attempting a necessarily incomplete economic analysis and restricts itself to simulating the environmental impacts of exogeneously determined energy scenarios. Thus 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 NO_x emissions are documented. 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 four categories, taking their major technical and economic properties as selection criteria. The following broad groups of technical emission control options are distinguished:

- In-furnace control of NO_x emissions for stationary sources, i.e., the so-called combustion modifications (CM) or primary NO_x reduction measures;
- Secondary measures depending on the treatment of flue gases (selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR));

[5] In the past, the results of national energy-environment models have been used as an input to the RAINS model for further analysis of environmental impacts (compare Rentz *et al.* (1994)).

- Measures to control process emissions;
- Measures in the transport sector.

The technical and economic properties of each of these major categories are represented by the characteristic features of the most widespread representative technology. Technologies included in the RAINS model are shortly described in the next paragraphs. Detailed description of emission control techniques can be found in several technical reports (e.g., UN/ECE, 1994a,b, 1997, Rodt et al., 1995, 1996, Takeshita, 1995, Touche Ross & Co., 1996).

6.1 Technologies for Stationary Sources

The following section presents brief characteristics of the emission control technologies available for stationary sources. RAINS contains the following NO_x control options for boilers and furnaces:
- Combustion modification (CM)
- Selective catalytic reduction (SCR)
- Selective non-catalytic reduction (SNCR)
- Combined measures (combustion modification and SCR or SNCR)

6.1.1 Primary Measures (Combustion Modification)

Improvements in the boiler design can result in considerable reductions of NO_x formation during the combustion processes. Although the level of NO_x emissions from the same fuel varies considerably with the type of the plant (depending on design characteristics such as the placing of burners or the fuel-to-air ratio), all combustion modification techniques or primary measures make use of the same principles:
- the reduction of excess oxygen levels (especially at periods of peak temperature);
- reduction of the peak flame temperature.

The most commonly used primary measure to reduce NO_x emissions from boilers and furnaces is the use of **low-NO_x burners (LNB)**. Compared with the classical burners, where the total amount of fuel and air is injected in the same point, low NO_x burners modify the way of injecting air and fuel to delay the mixing, reduce the availability of oxygen and reduce the peak flame temperature. LNB retard the conversion of fuel-bound nitrogen to NO_x and the formation of thermal NO_x, maintaining high combustion efficiency. LNB can be divided into three groups (UN/ECE, 1997):
- Air-staged low-NO_x burners (LNB),
- Flue gas recirculation LNB, and
- Fuel-staged LNB.

In the **air-staged burners** the primary air is mixed with the fuel to produce a fuel-rich flame, which is relatively cool and deficient in oxygen. These conditions inhibit the formation of nitrogen oxides. Then secondary air is added to allow a slow combustion of unburned fuel at rather low temperatures.

In burners with **flue gas recirculation** a portion of flue gases is injected into the combustion zone of the flame. In this way the flame temperature as well as oxygen concentrations are lowered, enabling the reduction of NO_x formation.

The **fuel-staged burner** aims at reducing the NO_x already formed by the addition of part of the fuel in the second stage. In this case, the flue gas is drawn from behind the boiler and led to the burners with additional fans. Initially only a portion of the fuel is injected, with high excess air. This makes it possible to achieve relatively low flame temperatures which inhibit the formation of nitrogen oxides. Then additional fuel is injected at the border of the primary combustion zone to form the so-called secondary flame. In this secondary zone the already created NO_x is reduced again to nitrogen. Finally the combustion is completed in the third zone.

The low NO_x burners are easy to install and are suitable for retrofit in existing plants. Energy losses caused by unburned fuel particles are small. The reductions of NO_x emissions achieved through the use of LNB are typically in the range of 50 percent; for lignite, oil, and gas furnaces efficiencies of up to 65 percent are reported.

Another NO_x emission reduction technology that falls into the 'Combustion modification' category is **fuel injection**, or **reburning** at boiler level (UN/ECE, 1997). This technology creates different combustion zones in the furnace by staged injection of fuel and air. The aim of reburning is to reduce the nitrogen oxides that have already been formed back to nitrogen. In boilers using that concept three combustion zones can be distinguished. In the primary zone 85 to 90 percent of fuel is burnt in an oxidizing or slightly reducing atmosphere. In the second (reburning) zone, the secondary fuel is injected into a reducing atmosphere. Hydrocarbon radicals produced in this zone react with already formed nitrogen oxides. Next, in the burnout zone, final air is added to complete the combustion. The reduction efficiency of that technology is in the range of 50 to 60 percent. The technology can be applied to boilers at power plants and in the industry. Implementation to waste incinerators as well as to some industrial processes (glass and cement production) is in the phase of development.

It is also possible to decrease emissions of nitrogen oxides through the use of oxygen instead of combustion air (the so-called **oxycombustion**). This decreases the nitrogen content in the combustion zone, leading to lower emissions of nitrogen oxides. Oxycombustion has found its application mainly in industrial furnaces (glass production), where high combustion temperatures are necessary due to technological reasons.

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 at relatively high efficiencies. The conditions (temperature, the residence time of particles in boilers) are very favorable for achieving low emissions of the above mentioned pollutants. There are, however, methodological difficulties to apportion the extra costs of the FBC technology (on top of conventional boilers) to the 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.

6.1.2 Secondary Measures (Flue Gas Cleaning)

A variety of flue gas treatment methods have been developed to remove NO_x after the combustion process. From the large number of available processes, the **selective catalytic reduction (SCR)** has become the most important technique and is at present widely applied in some countries. The SCR process uses ammonia to convert nitrogen oxides into molecular nitrogen (N_2) and water (H_2O) in presence of a catalyst. The most important chemical reactions are:

$$4\,NO + 4\,NH_2 + O_2 \rightarrow 2\,N_2 + 6\,H_2O$$
$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2 + 12\,H_2O$$

Titanium oxide TiO_2 is usually used as the catalytic material, but oxides of vanadium, molybdenum, tungsten, nickel and chromium are also applied. The major advantage of the SCR process is that it does not produce a by-product. The removal efficiency lies typically in the range between 70 and 80 percent and depends on the 'pace velocity', i.e., how quickly the exhaust gas stream is moving through the catalysts, and on the amount of NH_3 added. After some time in operation the activity of the catalysts declines, so that they have to be exchanged periodically.

The operation of the conversion process is crucially related to a certain temperature range (e.g., for catalysts of titanium oxides between 300 and 400 degree Celsius). Two most common design concepts are in use:

- **High-dust system**. The SCR reactor is situated directly after the boiler before the electrostatic precipitator and any desulfurization device.
- **Tail-gas system**. The catalyst is located at the end of the flue gas path after the removal of dust and sulfur. This design principle results in higher life times of the catalysts, since they are operated with almost dust-free flue gas at low concentrations of SO_2. Therefore, the plants can be designed independently of the fuel and boiler type, an advantage for retrofit applications. Any possible leaking of excess NH_3 will not have impacts on installations downstream of the SCR reactor. On the other hand, in order to maintain the necessary temperature of the conversion process, a heat exchanger and reheating have to be provided.

Selective non-catalytic reduction is another add-on technique that can be used for controlling NO_x emissions. It depends on injection of ammonia or other reducing agents into the flue gas; the NO_x reduction takes place without use of a catalyst. The use of urea, for example, results in the following chemical reaction:

$$CO(NH_2)_2 + 2NO + \frac{1}{2} O_2 \rightarrow 2N_2 + CO_2 + 2H_2O$$

The SNCR process is also temperature-sensitive and, therefore, the effectiveness of NO_x removal depends on successful temperature control. In contrast to SCR technologies, no catalysts are required, which lowers investments and maintenance costs because no replacement of catalyst is necessary. Furthermore, energy costs are lower, and less space is required. If combined with primary NO_x reduction measures, removal efficiencies of about 70 percent and more are possible. This technique has undergone significant improvements in recent years and is applicable particularly to smaller industrial boilers. It can also be used for controlling emissions from process furnaces (UN/ECE, 1997).

6.1.3 Combined NO_x Control

Because SCR and SNCR options apply to different parts of the NO_x formation process, it is also possible to combine primary measures such as combustion modification and secondary options such as SCR or SNCR. In case when SCR is combined with primary measures the resulting removal efficiency (compared to uncontrolled combustion) could reach 90 percent. Because of the lower NO_x concentration at the inlet of the SCR plant, the consumption of reaction agents (NH_3) is reduced compared with the exclusive use of add-on secondary reduction measure.

Table 6-1 presents the NO_x control technologies for stationary sources considered in the RAINS model. Since removal efficiencies of individual techniques as well as cost parameters are fuel-and sector-specific, separate technologies for the most important fuel/sector combinations are provided.

