# FOURTH INTERIM REPORT

# Cost-effective Control of Acidification and Ground-Level Ozone

Fourth Interim Report to the
European Commission, DG-XI

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February 1998

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This report constitutes Part A of the First Interim Report on the
Study Contract B4-3040/97/000654/MAR/B1
Economic Evaluation of Air Quality Targets for Tropospheric Ozone.

February 1998

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# Acknowledgments

The authors would like to express their gratitude to

- Arne Drud from ARKI Consulting and Development, Denmark, for making the CONOPT library for the non-linear optimization available,
- Prof. Anton Eliassen from the Norwegian Meteorological Institute, Oslo, and Peringe Grennfelt from the Swedish Institute for Environmental Research, Gothenburg, for offering thoughtful comments on the modeling approach,
- David Simpson from the Nowegian Meteorological Institute for producing the large number of scenarios required as input to the regression analysis,
- Steffen Unger and Prof. Achim Sydow (GMD-FIRST, Berlin, Germany) for transferring the EMEP model to parallel computers,
- Jean-Paul Hettelingh and Max Posch from the Coordination Centre for Effects (CCE) at the National Institute for Public Health and the Environment (RIVM) in Bilthoven, Netherlands, for providing the data bases on ecosystems and population densities,
- Mark Barret from SENCO, UK, for assisting in the interpretation of the documents relating to the Auto/Oil 1 study,
- Martina Jöstl from IIASA's Computer and Publication Departments for providing crucial insight into excitingly unexpected and undocumented features of the 1997 vintage of the text processing software used for the production of this report,
- Martin Lutz and Ger Klaassen from DGXI for guidance in performing this study.

# Cost-effective Control
# of Acidification
# and Ground-level Ozone

## Table of Contents

# Table of Scenarios

| Scenario | Target type | | Page |
|---|---|---|---|
| 1990 | | 1990 emissions | 42 |
| REF | | Reference case (current legislation) for the year 2010 | 42 |
| MFR | | Maximum feasible reductions in the year 2010 | 42 |
| D1/1 | AOT60 - ceiling | Uniform ceiling of 3.25 ppm.hours | 57 |
| D1/2 | AOT60 - ceiling | Uniform ceiling of 3.0 ppm.hours | 57 |
| D1/3 | AOT60 - ceiling | Uniform ceiling of 2.75 ppm.hours | 57 |
| D2/1 | AOT60 - gap closure | 55 % gap closure | 64 |
| D2/2 | AOT60 - gap closure | 60 % gap closure | 64 |
| D2/3 | AOT60 - gap closure | 65 % gap closure | 64 |
| D3 | Combined AOT60 3.0 ppm.hours ceiling and 60 % gap closure | | 70 |
| D4/1 | AOT40 ceiling | Uniform ceiling of 10.5 ppm.hours | 74 |
| D4/2 | AOT40 ceiling | Uniform ceiling of 10.0 ppm.hours | 74 |
| D4/3 | AOT40 ceiling | Uniform ceiling of 9.5 ppm.hours | 74 |
| D5/1 | AOT40 - gap closure | 30 % gap closure | 77 |
| D5/2 | AOT40 - gap closure | 35 % gap closure | 77 |
| D5/3 | AOT40 - gap closure | 40 % gap closure | 77 |
| D6 | Combined AOT40 10.0 ppm.hours ceiling and 35 % gap closure | | 81 |
| D7 | Combined AOT60 3.0 ppm.hours ceiling and 60 % gap closure and AOT40 10.0 ppm.hours ceiling and 35 % gap closure | | 85 |

# 1 Introduction

There is substantial concern about the environmental impacts of air pollution on the local, regional and global scale. It has been shown that observed levels of various air pollutants can threaten human health, vegetation, wild life, and cause damage to materials. In order to limit the negative effects of air pollution, measures to reduce emissions from a variety of sources have been initiated.

Once emitted, many air pollutants remain in the atmosphere for some time before they are finally deposited on the ground. During this time, they are transported with the air mass over long distances, often crossing national boundaries. As a consequence, at a given site the concentration of pollutants and their deposition on the ground is influenced by a large number of emission sources, frequently in many different countries. Thus, action to efficiently abate air pollution problems has to be coordinated internationally.

Over the last decade several international agreements have been reached in Europe to reduce emissions in a harmonized way. Protocols under the Convention on Long-range Transboundary Air Pollution focus on reducing emissions of sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$) and volatile organic compounds (VOC). Several directives of the European Union prescribe emission standards for large combustion plants, for mobile sources, and limit the sulfur content in liquid fuels.

Most of the current agreements determine required abatement measures solely in relation to technical and economic characteristics of the sources of emissions, such as available abatement technologies, costs, historic emission levels, etc. No relation is established to the actual environmental impacts of emissions. For achieving overall cost-effectiveness of strategies, however, the justification of potential measures in relation to their environmental benefits must also be taken into account. Recently, progress has been made in quantifying the environmental sensitivities of various ecosystems. Critical loads and critical levels have been established reflecting the maximum exposure of ecosystems to one or several pollutants not leading to environmental damage in the long run. Such threshold values have been determined on a European scale, focusing on acidification and eutrophication as well as on vegetation damage from tropospheric ozone.

It is generally expected that the current policies on emission reductions will greatly reduce the levels of tropospheric ozone. However, the measures will not be sufficient to eliminate the problem everywhere in Europe. To meet the environmental long-term targets aiming at the protection of human health and vegetation, as they are currently discussed in the context of the Commission’s ozone strategy, further measures will be necessary. Since most of the low-cost options for abating emissions are already adopted in the current strategies, further action aiming at the sustainability of Europe’s ecosystems will have to embark on more costly measures. Cost-effectiveness will be an important argument for gaining acceptance of proposed policies.