Table 6-1 Main groups of NO_x emission control technologies for stationary sources considered in RAINS

RAINS Sector/Technology	Technology abbreviation	Removal efficiency, %
Power plant sector (PP):		
Brown Coal - Combustion modification (CM) – existing plant	PBCCM	65
Brown Coal - Selective catalytic reduction (SCR) – new plant	PBCSCR	80
Brown Coal - CM + SCR – existing plant	PBCCSC	80
Hard Coal - CM – existing plant	PHCCM	50
Hard Coal - SCR – new plant	PHCSCR	80
Hard Coal - CM + SCR – existing plant	PHCCSC	80
Oil and Gas - CM – existing plant	POGCM	65
Oil and Gas - SCR – new plant	POGSCR	80
Oil and Gas - CM + SCR – existing plant	POGCSC	80
Industrial boilers (IN_BO) and furnaces (IN_OC):		
CM - Solid Fuels	ISFCM	50
CM - Oil&Gas	IOGCM	50
CM+SCR Solid Fuels	ISFCSC	80
CM+SCR Oil &Gas	IOGCSC	80
CM+ Selective non-catalytic reduction (SNCR) Solid Fuels	ISFCSN	70
CM+SNCR Oil &Gas	IOGCSN	70
Residential and Commercial (DOM):		
CM Heavy Fuel Oil - Commercial	DHFCM	50
CM Medium Distillates and Light Fractions (MD&LF)-Commercial	DMDCCO	12
CM Gas - Commercial	DGCCOM	22
CM MD&LF-Commercial and Residential	DMDCCR	30
CM Gas - Commercial and Residential	DGCCR	50
Process emissions:		
Stage 1 control	PRNOX1	40
Stage 2 control	PRNOX2	60
Stage 3 control	PRNOX3	80

6.2 Control of Process Emissions

Industrial activities emitting nitrogen oxides can be divided into combustion processes and processes where emissions cannot be directly linked to energy use. The latter are processes that release nitrogen contained in the raw material (e.g., during production of nitric acid) or processes where the emission factors are intrinsically different compared with the emissions from boilers due to different (much higher) process temperature (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 is an exception to this rule. It 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 SO_2 process emission factors. To avoid computational difficulties caused by negative emission factors, total emissions (also of NO_x) 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 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, the process temperature 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. Data are based on recent information about abatement options for individual industrial processes and their costs as compiled by the UN/ECE Task Force on Emission Abatement Techniques (UN/ECE, 1997). This information is consistent with Dutch sources (Van Oostvorn, 1984; VROM, 1987) as well as with assessments done by the experts from the German Environmental Protection Agency (UBA). However, one should stress that costs of controlling process emissions are burdened with high uncertainties and are subject to change when more detailed information becomes available.

6.3 Mobile Sources

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

- Changes in engine design to better control the combustion processes in the engine.
- Changes in fuel quality. For instance, a changed sulfur content of the fuel has an impact on emissions of particulate matter. Lower sulfur contents enable the application of more advanced catalytic converters. Changes in the contents of aromatics and benzene impact emissions of NO_x and VOC.
- After-treatment of the exhaust gas by various types of catalytic converters.
- Better inspection and maintenance, e.g., by in-use compliance testing, in-service inspection and maintenance, on-board diagnostic systems, etc.

The most important technical control options applicable to mobile sources are described below. A comprehensive description of all options can be found in the literature (e.g., UN/ECE, 1994a,b; Touche Ross & Co., 1996; Rodt et al., 1995,1996).

6.3.1 NO_x Control for Otto Engines

The formation of NO_x in gasoline fueled Otto engines is determined by the combustion temperature, the residence time in the peak temperature zone and by the oxygen content of the fuel-to-air ratio.

Gasoline engines without emission control are usually operated with stoichiometric or slightly over-stoichiometric fuel-to-air ratio, whereas engines built in the sixties were designed to operate below stoichiometry. The resulting high CO emissions of the early design initiated the first technical regulations to limit CO emissions. The new engines indeed reduced the CO and VOC emissions, but at the same time (due to the higher stoichiometric ratio) the NO_x emissions increased drastically. There are several means to reduce NO_x emissions from gasoline fueled cars. Examples of available control techniques are described below.

Exhaust gas recirculation (EGR). The recirculation of exhaust gases substitutes part of the fresh intake air by exhaust gas, reducing the oxygen content in the combustion chamber and dampening through its additional heat capacity the temperature peaks. Both effects contribute to lower NO_x emissions. Removal efficiencies of up to 30 percent are achievable without any increase in fuel consumption.

Lean burn engines. A change in the stoichiometry of the fuel-to-air ratio towards leaner mixtures results also in reduced NO_x emissions. To guarantee satisfactory operation of the engines, some changes in the general design of the engines are necessary. Therefore, only new engines can be designed along the lean burn concept.

Catalytic reduction. A catalytic converter enables and accelerates the chemical conversion of CO, VOC and NO_x to CO_2, H_2O and N_2 at temperatures well below that at which it would occur spontaneously. The oxidation of CO and VOC is facilitated by completing the combustion process, nitrogen oxides are catalytically reduced. The catalysts consist of ceramic materials coated with precious metals (platinum, palladium or rhodium) or with active metal oxides (e.g., gamma alumina, copper oxide, etc.). Catalysts require the use of lead-free fuels, since the leaded antiknock additives form inorganic lead salts, which deposit on the catalytic surface, deactivating it.

The **three-way catalyst**, which is standard equipment for currently produced cars, uses a single unit, which oxidizes CO and VOC to carbon dioxide and reduces NO_x to nitrogen. For this process to work, it is necessary to have a very careful control of the concentrations of all the gases on the catalytic surface. Therefore, these systems require a fuel injection system capable of maintaining precise control of the fuel-to-air ratios under all driving conditions. This is achieved by means of electronic fuel injection combined with an oxygen sensor in the exhaust gas stream. The catalytic unit is programmed to control some 70 to 90 percent of the CO/VOC/NO_x during urban diving and up to 99 percent at high speed.

The **advanced catalysts** are characterized by a shorter warm-up periods to avoid idle operation after starting up the car. Possible solutions depend on splitting the whole mass of catalyst into two parts - one located close to the engine manifold and the main catalyst. The pre-catalyst warms-up quickly and reduces the emissions in the period when the main catalyst has not yet reached its working temperature. Also electrically heated catalysts and burner-heated catalysts with are under development.

There are also other catalytic systems available, e.g., the oxidation catalyst. They reduce mainly the emissions of carbon monoxide (CO) and the emissions of VOC. Since their impact on NO_x emissions is minimal, such control technologies are included in the VOC module of the RAINS model, available for two stroke engines.

Work to improve emission characteristics of gasoline engines is under way. In spite of further advancement of the previously mentioned methods, there are many other engine modifications that result in lower emissions of pollutants. Measures having the largest potential are variable intake manifold with exhaust gas recirculation, improved lambda control or variable valve timing with internal EGR.

6.3.2 Diesel Engines

The high pressures and temperatures and the relatively low fuel-to-air ratios in diesel engines reduce the incomplete combustion, making these engines more fuel efficient than spark-ignition engines. Due to the lower degree of incomplete combustion, diesel engines emit lower amounts of VOC and CO than do Otto engines, whereas NO_x emissions depend on the design and the rated power of the engine. Approximately 10 to 20 percent of nitrogen oxides from diesel engines are emitted as NO_2 (nitrogen oxide), which is five times more toxic than NO (nitrogen monoxide). Gasoline engines emit less than 10 percent as NO_2. However, this NO is converted to NO_x within short time.

For diesel engines there is also an inherent conflict between some of the most powerful NO_x control techniques and the emissions of particulates. This 'tradeoff' is not absolute – various NO_x control techniques have varying effects on soot and VOC emissions, and the importance of these effects varies with engine speed and load. These tradeoffs place limits on the extent to which any of the three pollutants can be reduced. At the moment there is no after-treatment technique commercially available to reduce NO_x emissions from diesel engines. The process of catalytic NO_x reduction used on gasoline vehicles is inapplicable to diesel. Because of their heterogenous combustion process, diesel engines require substantial excess air, and their exhaust thus inherently contains significant oxygen. The three-way catalysts used on automobiles require precise stoichiometric mixture in the exhaust gas to properly function; in the presence of excess oxygen, their NO_x conversion efficiency rapidly approaches zero. A number of after-treatment NO_x reduction techniques that are efficient in an oxidizing exhaust stream are currently under development. They should be commercially available within the next two to three years.

Modern engines of diesel passenger cars and light duty trucks are built according to two concepts: the direct injection and the indirect injection of fuel. Engines for heavy-duty trucks are built as direct injection engines. The uncontrolled emissions of NO_x for direct injection engines is typically twice as high as with the indirect injection design. However, after implementation of appropriate control measures the emissions from these two types of engines become comparable.

There is no single technology to drastically reduce NO_x emissions from light- and heavy-duty diesel engines without major adverse impacts on the emissions of soot, VOC and noise, and on the fuel efficiency. Thus usually reduction measures are applied in combination and need to be optimized to achieve a reasonable trade-off between the emissions of individual pollutants. Measures available are discussed below.

Injection Timing. The timing relationship between the beginning of the fuel injection and the top of the compression stroke of the piston has an important effect on diesel engine emissions and fuel economy. For purposes of fuel efficiency it is preferable that the combustion begins just at the point of greatest compression, which requires fuel injection somewhat before this point. A long ignition delay provides more time for air and fuel to mix, which increases both the amount of fuel that burns in the premixed combustion phase and the maximum temperature in the cylinder. Both of these effects tend to increase NO_x emissions, but reduce particulate and VOC emissions. Therefore, the injection timing must compromise between emissions of particulates and VOC and fuel economy on one hand and noise, NO_x emissions and maximum cylinder pressure on the other. A higher injection pressure might alleviate the need for this compromise. The injection pressure in modern engines reach 1500 bar.

Turbocharging and intercooling. A turbocharger consists of a centrifugal air compressor feeding the intake manifold, mounted on the same shaft as an exhaust gas turbine in the exhaust stream. By increasing the mass of air in the cylinder prior to compression, turbocharging correspondingly increases the amount of fuel that can be burned without excessive smoke, the potential maximum power output and the fuel efficiency of the engine. The compressed air can be cooled in an intercooler before it enters the cylinder. This increase of the air mass in the cylinder and the reduction of its temperature can reduce both NO_x and particulate emissions. In the USA, virtually all heavy-duty engines produced since 1991 are equipped with these systems.

Exhaust gas recirculation (EGR). EGR reduces the partial pressure for oxygen and the combustion temperature, leading to reduced NO_x formation. EGR is a proven NO_x control technique for light-duty gasoline and diesel vehicles. In heavy-duty trucks, EGR has shown to increase wear rates and oil contamination, resulting in higher maintenance expenses and shorter engine life. After initial difficulties the EGR is also considered as a viable option for heavy-duty engines.

Besides the above mentioned technologies, which can be regarded as changes in engine design, application of catalytic converters to diesel engines is intensively tested. For light duty engines the zeolyte catalyst with reducing agent as well as other types of de-NO_x catalysts offer a promising solution that should be commercially available within the next two to three years. NO_x catalytic converters for heavy-duty engines are expected to be on a market within the next three to five years (Rodt et al., 1995, 1996). The catalysts enable to reduce the emissions by more than 80 percent compared with the uncontrolled emissions from engines with the late 1980's design.

6.3.3 Control Options for Seagoing Ships

For some countries in Europe a large proportion of total emissions of NO_x originates from maritime transport activities, i.e., from ships cruising between the ports in the same country as well as from fishing vessels. Also for these sources emission control options are available. They include changes in engine design (the combustion modifications measures) as well as the use of the SCR technology. The estimates of control efficiencies and costs for reducing emissions from ships are based on Norwegian sources (Klokk, 1995; Selvig, 1997).

6.3.4 Representation of Control Options for Mobile Sources in RAINS

As mentioned above, detailed modeling of each technically available control technology on the emission levels at a European scale is not feasible in the integrated assessment model like RAINS. Thus the available control options have been grouped into technology packages that enable to meet the current emission standards as well as legislative proposals discussed in the European context for individual categories of vehicles. It should be stressed that these packages comprise different types of measures, i.e., not only the changes in engine technology and the use of catalytic converters, but also changes in fuel specifications and measures to improve inspection and maintenance.

Table 6-2 presents the packages for controlling NO_x and VOC emissions for mobile sources as contained in the RAINS database with the reduction efficiencies for the pollutants under study. These efficiencies relate to uncontrolled emissions from vehicles according to the end of 1980's design. Data have been derived from various reports developed within the Auto/Oil program (EC, 1996a, b, Touche Ross & Co., 1995). Characterizations of future technologies, which were not covered by the Auto/Oil I study, are based on McArragher *et al.*, 1994, Rodt *et al.*, 1995, 1996, UN/ECE, 1994a,b. The assistance of consultants participating in the Auto/Oil study helped to incorporate the suggested measures on fuel quality improvement and inspection and maintenance schemes into the RAINS model in a fully consistent way (Barrett, 1996).

The costs and control efficiencies presented in this report include the decisions of the Environment Council of October 1997 regarding the common positions on the quality of petrol and diesel fuels as well as on pollution control measures from motor vehicles (OJ 97/C 351/01, 1997a and OJ 97/C 351/02, 1997b). In particular, the following measures have been included in addition to the original Auto/Oil proposal:

- Change in petrol characteristics. For the year 2000, a reduction of the sulfur content to 150 ppm, of benzene to 1 percent and of aromatics to 42 percent. For 2005, further reductions to 50 ppm for sulfur and 35 percent for aromatics, as outlined in the indicative standards. These changes have an impact on NO_x and VOC emission factors.
- Reduction of the maximum sulfur content in diesel oil to 50 ppm. It has been assumed that this low sulfur diesel fuel will be progressively introduced between 2005 and 2015. Additional costs of that fuel are allocated to the SO_2 control.
- For petrol cars, Stage 3 controls from the year 2000 and Stage 4 controls after 2005, taking into account the costs of the cold start test. Since the original proposal of the Auto/Oil programme for the increased durability of catalytic converters has not been accepted by the Commission (compare COM(96) 248, 1996), the unit costs of Stage 3 control have been corrected to reflect this change.
- Stage 4 controls for diesel cars, including the requirement for on-board diagnostic systems.

- Costs of Stage 4 controls have been reviewed and corrected taking into account information provided in Rodt *et al.* (1995, 1996).

The estimate of the effects of the Common Position on emission control efficiencies and costs is based on Auto/Oil data (EC, 1996a; Touche Ross & Co., 1995) and on information available in DG-XI (Mackowski, 1998).

It is important to mention that the European Auto/Oil program used the net present value costing methodology, whereas RAINS expresses costs in terms of total annual costs, based on annualized investments over the entire technical life time of the equipment and the fixed and variable operating costs. Although there is consistency between Auto/Oil and RAINS in the input data of the cost evaluation, the resulting output cost numbers are not directly comparable. Besides, Auto/Oil costs are in 1995 prices, while RAINS uses constant prices from 1990 as a basis for calculations.

Table 6-2 Control options for NO_x and VOC emissions from mobile sources in RAINS

Fuel/vehicle type/control technology	RAINS abbreviation	Removal efficiency NO_x/VOC [%]
Gasoline 4-stroke passenger cars and LDV[6]		
3-way catalytic converter - 1992 standards	LFCC1	75/75
3-way catalytic converter - 1996 standards	LFCC2	87/87
Advanced converter with maintenance schemes - EU 2000 standard	LFCC3	93/93
Advanced converter with maintenance schemes – possible EU post-2005 standard (**)	LFCC4	97/97
Gasoline 4-stroke passenger cars and LDV		
3-way catalytic converter	GLDCC	85/85
Diesel passenger cars and LDV		
Combustion modification - 1992 standards	MDLDCM	31/31
Combustion modification - 1996 standards	MDLDAM	50/50
Advanced combustion modification with maintenance schemes - EU 2000 standards	MDLDEC	60/60
NO_x converter(**)	MDLDNX	80/80
Heavy duty vehicles - diesel		
Euro I - 1993 standards	EUR1	33/36
Euro II - 1996 standards	EUR2	43/47
Euro III - EU 2000 standards with maintenance schemes	EUR3	60/66
Euro IV (NO_x converter) (**)	EUR4	85/93
Heavy duty vehicles		
Natural gas - catalytic converter	GHDCC	85/85
Gasoline - catalytic converter	LFHDCC	85/85
Seagoing ships		
Combustion modifications – medium vessels[7]	STMCM	40/0
Combustion modifications – large vessels[8]	STLCM	40/0
SCR – large vessels	STLSCR	90/0

(**) - Not yet commercially available. Preliminary cost estimates are based on Rodt *et al*, (1995, 1996), and UN/ECE (1994a, b).

[6] LDV - light duty vehicles.

[7] about 300 kW thermal

[8] about 2500 kW thermal

7 Cost Evaluation Methodology

This section introduces the methodology for calculating abatement costs in the RAINS-NO_x module. The approach is in line with the methodologies currently applied in RAINS for the calculations of SO_2, VOC and ammonia emissions (Cofala and Syri, 1988, Klimont *et al.,* 1998, Klaassen, 1991).

The basic intention of the cost evaluation is to identify the values to society of the resources diverted in order to reduce NO_x 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 must 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 denitrification equipment throughout Europe accessible for all Parties at the same conditions. This means that the same 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 NO_x removal with a given technology cheaper of more expensive. Due to variations in average boiler sizes, capacity utilization rates, boiler designs and (for mobile sources) different composition of vehicle fleet as well as different driving conditions, costs on a unit basis (i.e., per ton of NO_x emissions removed) differ notably among countries. The RAINS cost calculation routine is designed to capture these differences in a systematic way.