## *1.1 Structure of this Report*

This Fourth Interim Report is a further step in a series of reports analyzing the features of cost-effective approaches to control European air quality. The first two Interim Reports to the European Commission focused on acidification-related aspects and provided input to the Commission's Acidification Strategy. The Third Interim Report drew attention to ground-level ozone and explored the implications of the different chemical regimes of ozone formation prevailing in Europe. Another important subject of the Third Interim Report was the treatment of the inter-annual meteorological variability in the context of strategy development.

This fourth report carries the analysis further and focuses on the crucial role of selecting appropriate environmental targets for an emission control strategy. The report reviews alternative principles for defining interim targets on the way towards the full achievement of environmental long-term goals and assesses the implications of these alternative concepts for the distribution of national emission reduction requirements and environmental benefits. In order to provide practical input for the discussions on the EU ozone strategy, the analysis identifies a range of possible environmental interim targets and explores the overall robustness of the resulting emission reductions implied by these illustrative targets.

It is planned to produce a Fifth Interim Report, which will then perform an extensive robustness analysis for an environmental interim target suggested by the Commission Services. This robustness analysis will explore, i.a.,

- the interaction of emission reductions targeted at ground-level ozone with acidification related strategies,
- the implications of alternative energy and agricultural scenarios for optimized allocation of emission reductions (taking into account a post-Kyoto scenario),
- the impacts of non-EU countries on required emission reductions within the EU,
- and possible alternative definitions of environmental targets.

After completion of the ongoing review process on input data used for cost calculations and the incorporation of the feedbacks into the model database, a comprehensive documentation of the revised databases is foreseen.

Section 2 of the report provides a summary of the basic methodology applied for the analysis and introduces the approach for the integrated assessment of ozone-related emission control strategies. The section also reviews the main assumptions on emission control options for $NO_x$ and VOC emissions. Section 3 discusses the main input data used for the analysis. Section 4 reviews the possible range of emission development between 1990 and 2010. This is determined on the one side by the emission control policies already adopted by the European countries and on the other side by the limits of the available emission control technologies.

The main part of the paper addresses alternative concepts for selecting appropriate environmental interim targets. Section 5 reviews the two major principles which could be used for effect-based strategies (priority to hot-spots or on general progress towards the long-term targets). The practical implications of these alternative concepts for health-related ozone control strategies are illustrated in Section 6. Section 7 repeats the analysis for vegetation-related strategies. The integration of both targets into one coherent strategy is presented in Section 8. The final Section 9 summarizes the findings of the scenario analysis, discusses various issues in relation to the robustness of the model results and draws conclusions from the exercise.

It is mentioned above that this Interim Report is the fourth in a series of reports to the Commission. It is in the nature of such a sequential approach that several aspects, which are important for the understanding of the analysis presented in this volume, were described in earlier reports. In the interest of providing a self-contained document, which offers a first-time reader a chance to follow the argumentation, the key parts of the methodology description are repeated. Although many of these elements were updated where necessary, a reader familiar with the earlier reports could focus his attention on the second part of the paper starting with Section 5. For convenience, Section 3.3 provides a brief summary of the most important changes introduced since the Third Interim Report.

# 2 Methodology

The recent progress in quantifying the sensitivities of ecosystems adds an important feature to the analysis and the development of cost-effective strategies to achieve and maintain emission levels that do not endanger the sustainability of ecosystems. Integrated assessment models are tools to combine information and databases on the economic, physical and environmental aspects relevant for strategy development.

## 2.1 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 2.1.

The European implementation of the RAINS model incorporates databases on energy consumption for 38 regions in Europe, distinguishing 22 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010 (Bertok *et al.*, 1994). Emissions of $SO_2$, $NO_x$, $NH_3$ and VOC for 1990 are estimated based on information collected by the CORINAIR 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).

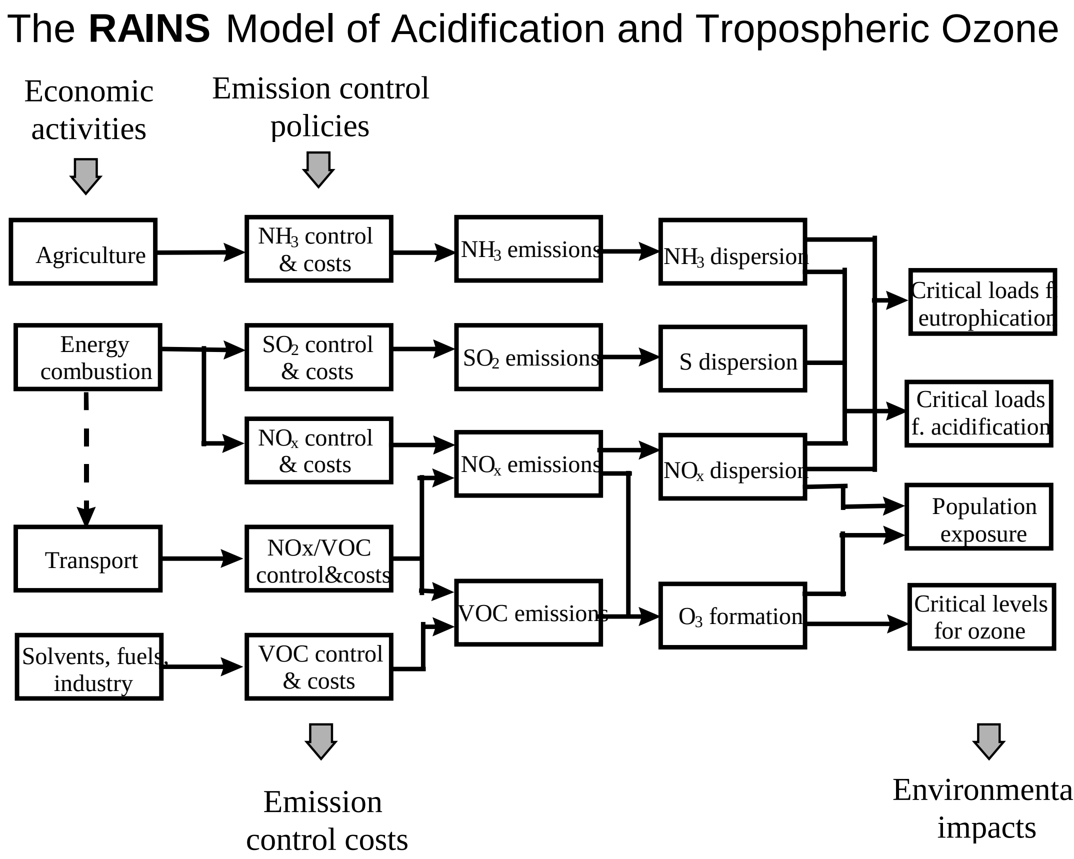

Figure 2.1: Schematic flowchart of the RAINS model framework

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 and was used for this study.

## *2.2 Scenarios of Emission Generating Anthropogenic Activities*

Inputs to the RAINS model include projections of future energy consumption on a national scale up to the year 2010. The model stores this information as energy balances for selected future years, distinguishing fuel production, conversion and consumption for 22 fuel types in six economic sectors. These energy balances are complemented by additional information relevant for emission projections, such as boiler types (e.g., dry bottom vs. wet bottom boilers), size distribution of plants, age structures, fleet composition of the vehicle stock, etc..

Agricultural activities are a major source of ammonia emissions, which in turn make a contribution to the acidification problem. Next to specific measures directed at limiting the emissions from livestock farming, the development of the animal stock is an important determinant of future emissions. The projections of future agricultural activities currently implemented in the RAINS model have been compiled from a variety of national and international studies on the likely development of the agricultural system in Europe.

The forecast of the future development of VOC emission generating activities is linked to other information on general economic development. About half of the anthropogenic emissions of VOC originates from combustion, extraction and distribution of fossil fuels. Therefore, the information on projected levels of fuel consumption in the countries of the UN/ECE region contained in RAINS is used to estimate future emissions of VOC from relevant sources, i.e. traffic, stationary combustion, extraction and distribution of fuels. The development of the other VOC emitting sectors in the EU is based on information provided in the reports to the European Commission on the development of the EU energy system between 1995-2020 (Capros *et al.*, 1997). The forecasts of GDP values in various industrial sectors, as well as population, were linked to the projected development in the sectors distinguished in the RAINS-VOC module. A similar exercise was performed for non-EU countries.

A detailed description of the actual projections used for this report is provided in Section 3.

## 2.3 Emission Estimates

The RAINS model estimates current and future levels of $SO_2$, $NO_x$, VOC and $NH_3$ emissions based on information provided by the energy- and economic scenario as exogenous input and on emission factors derived from the CORINAIR emission inventory (EEA, 1996), national reports as well as contacts with national experts. Emission estimates are performed on a disaggregated level, which is determined by the available details of the energy and agricultural projections and the CORINAIR emission inventory. The relations between CORINAIR categories and the RAINS sectors are shown in Table 2.1 to Table 2.3. Due to the differences in the format of the energy and agricultural statistics and CORINAIR, a direct and full comparison of RAINS estimates with CORINAIR data is only possible at a more aggregated level.

Considering the intended purposes of integrated assessment, the major criteria for aggregation are:

- Contribution to total emissions (compared to total European emissions and to emissions for a particular country). It was decided to aim for individual source categories in a share from 0.5 to 2 percent of total anthropogenic emissions;
- Possibility to define uniform activity rates and emission factors;
- 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 be constructed or derived;
- Availability and applicability of ‘similar’ control technologies;
- Availability of relevant data. Ultimately, the successful implementation of a VOC module will only be possible if the required data are available. As far as possible, emission related data should be compatible with the CORINAIR emission inventory.

Table 2.1: Main activity groups distinguished in the CORINAIR inventory and their relation to the sectors of the RAINS $SO_2/NO_x$ model

| **CORINAIR'90 category** | **CORINAIR'90 SNAP code** | **RAINS sectors** |
|---|---|---|
| Extraction and distribution of fossil fuels | 05 | Fuel production and Conversion - Combustion |
| | | Fuel production and Conversion - Losses |
| Public power and co-generation plants | 01 | Power Plants and district heating plants |
| Commercial, institutional and residential combustion plants | 02 | Households and other |
| Road transport | 07 | Transport - Road |
| Other mobile sources and machinery | 08 | Transport - Other (rail, inland water, coastal zone) |
| Combustion boilers, gas turbines and stationary engines | 0301 | Industry - Combustion in boilers |
| Industrial combustion (other than 0301) | 03-0301[1] | Industry - Other combustion |
| Production processes[2] | 04 | Industry - Process emissions[3] |