The approach considers some of the parameters as country- specific while others are common for all the countries. For stationary sources country-specific parameters include the average size of installations in a given sector/class, prices for labor and electricity and prices of material. For mobile sources the most important country-specific parameter is the annual fuel consumption per vehicle in 1990. Also assumptions about the improvement in fuel efficiency for each vehicle category are country-specific. Common parameters include the interest rate and technology-specific data, e.g., removal efficiencies, investments, maintenance costs, specific demand for labor, energy, and materials.

Although based on the same principles, the cost assessment in RAINS is different for stationary and mobile sources. Thus the costing methodology is presented separately for these two groups of emission sources.

7.1 Stationary Sources

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.

7.1.1 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. The shape of the function is described by its coefficients ci^f and ci^v. 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}. When existing plant is retrofitted with add-on controls (SCR, SNCR) investments are multiplied by a retrofit cost factor r. The coefficients of investment functions describe only the costs for construction of the equipment. In order to calculate total investment costs, cost of catalyst is then added (if applicable). Since the lifetime of catalyst is much shorter than the lifetime of the plant, subsequent replacements of catalyst are included in the cost item 'variable operating costs'. Investments are calculated using Equation 7.1:

$$I = (ci_1^{\,f} + \frac{ci_1^{\,v}}{bs}) + (ci_2^{\,f} + \frac{ci_2^{\,v}}{bs}) * (1 + r) + \lambda^{cat} * ci^{cat} \qquad (7.1)$$

where:

ci_1^f, ci_1^v, ci_2^f, ci_2^v – coefficients of investment function; ci_1 have non-zero values only for combinations of technologies (e.g., CM plus SCR)

bs – boiler size

λ^{cat} catalyst volume (per unit of installed capacity)

ci^{cat} unit cost of catalysts

r retrofit cost factor

The investments are **annualized** over the technical lifetime of the plant *lt*, using the real interest rate *q* (as %/100).

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \tag{7.2}$$

7.1.2 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:

$$OM^{fix} = I * f \tag{7.3}$$

The **variable operating costs** OM^{var} related to the actual operation of the plant take into account the costs for the increased energy demand for operating the device (e.g., for fans and for reheating) and for sorbent material (e.g., NH_3). These cost items are calculated based on the specific demand λ^x of a certain control technology and its (country-specific) price c^x.

$$OM^{var} = \lambda^e c^e + ef\ \eta\ \lambda^s c^s \tag{7.4}$$

where:

λ^e	additional electricity demand
λ^s	sorbents demand
c^s	sorbents price
c^e	energy price
ef	unabated NO_x emission factor
η	removal efficiency

If a control technology makes use of catalyst, the periodical replacement costs for this equipment (depending on the real operation time of the plant) is also included in this cost category:

$$OM^{cat} = (pf\ /\ lt^{cat}) * (\lambda^{cat}\ \ ci^{cat})\ /pf \tag{7.5}$$

where:

pf capacity utilization (operating hours/year)

lt^{cat} lifetime of catalyst.

7.1.3 Unit Reduction Costs

7.1.3.1 Unit Costs per PJ

Based on the above-mentioned cost items, the unit costs for the removal of NO_x emissions can be calculated. In Equation 7.6 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):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} + OM^{cat} \tag{7.6}$$

where:

c_{PJ} cost per unit of energy input.

7.1.3.2 Unit Costs per Ton of NO_x Removed

Although this cost coefficient c_{PJ} is useful for the calculation of effects on the electricity price, the cost efficiency of different control options can only be evaluated by relating the abatement costs to the amount of reduced NO_x emissions. For this purpose Equation 7.7 is used:

$$c_{NOx} = \frac{c_{PJ}}{nox\ x} \tag{7.7}$$

where:

c_{NOx} cost per unit of NO_x reduced.

7.1.4 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'.

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

$$mc_m = \frac{c_m \eta_m - c_{m-1} \eta_{m-1}}{\eta_m - \eta_{m-1}} \tag{7.8}$$

with:

c_m unit costs for option m and

η_m removal efficiency of option m.

7.2 Mobile Sources

The cost evaluation for mobile sources follows the same basic approach as for stationary sources. However, due to structural differences, modifications are necessary. The most important difference is that the investment costs are given per vehicle, not per MW capacity. The number of vehicles is computed using the information on total annual fuel consumption by a given vehicle category and the average fuel consumption per vehicle per year.

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

i denotes the country

j the economic sector

k the control technology

The annual costs are calculated for each sector/control option. The amount of abated NO_x emissions is calculated based on the unabated emission factor and the removal efficiency of the control option:

$$rN(t)_{i,j,k} = act_{i,j} * ef_{i,j}^{\ N} * \eta_{j,k}^{N} * af_{i,j,k}(t) \tag{7.9}$$

where:

$rN_{i,j,k}(t)$	NO_x emissions removed in country i in time step t from transport sector j with technology k
$act_{i,j}(t)$	activity level of sector j in time step t
$ef_{i,j}^{N}$	(unabated) NO_x emission factor per unit of activity for country i and sector j, expressed in kg pollutant per GJ fuel
$\eta_{j,k}^{N}$	NO_x 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.

Since the technologies in the transport sector simultaneously abate the emissions of VOC, the same calculations are performed for the abatement of VOC:

$$rV(t)_{i,j,k} = act_{i,j} * ef_{i,j}^{V} * \eta_{j,k}^{V} * af_{i,j,k}(t) \qquad (7.10)$$

where:

$rV_{i,j,k}(t)$	VOC emissions removed in country i in time step t from transport sector j with technology k
$ef_{i,j}^{V}$	(unabated) VOC emission factor per unit of activity for country i and sector j, expressed in kg pollutant per GJ fuel
$\eta_{j,k}^{V}$	VOC removal efficiency of technology k in sector j.

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
- change (positive or negative) in fuel consumption after inclusion of emission control.

The investment costs $I_{i,j,k}$ are given in ECU/vehicle and are available separately for each technology and vehicle category. They are annualized using Equation 7.11:

$$I_{i,j,k}^{an} = I_{j,k} \cdot \frac{(1+q)^{lt_{i,j,k}} \cdot q}{(1+q)^{lt_{i,j,k}} - 1} \qquad (7.11)$$

where:

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

The increase in maintenance costs is expressed as a percentage f of total investments:

$$OM_{i,j,k}^{fix} = I_{i,j,k} \cdot f_k \qquad (7.12)$$

Finally, the change in fuel consumption after inclusion of emission controls can be calculated as follows:

$$OM^{e}_{i,j,k}(t) = \lambda^{e}_{j,k} fuel_{i,j}(t) * c^{e}_{i,j} \qquad (7.13)$$

where:

$\lambda^{e}_{j.k}$ percentage change in fuel consumption in sector j caused by implementation of control measure k

$fuel_{i,j}(t)$ fuel use per vehicle in country i and sector j in time step t.

$c^{e}_{i,j,k}$ fuel price (net of taxes) in country i and sector j.

Annual fuel consumption per vehicle is a function of the consumption in the base year (t_0=1990) and the assumed fuel efficiency improvement:

$$fuel_{i,j}(t) = fuel_{i,j}(t_0) * fe_{i,j}(t) \qquad (7.14)$$

where:

$fe_{i,j}(t)$ fuel efficiency improvement in time step t relative to the base year (1990 = 1.00).

Operating experience of vehicles with catalytic converters has shown that the lifetime of catalyst is the same as the lifetime of the vehicle. Thus no provision is made for catalyst replacement. Possible repairs of the catalytic converter are included in the fixed maintenance cost.

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

$$ce_{PJ,i,j,k}(t) = \frac{I^{an}_{i,j,k} \div OM^{fix}_{i,j,k} + OM^{e}_{i,j,k}(t)}{fuel_{i,j,k}(t)} \qquad (7.14)$$

These costs can be related to the achieved emission reductions. In the current version of the model the costs of emissions control from the transport sector are fully attributed to NO_x reduction. In the optimization routine the reduction of NO_x is functionally linked to the reduction of VOC emissions. Such a solution avoids subjective and always questionable assumptions about the division of costs in combined processes. Thus the costs per unit of NO_x abated are as follows:

$$cn_{i,j,k}(t) = \frac{ce_{i,j,k}(t)}{ef^{N}_{i,j,k} * \eta^{N}_{j,k}} \qquad (7.15)$$

The most important factors leading to differences among countries in unit abatement costs are variations in annual energy consumption per vehicle and in unabated emission factors. Emission factors differ due to the structures of fleet composition and due to characteristic driving patterns (e.g., shares between urban and. highway driving, depending on the available infrastructure in a given country).

8 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 for stationary sources the proceedings presented at the various UN/ECE Seminars on Emission Control Technologies (e.g., UN/ECE, 1996b; UN/ECE, 1997, etc.) and for mobile sources the material prepared within the Auto/Oil programme. Other important information sources were published reports and costing studies (e.g., CEC, 1996; Rentz *et al.*, 1987; 1996; Schärer, 1993; OECD, 1993; Takeshita, 1995). Country-specific information has been either extracted from relevant national and international statistics (e.g., IMF, 1995; UN, 1995, 1996; UN/ECE, 1995a; UN/ECE, 1996a) or provided by national experts. The basic input data on NO_x control technologies used in RAINS have been reviewed in the beginning of 1997 by the Parties to the Convention on Long-range Transboundary Air Pollution (IASA, 1996) and have been recently updated to take into account latest operating experience. All costs are given in constant 1990 ECU.