Table 2.2: Sectors in the RAINS module for mobile sources

| | **RAINS sectors** | **CORINAIR** |
|---|---|---|
| **Primary** | **Secondary** | **SNAP code** |
| **Road Transport** | Light duty trucks | 0702 |
| | Passenger cars | 0701 |
| | Gasoline evaporation | 0706 |
| | Trucks and busses | 0703 |
| | Motorcycles and mopeds | 0704-05 |
| **Other Transport** | Airports | 0805 |
| | Off-Road vehicles | 0801 |
| | Railways | 0802 |
| | Ships | 0803-04 |

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

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

[3] 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 2.3: Sectors in the RAINS VOC module for stationary sources

| **RAINS sectors** | | **CORINAIR** |
|---|---|---|
| **Primary** | **Secondary** | **SNAP code** |
| **Solvent Use** | Dry cleaning | 060202 |
| | Metal degreasing | 060201 |
| | Treatment of vehicles | 060407,9 |
| | Domestic solvent use (excluding paint) | 060408 |
| | Architectural painting | 060103 |
| | Domestic use of paints | 060104 |
| | Manufacture of automobiles | 060101 |
| | Other industrial use of paints | 060102 |
| | Products incorporating solvents | 060307-11 |
| | Products not incorporating solvents | 060301-05 |
| | *Pharmaceutical industry* | *060306* |
| | Printing industry | 060403 |
| | Application of glues, adhesives in industry | 060405 |
| | Preservation of wood | 060406 |
| | Other industrial use of solvents | 060401,2,4 |
| **Chemical Industry** | Inorganic chemical industry | 040401-09 |
| | Production processes in organic chemistry | 040501-21 |
| | Storage and handling of chemical products | 040522 |
| **Refineries** | Refineries - process | 040101-03 |
| | Refineries - storage | 040104 |
| **Fuel Extraction and Distribution** | Gaseous fuels - extr., loading and distr. | 0503,0506 |
| | Liquid fuels - extr., loading and distr. | 0502,0504 |
| **Gasoline Distribution** | Service Stations | 050503 |
| | Transport and Depots | 050501,2 |
| **Stationary Combustion** | Public power, cogeneration, district heat | 0101,0102 |
| | Industrial combustion | 0301-03 |
| | Commercial and residential combustion | 0200 |
| **Miscellaneous** | Stubble & other agricultural waste burning | 1003,0907 |
| | Cultures with and without fertilizers | 1001,1002 |
| | Food and drink industry | 040605-08 |
| | Other industrial sources | 0402,3,6,7 |
| | Waste treatment and disposal | 0901-04,6 |

### 2.3.1 Comparison of RAINS Emission Estimates for 1990 with other Inventories

Table 2.4 compares the 1990 estimates for $NO_x$ and VOC emissions incorporated into the RAINS model with the results from the CORINAIR 1990 inventory and with the EMEP database. As indicated above, RAINS generally uses information on emission factors provided by the CORINAIR'90 inventory. Consequently, $NO_x$ emission levels calculated by RAINS are usually in good agreement with CORINAIR'90 with the largest differences below five percent. The only exception is Greece, where CORINAIR estimates are more than 20 percent higher than RAINS. The reason is that the Greek submission to CORINAIR includes emissions from the total marine bunker fuel purchased in Greece, whereas the energy balances used in RAINS exclude marine bunkering from gross inland energy consumption. In reality, only a small portion of fuel purchased by sea vessels in Greece is used in the Greek coastal zone. EMEP estimates for the land-based sources in Greece (UN/ECE, 1995b) are much lower than CORINAIR results and are close to the RAINS estimates. Emission estimates for other economic sectors in Greece are in good agreement. Obviously, this issue requires further explanation with participation of national CORINAIR experts.

Efforts have been undertaken to harmonize the treatment of emissions from coastal shipping in the RAINS model. An attempt has been made to include coastal shipping into the national emissions for the respective countries, and to apportion emissions from international shipping into separate categories for the various regional seas. However, some issues require further clarification. For instance, there is still a discrepancy between the RAINS estimate and the official Swedish EMEP submission, which includes also emissions from the ferry traffic in the Baltic Sea. RAINS numbers are consistent with CORINAIR. Also emissions from off-shore oil platforms are also treated differently in different national emission inventories. Whereas the Norwegian inventory includes such emissions, they are not contained, e.g., in the UK database.

For VOC emissions, the differences between RAINS and CORINAIR estimates for the majority of countries lie within ten percent. Most of these differences result from corrections of obvious inconsistencies in the CORINAIR database, which were identified in cooperation with national experts. For example, corrections were applied inter alia in the following cases:

- The CORINAIR'90 database for Finland does not include estimates for domestic solvent use, residential combustion, wood preservation, as well as from some of the chemical industries;
- Hungary's CORINAIR database does not include emissions from the domestic use of paints;
- Italy is the only country that reports emissions of VOC from animal breeding. These emissions constitute the third largest source of VOC emissions in this country, contributing some 15 percent.
- According to CORINAIR, Poland's biggest single source of VOC emissions is the burning of stubble and other agricultural waste. Despite considerable uncertainties, the reported number seems to be too high by about one order of magnitude.

The CORINAIR'94 emission inventory, which became available recently, provides important additional information contributing to a better understanding of VOC emission sources. It is envisaged to further update the RAINS emission calculation using these new data.

Table 2.4: Comparison of RAINS 1990 emission estimates of $NO_x$ and VOC with results from the CORINAIR 1990 inventory and the EMEP database (in kilotons).

| | $NO_x$ | | | VOC | | |
|---|---|---|---|---|---|---|
| | RAINS | EMEP | CORINAIR'90 | RAINS | EMEP | CORINAIR'90 |
| Albania | 24 | 24 | n.a. | 30 | 32 | n.a. |
| Austria | 236 | 222 | 227 | 430 | 418 | 404 |
| Belarus | 402 | 285 | n.a. | 279 | 533 | n.a. |
| Belgium | 362 | 352 | 343 | 343 | 332 | 364 |
| Bosnia-H | 80 | 80 | n.a. | 46 | 101 | n.a. |
| Bulgaria | 354 | 376 | 361 | 200 | 187 | 189 |
| Croatia | 83 | 83 | n.a. | 79 | 105 | 97 |
| Czech R. | 522 | 742 | 773 | 322 | 435 | 253 |
| Denmark | 271 | 269 | 273 | 165 | 175 | 167 |
| Estonia | 84 | 73 | 72 | 44 | 23 | 50 |
| Finland | 279 | 300 | 269 | 206 | 209 | 165 |
| France | 1620 | 1585 | 1585 | 2145 | 2393 | 2393 |
| Germany | 2644 | 2640 | 2980 | 3116 | 3155 | 2937 |
| Greece | 392 | 392 | 543 | 302 | 293 | 312 |
| Hungary | 214 | 238 | 191 | 206 | 205 | 148 |
| Ireland | 107 | 115 | 116 | 111 | 102 | 102 |
| Italy | 1998 | 2047 | 2041 | 1846 | 2080 | 2002 |
| Latvia | 114 | 90 | 93 | 52 | 63 | 47 |
| Lithuania | 151 | 158 | 158 | 105 | 111 | 108 |
| Luxembourg | 21 | 23 | 23 | 18 | 19 | 19 |
| Netherlands | 539 | 575 | 537 | 481 | 420 | 452 |
| Norway | 231 | 227 | 232 | 300 | 299 | 270 |
| Poland | 1209 | 1279 | 1445 | 709 | 797 | 971 |
| Portugal | 208 | 221 | 215 | 217 | 202 | 202 |
| Moldova | 87 | 39 | n.a. | 52 | 11 | n.a. |
| Romania | 513 | 546 | 546 | 488 | 568 | 571 |
| Russia | 3485 | 2675 | n.a. | 3332 | 3566 | n.a. |
| Slovakia | 207 | 227 | 227 | 143 | 149 | 150 |
| Slovenia | 60 | 57 | 57 | 60 | 35 | 35 |
| Spain | 1159 | 1178 | 1247 | 1062 | 1051 | 1044 |
| Sweden | 344 | 411 | 345 | 432 | 526 | 451 |
| Switzerland | 161 | 165 | 159 | 288 | 284 | 282 |
| FYR Macedonia | 39 | 39 | n.a. | 20 | 7 | n.a. |
| Ukraine | 1888 | 1097 | n.a. | 1074 | 1079 | n.a. |
| United Kingdom | 2664 | 2897 | 2773 | 2661 | 2623 | 2602 |
| F.Yugoslavia | 211 | 66 | n.a. | 124 | 66 | n.a. |
| | | | | | | |
| Atlantic Sea | 910 | 910 | n.a. | 0 | n.a. | n.a. |
| Baltic Sea | 80 | 80 | n.a. | 0 | n.a. | n.a. |
| North Sea | 638 | 638 | n.a. | 0 | n.a. | n.a. |
| | | | | | | |
| Total | 24591 | 23421 | n.a. | 21488 | 22654 | n.a. |

It is important to mention that when calculating ozone concentrations, the EMEP model internally calculates natural and agricultural emissions of VOC as a function of temperature, land use, etc. On the other hand, the agricultural emissions are also fully included in the CORINAIR estimates (sector 10). In order to avoid double-counting of these emissions, the RAINS calculations presented later on exclude these emissions from the anthropogenic sources (and the cost curves). Consequently, the numbers presented in the remainder of this paper refer only to anthropogenic sources and are not directly comparable with the CORINAIR estimates for 1990.

## 2.4 Emission Control Options and Costs

Although there is a large variety of options to control emissions, an integrated assessment model focusing on the pan-European scale has to restrict itself to a manageable number of typical abatement options in order to estimate future emission control potentials and costs. Consequently, the RAINS model identifies for each of its application areas (i.e., emission source categories considered in the model) a limited list of characteristic emission control options. For each of these measures, the model extrapolates the current operating experience to future years, taking into account the most important country- and situation-specific circumstances modifying the applicability and costs of the techniques.

For each of the available emission control options, RAINS estimates the specific costs of reductions, taking into account investment-related and operating costs. Investments are annualized over the technical lifetime of the pollution control equipment, using a discount factor of four percent. The technical performance as well as investments, maintenance and material consumption are considered to be technology-specific and thereby, for a given technology, equal for all European countries. Fuel characteristics, boiler sizes, capacity utilization, labor and material costs (and stable sizes and applicability rates of abatement options for ammonia) are important country-specific factors influencing the actual costs of emission reduction under given conditions. A detailed description of the methodology adopted to estimate emission control costs can be found in Amann (1990), Cofala *et al.* (1997), Klimont *et al.* (1998) and Klaassen (1991b).