8.1 Technologies for Stationary Sources

Data distinguish technology-specific and country-specific parameters. The technology-specific parameters are common for all countries in Europe. The naming conventions and units of the technology-specific parameters are presented in Table 8-1. The values of the coefficients of the investment functions for individual technologies are given in Table 8-2 and Table 8-3. The coefficients are estimated separately for three capacity ranges. Values of the other common parameters used in the calculation of emission control costs in RAINS are listed in Table 8-4.

Table 8-1: 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_1^f, ci_2^f	Intercept of the investment function	ECU/kW_{th}
ci_1^v, ci_2^v	Slope of the investment function	10^3 ECU
r	Retrofit cost factor (for secondary measures)	%/100
η	NO_x removal efficiency	%/100
f	Maintenance costs and overheads	%/100/year
λ^e	Specific demand for electricity	kWh/GJ_{th}
lt^{cat}	Lifetime of catalyst	hours
λ^s	Specific demand for sorbent (NH_3)	ton/t NO_x removed

Table 8-2: Coefficients of the investment function for 'combustion modification' technologies used in boilers and furnaces

Technology abbreviation	ci^f_2 ECU/kW_{th}	ci^v_2 10^3 ECU	Capacity range MW_{th}
DHFCM	5.67	0.00	>0
DMDCCO	3.00	0.00	>0
DGCCOM	2.50	0.00	>0
DMDCCR	12.00	0.00	>0
DGCCR	16.25	0.00	>0
	6.30	0.00	<20
ISFCM	5.18	22.50	20
	2.33	876.50	300
	5.67	0.00	<20
IOGCM	4.66	20.25	20-300
	2.10	788.85	>300
	10.20	0.00	<20
PBCCM	8.28	38.40	20-300
	5.29	933.00	>300
	6.30	0.00	<20
PHCCM	5.18	22.50	20-300
	2.33	876.50	300
	3.83	0.00	<20
POGCM	3.10	14.40	20-300
	1.99	799.65	>300

Table 8-3: Coefficients of the investment function for add-on technologies and combined measures used in boilers and furnaces

Technology abbreviation	ci^f_1 ECU/kW$_{th}$	ci^v_1 10^3 ECU	ci^f_2 ECU/kW$_{th}$	ci^v_2 10^3 ECU	Capacity range MW$_{th}$
ISFCSC	6.30	0.00	19.60	0.00	<20
	5.18	22.50	14.60	102.00	20-300
	2.33	876.50	5.10	2950.00	>300
IOGCSC	5.67	0.00	14.63	0.00	<20
	4.66	20.25	11.25	68.85	20-300
	2.10	788.85	4.73	1991.25	>300
ISFCSN	6.30	0.00	6.54	0.00	<20
	5.18	22.50	4.87	34.00	20-300
	2.33	876.50	1.70	983.34	>300
IOGCSN	5.67	0.00	4.88	0.00	<20
	4.66	20.25	3.75	22.95	20-300
	2.10	788.85	1.58	663.75	>300
PBCSCR	0.00	0.00	23.52	0.00	<20
	0.00	0.00	17.52	122.40	20-300
	0.00	0.00	6.12	3540.00	>300
PBCCSC	10.20	0.00	23.52	0.00	<20
	8.28	38.40	17.52	122.40	20-300
	5.29	933.00	6.12	3540.00	>300
PHCSCR	0.00	0.00	19.60	0.00	<20
	0.00	0.00	14.60	102.00	20-300
	0.00	0.00	5.10	2950.00	>300
PHCCSC	6.30	0.00	19.60	0.00	<20
	5.18	22.50	14.60	102.00	20-300
	2.33	876.50	5.10	2950.00	>300
POGSCR	0.00	0.00	14.63	0.00	<20
	0.00	0.00	11.25	68.85	20-300
	0.00	0.00	4.73	1991.25	>300
POGCSC	3.83	0.00	14.63	0.00	<20
	3.10	14.40	11.25	68.85	20-300
	1.99	799.65	4.73	1991.25	>300

Table 8-4: Other technology-specific parameters for add-on control technologies (secondary and combined measures)

Parameter	Unit	Value
Retrofit coefficient r	%/100	0.5
Fixed O+M cost f	%/100/yr	0.06
Catalyst cost ci^{cat}	$kECU/m^3$	10
Electricity demand λ^e		
- coal boilers	GWh/PJ fuel input	0.36
- oil and gas boilers		0.30
Catalyst volume λ^{cat}		
Brown coal boilers	m^3/MW_{th}	0.41
Hard coal, dry bottom boilers		0.34
Hard coal, wet bottom boilers		0.46
Oil and gas boilers		0.11
Sorbent demand λ^s, technology:		
PBCSCR, PHCSCR, POGSCR	t/t NO_x	0.390
PBCCSC, POGCSC		0.117
PHCCSC, ISFCSC, IOGSCS		0.173
ISFSCN, IOGCSN		0.390

Table 8-5 provides the country-specific parameters used in emissions and control costs calculations in the NO_x module of RAINS. The most essential country-specific parameters with largest influence on reduction costs are:

- unabated emission factors for NO_x and (for transport sources) also for VOC,
- 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 (electricity, ammonia)
- lifetime of control equipment and lifetime of vehicles.

Values of country-specific parameters are extracted from relevant national and international sources. The actual values of the country-specific parameters are presented 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 were 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)[9]. 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 8-5: Country-specific parameters for calculating costs of controls on boilers and furnaces

Symbol	Item	Unit
ef^N	Unabated NO_x emission factor	kton NO_x/PJ
bs	Average boiler size	MW_{th}
pf	Capacity utilization	hours/year
c^e	Electricity price	ECU/kWh
c^s	Sorbent (ammonia) cost	ECU/ton
lt	Control equipment lifetime	years
q	Real interest rate	%/100

8.2 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 process emissions. The assumed reduction efficiencies and related costs, equal all over Europe, are given in Table 8-6. Data is based on recent information about abatement options for individual industrial processes and their costs as compiled by the UN/ECE Task Force on Emission Abatement Techniques (UN/ECE, 1997). This information is consistent with Dutch sources (Van Oostvorn, 1984; VROM, 1987) as well as with assessments done by the experts from the German Environmental Protection Agency (UBA). However, one should once more stress that costs of controlling process emissions are highly uncertain and depend on many local factors, which were not possible to fully include in the current structure of the model. Since processes contribute less than five percent of total NO_x emissions, the simplified treatment of that sector seems to be justified.

[9] However, the lifetime of control equipment for stationary sources and of vehicles in transport is treated by the calculation routine as country-specific parameter.

Table 8-6: NO_x process emission reduction efficiencies and related costs in RAINS.

Measure	**RAINS code**	**Reduction efficiency**	**Reduction costs ECU/ton NO_x**
Stage 1 control	PRNOX1	40 %	1000
Stage 2 control	PRNOX2	60 %	3000
Stage 3 control	PRNOX3	80 %	5000

8.3 Cost Parameters for Mobile Sources:

Technology-specific parameters for mobile sources include information on extra investment in control equipment and on its operation and maintenance cost. Also a possible change in unit fuel consumption caused by an installation of control measures belongs to that category of parameters. The values of these parameters, as currently used by RAINS, are shown in Table 8-7. Since, according to the current operating experience, present control measures for vehicles do not cause an increase in overall fuel consumption, the value of the latter parameter is set to zero. However, the RAINS calculation routine enables to include that cost component. Higher costs of fuels (per liter) caused by changes in fuel specification (e.g., different contents of aromatics and/or benzene) are included in the O+M costs.

Compared with stationary sources, there are three additional country-specific parameters for mobile sources. These are:

- Unabated VOC emission factor - ef^V, kton VOC/PJ,
- Fuel consumption per vehicle in the base year (1990) - *fuel(1990)*
- Fuel economy improvement in the time step t - $fe_{i,j}(t)$. This improvement is measured in relation to fuel use in the base year (1990 = 1.00).
- Fuel prices (net of taxes) - c^e.

Values of the country-specific parameters are presented in Appendix 3.

Table 8-7 Technology-specific parameters for mobile sources

Technology	Investments *I*, ECU/vehicle[10]	Fixed O+M cost *f*, %/100	Additional fuel demand, %
GLDCC	275	0.02	0
LFCC1	250	0.30	0
LFCC2	300	0.25	0
LFCC3	709	0.11	0
LFCC4	884	0.08	0
MDLDCM	150	0.34	0
MDLDAM	275	0.19	0
MDLDEC	780	0.07	0
MDLDNX	1027	0.05	0
GHDCC	2750	0.02	0
LFHDCC	2750	0.07	0
EUR1	600	0.41	0
EUR2	1800	0.13	0
EUR3	4047	0.06	0
EUR4	8047	0.03	0
STMCM	115	0.04	0
STLCM	166	0.04	0
STLSCR	526	0.04	0

[10] For sea vessels investments are given in kECU/vessel.

9 Example Cost Calculations

This section presents two examples that illustrate the costing methodology used in RAINS. The first case shows how costs are calculated for add-on control technologies for a stationary source in the power plant sector. Parameters used in the example are for an existing brown coal fired power plant. The second example demonstrates the method for calculating costs for mobile sources. In this case the cost of implementation of Stage 3 controls (Auto/Oil I standard) for gasoline light duty vehicle has been calculated.

9.1 Cost of Combined Measures (CM+SCSR) for an Existing Brown Coal Fired Plant

I. Values of the input parameters:

Sector/Fuel type: existing power plant, brown coal (PP_EX_OTH, BC1)	
Boiler size:	$bs = 610$ MW_{th}
Capacity utilization	$pf = 6000$ hours/year
Retrofit cost factor	$r = 0.5$
Interest rate	$q = 4\%$
Lifetime of control equipment	$lt = 20$ years
Parameters of the investment function:	
ci^f_1	5.3 ECU/kW_{th}
ci^v_1	933 kECU
ci^f_2	6.12 ECU/kW_{th}
ci^v_2	3540 kECU
Catalyst volume	$\lambda^{cat} = 0.41$ m^3/MW_{th}
Catalyst cost	$ci^{cat} = 10000$ ECU/m^3
Catalyst lifetime	$lt^{cat} = 24000$ hours
Unabated NO_x emission factor:	$ef = 270$ tons NO_x/PJ
Electricity price	0.04 ECU/kWh
Additional energy demand	0.36 GWh/PJ fuel input
Sorbent (ammonia) demand	0.117 t/t NO_x
Sorbent cost	250 ECU/ton
Efficiency of control technology	$\eta = 80$ %

II. Investment-related costs:

a. Investments:

$$5.29 + 933/610 + (6.12+3540/610) * (1+0.5) + 0.41 * 10000*10^{-3} = 28.8 \text{ ECU/kWth}$$

b. Annualized capital costs:

$$0.074* \text{ investment} = 2.13 \text{ ECU/kWth/year}$$

[Annuity (for q = 4 %, and lt = 20 years) = 0.074]

c. Fixed operating costs:

6 % of investment = 1.73 ECU/kWth/year

III. Variable costs:

a. Electricity and ammonia costs:

$$0.36 * 0.04 + .27 * 90/100 * 0.117 * 250 * 10^{-3} = 0.022 * 10^{6} \text{ ECU/PJ}$$

b. Cost of periodical catalyst replacement:

$$6000/24000*0.41 * 10000/6000/3.6 = 0.047 * 10^{6} \text{ ECU/PJ}$$

IV. Costs per unit energy input:

$$(2.13 + 1.73)/(6000*3.6*10^{-3}) + 0.022 + 0.047 = 0.248 * 10^{6} \text{ ECU/PJ}$$

V. Costs per ton NO_x abated:

$$0.248*10^{6} /(270 * 80/100) = 1.148 \text{ thousand ECU/ton } NO_x$$

9.2 Cost Of Stage 3 Controls for a Gasoline Light Duty Vehicle in 2010

I. Parameter values:

Unit investments	709 ECU/vehicle
Fixed operation and maintenance cost	11 %/a
Additional fuel demand	0.0 %
Gasoline consumption per vehicle in 1990	40 GJ/vehicle
Gasoline price (net of taxes)	7.3 ECU/GJ
Fuel efficiency improvement until 2010 (1990 =1.00)	0.83
Removal efficiency for stage 3 controls	93.3 %
Unabated emission factor:	800 t NO_x/PJ
Lifetime of vehicle	12 years

II. Investment-related costs:

a. Annualized capital costs:

Annuity for q=4 % and lt = 12 years = 0.107
0.107*investment = 26.8 ECU/vehicle/year

b. Fixed O+M costs:

11 % of investment = 27.5 ECU/vehicle

III. Variable costs:

a Cost of additional fuel consumption:

0*40*7.3 = 0 ECU/vehicle

IV. Cost per unit energy input:

Fuel consumption in 2010:

40*0.83 = 33.2 GJ/vehicle

Cost per PJ:

$(25.8 + 27.5)/33.2 * 10^3 = 1605 * 10^3$ ECU/PJ

V. Costs per ton of NO_x abated:

$1605*10^3/(800*93.3/100) = 2150$ ECU/t NO_x

10 Control Strategies and Cost Curves

10.1 Scenario Construction in RAINS

10.1.1 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 6-1 and Table 6-2 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 10-1 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 10-1 includes only controls for two fuel/sector combinations, i.e., for existing hard coal fired power plants and for the gasoline four-stroke light duty vehicles. 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 SCR technology (PHCCSC). Another 30 percent was controlled through the implementation of combustion modification measures (PHCCM). For 2010, the strategy assumes that 90 percent of capacities will be equipped with SCR. The share of uncontrolled capacities decreases to only 10 percent, of which two percent is not suitable for control (NSC).

Table 10-1: A control strategy file (an example)

Fuel	Sector	Technology	Percent capacities controlled in 1990	1995	2000	2005	2010
HC1	PP_EX_OTH	NOC	38	38	18	8	8
HC1	PP_EX_OTH	NSC	2	2	2	2	2
HC1	PP_EX_OTH	PHCCM	30	30	30	30	0
HC1	PP_EX_OTH	PHCCSC	30	30	50	60	90
LF	TRA_RD_LD4	NOC	100	70	10	4	2
LF	TRA_RD_LD4	NSC	0	0	0	0	0
LF	TRA_RD_LD4	LFCC1	0	30	20	8	3
LF	TRA_RD_LD4	LFCC2	0	0	70	43	10
LF	TRA_RD_LD4	LFCC3	0	0	0	45	85
LF	TRA_RD_LD4	LFCC4	0	0	0	0	0

The second part of Table 10-1 explains the control strategy for gasoline light duty vehicles with four-stroke engines in road transport sector. In 1990, all vehicles remain uncontrolled. In 1995, 30 percent of total vehicle stock is equipped with Stage 1 controls (LFCC1). In 2000, 70 percent of vehicles have Stage 2 controls, 20 percent is equipped with Stage 1 technology, and 10 percent remains uncontrolled. In 2010 the predominant technology is Stage 3 (85 percent share). Only two percent of all vehicles are not equipped with any controls.

10.1.2 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.

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). An inventory of national and international emission standards in Europe can be found in Bouscaren & Boucherau (1996). In addition, information on power plant emission standards has been taken from the survey of the IEA Coal Research (McConville, 1997). For countries of Central and Eastern Europe the environmental standards database developed by the Central European University (CEU, 1996) has also been used.

For the control of NO_x emissions from mobile sources, the scenario considers the implementation of the current UN/ECE legislation as well as country-specific standards if stricter. For the Member States of the European Union the current EU standards for new cars, light commercial vehicles and heavy duty vehicles (HDV) have been taken into account: the Directives 70/220/EEC as amended by 96/69/EC, and 88/77/EEC as amended by 96/1/EC; see McArragher (1994). Additionally, the scenario assumes for all EU countries after the year 2000 the implementation of the measures outlined in the Communication COM(96) 248 presenting the results and consequences from the Auto/Oil 1 programme. The agreement resulting from conciliation between Council and European Parliament on the envisaged legislation referred to by this Communication and the Commission's proposal on emissions from HDV (COM(97) 627) is also taken into account. This includes vehicle-related measures like improved catalytic converters, engine modifications and on-board diagnostic systems. Furthermore, the impacts of the envisaged improved inspection and maintenance practices and the changes in fuel quality are incorporated. The pace of the implementation of the vehicle-related measures depends on the turnover of vehicle stock and has been based on modeling work performed for the Auto/Oil 1 study.

NO_x control measures assumed in the 'Current Legislation' scenario in individual countries or groups of countries are specified in Table 10-2 and Table 10-3. The control technologies assumed for major stationary emission sources in EU countries are presented in Table 10-4.

Table 10-2: Measures assumed for the 'Current Legislation' (CLE) scenario for NO_x emissions in the countries of the European Union

Stationary sources:

- Emission standards for new plant and emission ceilings for existing plant from the Large Combustion Plant Directive - LCPD (OJ, 1988). These standards require implementation of primary emission measures (combustion modification) on large boilers in the power plant sector and in industry.
- National emission standards on stationary sources – if stricter than in the LCPD. Control measures for stationary sources included in the CLE scenario for individual countries of the EU are shown in Table 10-4.