The databases on emission control costs have been constructed based on the actual operating experience of various emission control options documented in a number of national studies (e.g., Schärer, 1993) as well as in reports of international organizations (e.g., OECD, 1993; Takeshita, 1995; Rentz *et al.*, 1987). Country-specific information has been extracted from relevant national and international statistics (UN/ECE, 1996). The list of control options for $NO_x$, $NH_3$ and VOC and the country-specific data used for the cost calculations were presented to the negotiating parties of the Convention on Long-range Transboundary Air Pollution for review.

### 2.4.1 Control Options for Reducing $NO_x$ Emissions and their Costs

Table 2.5 to Table 2.9 present the options for controlling $NO_x$ emissions as contained in the RAINS database. Data for mobile sources have been derived from various reports developed within the Auto/Oil program (European Commission, 1996, Touche-Ross & Co., 1995) and from other national and international sources (i.a., Gorißen, 1992, HMSO, 1994, McArragher *et al.*, 1994, Rodt *et al.*, 1995, UN/ECE, 1994b, UN/ECE 1994c). The assistance of consultants participating in the Auto/Oil study helped to incorporate also the suggested measures on fuel quality improvement and inspection and maintenance schemes into the RAINS model in a fully consistent way (Barrett, 1996).

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.

Table 2.5: Control options for $NO_x$ emissions from the power plant sector considered in RAINS

| **Sector/control option** | **Removal efficiency [%]** | **Costs[4]** | |
|---|---|---|---|
| | | **Investment [ECU/$MW_{th}$]** | **Operating and maintenance [%/year][5]** |
| ***Retrofits of existing boilers:*** | | | |
| Combustion modification and Primary measures (CM)[6] | | | |
| Brown coal and lignite | 65 | 6.8 | - |
| Hard coal | 50 | 3.9 | - |
| Heavy fuel oil | 65 | 4.7 | - |
| Gas | 65 | 5 | - |
| CM + selective cat. reduction (SCR) | | | |
| Brown coal and lignite | 80 | 24.8 | 6 |
| Hard coal | 80 | 19.6 | 6 |
| Heavy fuel oil | 80 | 21.8 | 6 |
| Gas | 80 | 23.6 | 6 |
| ***New boilers*** [7] | | | |
| SCR | | | |
| Brown coal and lignite | 80 | 10.0 | 6 |
| Hard coal | 80 | 8.8 | 6 |
| Heavy fuel oil | 80 | 8.7 | 6 |
| Gas | 80 | 11.8 | 6 |

---

[4] Values are for typical boilers for each source category.

[5] Percent of investment cost per year

[6] Combination of various measures (e.g., low $NO_x$ burners, overfire air, etc.)

[7] Low-NOx burners are assumed by default; thus, new boilers have lower emission factors than the existing ones

Table 2.6: Control options for $NO_x$ emissions from industrial boilers considered in RAINS

| **Sector/control option** | **Removal efficiency [%]** | **Costs**[8]<br>**Investment [ECU/MW$_{th}$]** | <br>**Operating and maintenance [%/year]**[9] |
|---|---|---|---|
| Combustion modification and Primary measures (CM) | | | |
| Brown coal and lignite | 50 | 5.6 | - |
| Hard coal | 50 | 5.6 | - |
| Heavy fuel oil | 50 | 5.0 | - |
| Medium distillates and gas | 50 | 5.7 | - |
| CM + Selective Non-catalytic Reduction (SNCR) | | | |
| Brown coal and lignite | 70 | 11.0 | 6 |
| Hard coal | 70 | 11.0 | 6 |
| Heavy fuel oil | 70 | 9.1 | 6 |
| Gas | 70 | 10.6 | 6 |
| CM + Selective Catalytic Reduction (SCR) | | | |
| Brown coal and lignite | 80 | 21.9 | 6 |
| Hard coal | 80 | 21.9 | 6 |
| Heavy fuel oil | 80 | 17.4 | 6 |
| Gas | 80 | 20.3 | 6 |

Table 2.7: Control options for $NO_x$ emissions from the residential and commercial sector and from ships

| **Sector/control option** | **Removal efficiency [%]** | **Costs**[10]<br>**Investment [ECU/MW$_{th}$]** | <br>**Operating and maintenance [%/year]**[11] |
|---|---|---|---|
| **Residential and commercial sector**[12] | | | |
| Combustion modification, low-$NO_x$ burners (CM) | | | |
| Heavy fuel oil | 50 | 5.6 | - |
| Medium distillates | 30 | 12 | - |
| Natural gas | 50 | 16.3 | - |
| **Ships** | | | |
| SCR | 80 | 25 | 6 |

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[8] Values are for typical boilers for each source category.

[9] Percent of investment cost per year

[10] Values are for typical boilers for each source category.

[11] Percent of investment cost per year.

[12] Weighted average for residential and commercial sector. Unit control costs for gas and gas oil fired boilers in commercial sector are 40 - 50 % lower.

Table 2.8: Control options for $NO_x$ emissions from industrial processes

| Control option | Removal efficiency [%] | Costs [ECU/t $NO_x$] |
|---|---|---|
| Stage 1 | 40 | 1000 |
| Stage 2 | 60 | 3000 |
| Stage 3 | 80 | 5000 |

Table 2.9: Control options for $NO_x$ and VOC emissions from mobile sources considered in RAINS

| Fuel/vehicle type/control technology | Removal efficiency $NO_x$/VOC [%] | Costs Investments [ECU/vehicle] | Costs Operating and maintenance [%/year][13] |
|---|---|---|---|
| **Gasoline 4-stroke passenger cars and LDV**[14] | | | |
| 3-way catalytic converter - 1992 standards | 77/77 | 250 | 24 |
| 3-way catalytic converter - 1996 standards | 88/88 | 300 | 20 |
| Advanced converter with maintenance schemes - EU 2000 standard | 94/94 | 715 | 8.4 |
| Advanced converter with maintenance schemes - EU 2005 standard (**) | 97/97 | 1130 | 5.3 |
| **Diesel passenger cars and LDV** | | | |
| Combustion modification - 1992 standards | 30/30 | 150 | 36.0 |
| Combustion modification - 1996 standards | 49/49 | 275 | 19.5 |
| Advanced combustion modification with Maintenance schemes - EU 2000 standards | 59/59 | 780 | 6.9 |
| $NO_x$ converter(**) | 80/80 | 1285 | 4.2 |
| **Heavy duty vehicles** | | | |
| Euro I - 1993 standards | 32/35 | 600 | 46 |
| Euro II - 1996 standards | 42/46 | 1800 | 15 |
| Euro III - EU 2000 standards with Maintenance schemes | 59/65 | 4047 | 6.8 |
| Euro IV ($NO_x$ converter) (**) | 85/93 | 15000 | 1.8 |

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

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[13] Percent of investment cost per year.

[14] LDV - light duty vehicles.

### 2.4.2 Options for Reducing VOC Emissions and their Costs

The emissions of VOC originate both from mobile and stationary sources. Emission reduction measures for the mobile sources are described in the section on nitrogen oxides as they are the same as for controlling VOC emissions. The only exceptions are carbon canisters; although in reality they are installed in vehicles, they are included in the “stationary” part of the model.

A number of sources describe the available options for controlling VOC emissions from stationary sources, i.a., Jourdan and Rentz (1991), EPA (1994), OECD (1990, 1992). EEC (1990), ERM (1996), Hein *et al.* (1994), CONCAWE (1987-1990), KWS 2000 (1989-1995), VROM (1997) etc. However, it is important to understand that the choice of a certain technology will not only depend on the availability of the technology, but will also be strongly determined by the applicability in a given situation.

Commonly employed methods for reducing VOC emissions from stationary sources include modification of the production process or storage tanks, improvement of the management practices (e.g., good housekeeping, leak monitoring and repair programs), solvent substitution, and finally add-on technologies, such as thermal or catalytic incineration, adsorption, absorption, condensation/refrigeration, and bio-oxidation. Major reduction measures and RAINS-VOC sectors to which they apply are listed in Table 2.10. Note that the listed efficiencies refer to the assumed technical efficiency of the option. In reality, the most efficient options in a sector often have only limited applicability.

The applicability of a given technology for the processes aggregated within a sector in the RAINS model is a very important element of the abatement module. There are many reasons for differences in applicability:

- In many cases the applicability will depend more on the characteristics of a specific source of emissions (e.g., drying oven) rather than on the type of the source category (e.g., automobile manufacturing/ surface coating);
- Some sectors, e.g., printing, include several processes, such as rotogravure, flexography, lithography, letterpress, and the applicability of a selected technology depends on the parameters of the specific process;
- The size distribution of the installations considered in a given category;
- Reformulated products may not be available for all applications within a given source category;
- Variable parameters of emission streams, e.g., too low or too high concentrations of VOC in the stream gas or too low or high flow rates limiting the application of particular add-on techniques such as oxidation/incineration;
- Mixture of solvents used in the process, making some of the add-on technologies less effective or economic, e.g., carbon adsorption, condensation.

Table 2.10: Major categories of abatement measures for stationary sources distinguished in the RAINS VOC model