Mobile sources:

- EU standards for cars and light commercial vehicles (LCV) (Directive 70/220/EC du Conseil, du 20 mars 1970, concernant le rapprochement des législations des États membres relatives au mesures à prendre contre la pollution de l'air par les gaz provenant des moteurs à allumage commandé équipant les véhicules à moteur, OJ 76, 6.4.70, p. 1, as amended by 96/69/EC, OJ L 282, 1.11.96, p. 1)
- EU standards for heavy duty vehicles (HDV) according to Council Directive 88/77/EC of 3 December 1987 on the approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous pollutants from diesel engines for use in vehicles, OJ L 36, 9.2.88, p. 33, as amended by 96/1/EC, OJ L 40, 17.2.96
- EU standards for non-road machinery engines (Directive 97/68/EC of the European Parliament and the Council of 16 December 1997 on the approximation of laws of the Member States relating to measures against the emissions of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery, OJ L 59, 27.2.98, p. 1-85, as well as for mopeds and motorcycles (Directive 97/24/EC of the European Parliament and the Council of 17 June 1997 on certain components and characteristics of tow or three-wheel motor vehicles, OJ L 226, 18.8.97, p. 1)
- From 2000 - fuel quality and emission standards (for LDV, LCV, HDV) and improved inspection/maintenance, as resulting from the Auto/Oil Programme (Communication from the Commission to the European Parliament and the Council on a future strategy for the control of atmospheric emissions from road transport taking into account the results from the Auto/Oil Programme (COM(96) 248, 18.6.1996), amended by the agreement resulting from conciliation between Council and European Parliament related to LDV, LCV, fuels (PE-CONS 3619/98, PE-CONS 3620/98) and by COM(97) 627, 3.12.97, on HDV-emissions. These standards are assumed to be implemented in the EU-15 as well as in Norway and in Switzerland.

Table 10-3: Measures assumed for the 'Current Legislation' (CLE) scenario for the control of NO_x emissions in the non-EU countries

Stationary sources:
- Czech Republic, Croatia, Hungary, Norway, Poland, Slovak Republic, Slovenia, Switzerland, Romania, Yugoslavia – controls according to national emission standards on new and existing sources
- Other countries in Central and Eastern Europe – no control[11]
Mobile sources:
- Czech Republic, Hungary, Poland, Slovak Republic, Slovenia - National mobile source standards comparable with 1992 and 1996 standards for the EU (requirement for catalytic converters for gasoline engines and combustion modifications on diesel engines)
- Other CEE countries - pre-1990 UN/ECE standards on mobile sources (no requirement for catalytic converters for gasoline engines and for combustion modifications on diesel engines)

[11] Because measures depending on implementation of primary NO_x reduction measures on new power plants are state of the art technology, such controls were assumed by default in all countries.

Table 10-4: NO_x 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	 Gas	Existing plants Coal	 Oil	 Gas
Austria						
10 - 50	CM	CM	CM	-	-	-
50 - 300	CM/SCR(1)	SCR	SCR	CM	CM	CM
> 300	SCR	SCR	SCR	SCR	SCR	SCR
Industrial processes:		Stage 2			Stage 2	
Belgium						
>50	SCR (4)	CM	CM	CM	CM	CM
Industrial processes:		Stage 1			Stage 1	
Denmark:						
>50	SCR	SCR	CM/SCR(2)	CM	CM	CM
Industrial processes:		Stage 1			Stage 1	
Finland:						
50 - 150	CM	CM	CM	CM	CM	-
150 - 300	SCR	CM	SCR	CM	CM	-
>300	SCR	SCR	SCR	CM	CM	CM
Industrial processes:		Stage 1			Stage 1	
France:						
>50	CM	CM	CM	CM	CM	-
Greece:						
>50	CM	CM	CM	CM	CM	-
Germany:						
50 - 100	CM	CM	-	CM	CM	-
100 - 300	CM	CM	CM	CM	CM	CM
> 300	CM/SCR (1)	SCR	SCR	CM/SCR (1)	SCR	SCR
Industrial processes:		Stage 2			Stage 2	
Ireland:						
>50	CM	CM	CM	CM	-	-
Italy:						
50 - 300	CM	CM	CM	-	-	-
>300	SCR	CM/SCR	CM/SCR	SCR	CM	CM
Luxembourg:						
>50	CM	CM	CM	CM	CM	CM
Industrial processes:		Stage 1			Stage 1	
Netherlands:						
<300(3)	SCR	SCR	SCR	CM	CM	CM
>300	SCR	SCR	SCR	CM/SCR	CM	CM
Industrial processes:		Stage 2			Stage 2	

Table 10-4 NO_x abatement technologies for the power plant and industrial sources assumed in the 'Current Legislation' (CLE) scenario for the EU countries, continued

Country	New plants			Existing plants		
Capacity class, MW_{th}	Coal	Oil	Gas	Coal	Oil	Gas
Portugal:						
>50	CM	CM	CM	CM	-	-
Spain:						
>50	CM	CM	CM	CM(4)	CM(4)	CM(4)
Sweden:						
<50	CM	CM	CM	CM	CM	CM
50 - 150	SCR	SCR	SCR	CM	CM	CM
>150	SCR	SCR	SCR	SCR	SCR	SCR
Industrial processes:		Stage 1			Stage 1	
UK:						
>50	CM	CM	CM	CM	CM	-

(1) Lignite/hard coal
(2) Standard slightly below of what is achievable with CM
(3) Includes also sources below 50 MWth
(4) Only in the power plant sector

Abbreviations:
CM - Combustion modification, primary measures
SCR - Selective catalytic reduction
Stage 1, 2, and 3 - Level of process emissions control

10.2 Cost Curves for Controlling NO_x 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 NO_x 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[12].

The cost curve can be displayed in RAINS in tabular or graphical form. Examples are presented in Table 10-5 and in Figure 10.1.

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. In addition, the table shows fuel consumption for each combination (in PJ) as well as application potential for each control technology. This potential is specified as a percentage of total capacity (percent of fuel consumption) that can be controlled with a given technology, on top of controls assumed as a starting point of the cost curve. This potential takes into account the already installed controls as well as the so-called applicability, i.e., the maximum share of total capacities to which a given control measure can be applied.

The cost curve displayed in Table 10-5 is constructed with the 'Current legislation' situation as a starting point. This means that this table ranks all available options for

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[12] 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.

emission control according to their cost-effectiveness, that are still available on top of measures required by the current legislation. In other words, the initial emissions and control costs include all measures, which are already adopted by the current legislation, and consider only the remaining potential for emission controls.

Table 10-5: NO_x abatement cost curve for stationary sources in tabular form (an example)

Category Class Fuel Sector Technology	Unit cost ECU/t NO_x	Marginal cost ECU/t NO_x	Remaining NO_x 1000t/a	Total cost Mio ECU/a	Fuel Consumption PJ	Application potential %
Initial emissions			52.9	60		
Acl1 MD IN_OC IOGCM	303	303	52.6	61	4	100
Acl1 MD CON_COMB IOGCM	303	303	52.5	61	2	100
Acl1 OS1 IN_OC ISFCM	388	388	51.9	61	9	100
Acl2 OS1 IN_OC ISFCM	388	388	51.3	61	9	100
Acl1 OS1 PP_EX_OTH PHCCM	391	391	50.6	61	11	100
Acl1 OS2 PP_EX_OTH PHCCM	391	391	50.5	61	1	100
Acl2 LF CON_COMB IOGCM	454	454	50.3	61	4	100
Acl1 LF CON_COMB IOGCM	454	454	50.2	62	4	100
Acl1 LF IN_OC IOGCM	649	649	50.1	62	1	100
Acl2 LF IN_OC IOGCM	649	649	50.1	62	1	100
Acl1 HF DOM DHFCM	805	805	50.0	62	2	100
Acl2 HF DOM DHFCM	805	805	49.7	62	3	100
Bcl1 HC1 PP_NEW PHCSCR	1394	1394	49.7	62	1	10
Bcl2 HC1 PP_NEW PHCSCR	1394	1394	49.7	62	1	10
Bcl1 HF PP_NEW POGSCR	1551	1551	49.5	62	4	50
Bcl2 HF PP_NEW POGSCR	1551	1551	49.4	62	4	50
Bcl1 HF CON_COMB IOGCSN	743	2012	49.3	63	3	100
Bcl2 HF CON_COMB IOGCSN	743	2012	49.2	63	3	100
Bcl1 HC1 IN_OC ISFCSN	738	2043	49.0	63	4	100
Bcl2 HC1 IN_OC ISFCSN	738	2043	48.8	64	4	100
Bcl1 HC1 CON_COMB ISFCSN	738	2043	48.8	64	0	100
Bcl2 HC1 CON_COMB ISFCSN	738	2043	48.8	64	0	100
Acl1 GAS DOM DGCCOM	2151	2151	48.3	65	38	100
Acl2 GAS DOM DGCCOM	2151	2151	47.3	67	77	100
Bcl1 HF IN_OC ISFCSN	873	2467	47.2	67	2	100
Bcl2 HF IN_OC ISFCSN	873	2467	47.1	67	2	100
Bcl1 GAS PP_NEW POGSCR	2863	2863	46.2	70	39	60
Bcl2 GAS PP_NEW POGSCR	2863	2863	45.3	73	39	60
Bcl2 HF IN_OC IOGCSC	1164	3207	45.2	73	2	80
Bcl1 HF IN_OC IOGCSC	1164	3207	45.2	73	2	80
Bcl2 BC1 IN_BO ISFCSN	1241	3329	45.2	73	1	100
Bcl1 BC1 IN_BO ISFCSN	1241	3329	45.1	73	1	100
Bcl1 GAS IN_OC IOGCSN	1344	3570	44.6	75	28	100
Bcl2 GAS IN_OC IOGCSN	1344	3570	44.0	77	28	100
Bcl1 GAS CON_COMB IOGCSN	1344	3570	43.8	78	10	100
Bcl2 GAS CON_COMB IOGCSN	1344	3570	43.6	79	10	100
Bcl2 HF IN_BO ISFCSN	1301	3593	43.4	79	4	100
Bcl1 HF IN_BO ISFCSN	1301	3593	43.3	80	4	100
Bcl2 OS2 PP_NEW PHCSCR	3654	3654	43.2	80	1	100
Bcl1 OS2 PP_NEW PHCSCR	3654	3654	43.2	80	1	100
Bcl1 HF CON_COMB IOGCSC	1164	4117	43.1	80	3	80

Category Class Fuel Sector Technology	Unit cost ECU/t NO_x	Marginal cost ECU/t NO_x	Remaining NO_x 1000t/a	Total cost Mio ECU/a	Fuel Consumption PJ	Application potential %
Bcl2 HF CON_COMB IOGCSC	1164	4117	43.1	80	3	80
Acl1 LF DOM DMDCCO	4732	4732	43.1	80	2	100
Acl2 LF DOM DMDCCO	4732	4732	43.0	80	4	100
Acl1 MD DOM DMDCCO	4732	4732	42.6	82	58	100
Bcl2 HF IN_BO IOGCSC	1795	5250	42.6	83	4	80
Bcl1 HF IN_BO IOGCSC	1795	5250	42.5	83	4	80
Bcl1 HC1 CON_COMB ISFCSC	1446	6404	42.5	83	0	80
Bcl1 HC1 IN_OC ISFCSC	1446	6404	42.4	84	4	80
Bcl2 HC1 CON_COMB ISFCSC	1446	6404	42.4	84	0	80
Bcl2 HC1 IN_OC ISFCSC	1446	6404	42.3	84	4	80
Bcl2 GAS IN_BO IOGCSN	2506	6453	41.9	87	20	100
Bcl1 GAS IN_BO IOGCSN	2506	6453	41.5	89	20	100
Bcl1 GAS IN_OC IOGCSC	2212	8282	41.3	91	28	80
Bcl1 GAS CON_COMB IOGCSC	2212	8282	41.2	92	10	80
Bcl2 GAS IN_OC IOGCSC	2212	8282	41.0	94	28	80
Bcl2 GAS CON_COMB IOGCSC	2212	8282	40.9	94	10	80
Bcl1 HF PP_EX_OTH POGCSC	1792	8579	40.9	95	3	50
Acl2 GAS DOM DGCCR	6151	9295	39.6	107	77	100
Acl1 GAS DOM DGCCR	6151	9295	38.9	113	38	100
Acl1 LF DOM DMDCCR	7571	9463	38.9	113	2	100
Acl1 MD DOM DMDCCR	7571	9463	38.3	119	58	100
Acl2 LF DOM DMDCCR	7571	9463	38.3	119	4	100
Acl1 NOF IN_PR PRNOX3	5000	11000	34.8	158	18	100
Bcl1 BC1 IN_BO ISFCSC	2580	11951	34.7	158	1	80
Bcl2 BC1 IN_BO ISFCSC	2580	11951	34.7	158	1	80
Bcl1 GAS PP_EX_OTH POGCSC	3055	15079	34.1	167	54	50
Bcl2 GAS IN_BO IOGCSC	4278	16684	34.0	170	20	80
Bcl1 GAS IN_BO IOGCSC	4278	16684	33.8	173	20	80

The control technologies that appear on the cost curve are divided into three categories:

- Category A: Technologies that can be - at any time - replaced by a more efficient technology. For SO_2, these are the technologies that do not require investments at plant level, like the use of low sulfur fuels. For NO_x, it is assumed that combustion modifications (CM) are "A" category technologies. Plants equipped with the primary emission control measures can be further retrofitted to include the secondary (add-on) control options like SNCR or SCR. For simplicity, it has been assumed that also controls of process emissions of SO_2 and NO_x belong to this category.
- Category B: Technologies that, if once installed, cannot be replaced by more efficient ones. These are technologies that require investments at the plant, e.g., wet flue gas desulfurization, SCR, SNCR.
- NO_x and VOC control technologies for transport sources (T): It is assumed that transport sources (vehicles) are controlled according to the legislation in force at the time of production of the vehicle. Retrofit with other control measures is not considered as possible. For the EU-15 and for Norway and Switzerland, the CLE

scenario treats the Auto/Oil I controls as binding up to the year 2005. After 2005, if necessary in an emission control scenario, stricter controls might be introduced. For the other countries, controls according to the current national legislation are assumed as binding until 2000. After 2000 the controls must be at least as strict as the 2000 controls. If necessary, more stringent controls from the list of technologies available in RAINS can be applied to new vehicles.

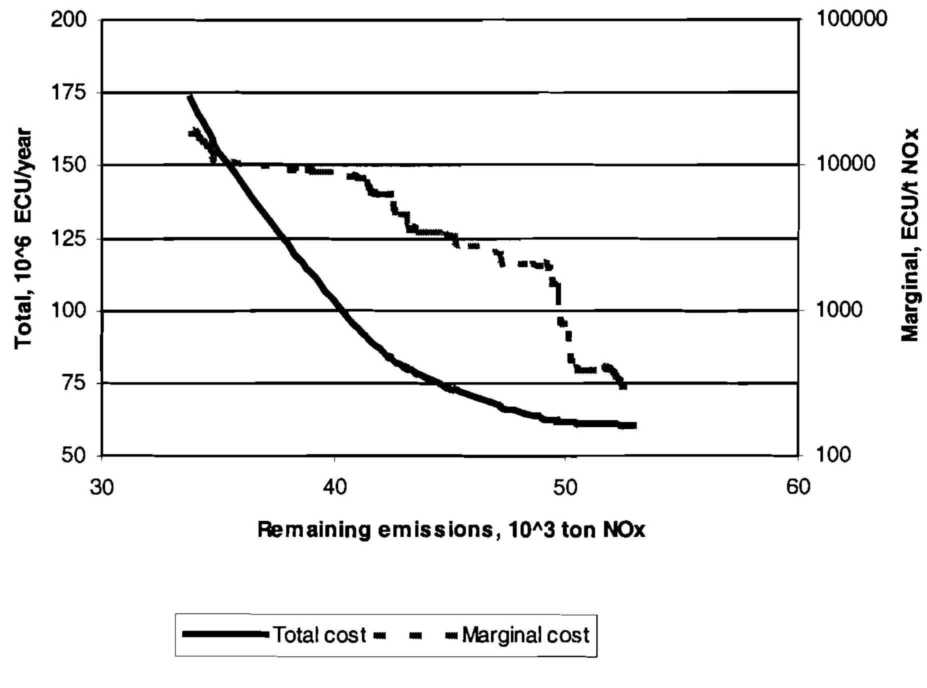

Figure 10.1: NO_x abatement cost curve for stationary sources in graphical format (an example)

For stationary sources, capacities are divided into two classes:

- Class 1 (cl1): For this class it is assumed that category B (add-on controls) resulting from current legislation are already implemented and cannot be replaced by other types of controls. This class includes all capacities commissioned before the year 2000. This assumption means that RAINS does not allow premature scrapping of equipment that has already been installed (or will be installed until 2000) in conformance with current legislation. For class 1 the controls with category A technologies can be replaced with add-on controls (category B) if such a measure is cost-efficient for a given control level.

- Class 2 (cl2). Capacities commissioned after the year 2000. For this class all cost-efficient control options can be applied. The control technology is selected according to cost-efficiency criteria for the required emission reduction level.

The NO_x cost curve for stationary sources is constructed with the assumption that the applicabilities of SCR technology in the industrial sector are limited to 80 percent of total capacities of boilers/furnaces. For the transport sector, the applicabilities are derived from the assumptions about the turnover of vehicle stock in each individual country.

For NO_x control, RAINS generates four separate cost curves:

- Stationary sources and sources from transport, where the available emission control options affect only NO_x emissions (vehicles with two-stroke engines, emissions from seagoing ships);
- Vehicles with gasoline four-stroke engines;
- Passenger and light duty vehicles with diesel engines;
- Heavy-duty diesel vehicles.

VOC reductions from sources included in curves 2-4 are linearly dependent from the reductions of NO_x.

Cost curves for NO_x reduction for 2010 for the "Current Legislation" scenario are given in the Appendix 6. This appendix also includes the information on the share of fuel use by old vehicles (i.e., equipped with predetermined controls).

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