| ***Sector*** | ***Technology*** | ***Efficiency*** ***[%]*** | ***Cost range*** ***[ECU/t VOC]*** |
|---|---|---|---|
| **Solvent use** | | | |
| Dry Cleaning | Good housekeeping and adsorption | 60 | ~600 |
| | Closed circuit conventional or new machines | 75/92 | 600/1200-4150 |
| Metal degreasing | Basic emission management techniques | 20 | < 200 |
| | Carbon adsorption | 80 | 1400-2000 |
| | Low temperature plasma process | 98 | 1600-3300 |
| | Conveyored degreaser with integrated adsorption | 95 | 1800-2300 |
| | Water based systems | 95 | 2700-4500 |
| Domestic solvent use | Substitution, Propelant insert | 30-50 | 3600-4300 |
| Non-industrial paint use | Water based paints | 80 | 600-850 |
| | High solids | 50-60 | 1850-2200 |
| | Powder paints | 100 | 1000-1300 |
| Industrial paint use | Good housekeeping , application technique modification | 20-45 | <100 |
| | Process modification and substitution | 55-70 | 1000-2500 |
| | Adsorption, Incineration | 95 | 1800-10000 |
| Vehicle refinishing | Good housekeeping , application technique modification | 15-30 | < 0 |
| | Housekeeping, application technique, water based paint | 75 | 150-650 |
| Products incorporating solvents | Substitution | 50 | <50 |
| | Basic emission management and end-of-pipe | 95 | 1200-2000 |
| Products not incorporating solvents | Solvent management plan and substitution | 50 | ~500 |
| | Basic emission management and end-of-pipe | 60 | ~1800 |
| Printing | Good housekeeping | 5 | <50 |
| | Water based inks | 90 | <100 |
| | Adsorption, Incineration | 90 | 300-1700 |
| Glues and adhesives in industry | Good housekeeping | 15 | <50 |
| | Substitution | 85 | ~500 |
| | Incineration | 80 | 800-1000 |
| Preservation of wood | Double vacuum impregnation & dryer enclosure | 40 | ~2800 |
| | as above plus end-of-pipe | 75 | 4300-7500 |
| Other industrial use of solvents | Process modification and biofiltration | 75 | ~600 |
| **Chemical industry** | | | |
| Organic chemical industry, processing and storage | Quarterly, monthly inspection and maintenance programs | 60/70 | ~1600/~6000 |
| | Flaring | 85 | ~350 |
| | Incineration | 96 | ~800 |
| | Internal floating covers and secondary seals | 90 | ~2800 |
| | Vapor recovery units | 95-99 | 5600-6200 |
| Pharmaceutical industry | Good housekeeping and end-of-pipe | 87 | 1500-2150 |
| **Refineries** | Quarterly, monthly inspection and maintenance programs | 60/70 | <200/500-1500 |
| | Covers on oil/water separators | 90 | 100-300 |
| | Internal floating covers and secondary seals | 85 | <400 |
| | Vapor recovery units (Stage IA) | 95-99 | 750-3700 |
| **Liquid fuel extraction and distribution** | | | |
| Fuel extraction, loading and transport | Venting alternatives and increased recovery | 90 | 1800-2200 |
| | Improved ignition system on flares | 62 | 4500-5500 |
| | Vapor balancing on tankers and loading facilities | 70 | 50-200 |
| Fuel distribution | Internal floating covers and secondary seals | 85 | <400 |
| | Vapor recovery units (Stage IA) | 95-99 | 750-3700 |
| | Stage II | 85 | 1300-1800 |
| | Stage IB | 95 | 300-450 |
| **Gasoline evaporation** | Small carbon canister | 85 | 100-500 |
| **Miscellaneous** | | | |
| Food and drink industry | End-of-pipe | 90 | 14000 |
| Agriculture | Ban on burning waste | 100 | 60 |
| Other industrial | Good housekeeping | 20 | <100 |
| | End-of-pipe | 98 | 10000 |
| Waste disposal | Improved landfills | 20 | 400 |

## *2.5 Atmospheric Source-Receptor Relationships for Tropospheric Ozone*

### 2.5.1 Modelling Ozone Formation

The formation of ozone involves chemical reactions between $NO_x$ and VOC driven by solar radiation and occurs on a regional scale in many parts of the world. The time scale of ozone production is such that ozone concentrations build up in polluted air over several days under suitable weather conditions, and this pollutant and its precursors can be transported over considerable distances and across national boundaries. An integrated assessment model for ozone needs to be able to relate ozone exposure to changes in the emissions of ozone precursors.

For application in an integrated assessment model for ozone, the source-receptor relationships need to be valid for a variety of spatial patterns of emission sources and for a range of emission levels, and not restricted to the present-day situation alone. For this reason, attempts to define these relationships solely on the basis of recent ozone measurement data are likely to prove inadequate. Instead, the ozone formation description needs to be based on mathematical models that have gained widespread international acceptance.

Within the framework of an integrated assessment model, source-receptor relationships must be computationally efficient to enable the numerous scenario runs for analyzing costs and benefits from a wide range of control strategies. Furthermore, extended uncertainty and robustness analyses will be necessary to derive solid conclusions from the model, taking into account the gaps and imperfections of the available databases and models. In many cases, methodologies for such analyses require sufficiently simple formulations of the underlying models. In addition, optimization analysis has proven to be a powerful feature in the integrated assessment process for the Second Sulfur Protocol. Optimization of the entire chain from the sources of emissions, over the costs for controlling them, up to the regional impacts on ozone levels, however, also requires sufficiently simple source-receptor relationships.

Most of the available models for ozone formation are process-oriented and contain a considerable degree of detail of the chemical mechanisms and meteorological factors relevant for ozone formation. Consequently, their computational complexity makes it impossible to use them directly within the framework of an integrated assessment model. In order to overcome this gap, an attempt has been made to construct a ‘reduced-form’ model, using statistical methods to summarize the reaction of a more complex ‘reference’ model.

To this end, the work was carried out in collaboration with EMEP’s Meteorological Synthesizing Centre-West, and the results of the EMEP ozone model (Simpson, 1993) provide the basis on which the reduced-form model has been built. The EMEP model has been selected for this analysis, i.a., because (i) it has repeatedly undergone extensive peer review and its structure and results have been compared with other ozone models, and (ii) the EMEP model is readily available for calculating ozone levels over all of Europe over a time period of six months, and the calculation of the necessarily large number of scenarios is a practical proposition with this model.

### 2.5.2 Ozone Isopleth Diagrams

Before starting the development of the simplified model, the EMEP ozone model was used to investigate the relationships in different areas of Europe between mean boundary layer ozone concentrations and changes in the emissions of $NO_x$ and VOCs. A convenient way to illustrate the results of these investigations is by means of ozone isopleth diagrams (Figure 2.2). Such diagrams have been most commonly used, particularly in North America, to show how maximum ozone concentrations depend on the initial concentrations of $NO_x$ and VOCs on a particular day at a specific location. Lines of constant value, or isopleths, of the maximum ozone concentrations are constructed by connecting points having the same ozone concentration but corresponding to various initial conditions. Ozone isopleth diagrams in this form provide a concise representation of the effect of reducing initial $NO_x$ and VOC concentrations on peak ozone concentrations. In the past, they have been used quantitatively to develop ozone control strategies as part of the U.S. EPA's empirical kinetic modeling approach (EKMA).

The isopleth diagrams used in this section are constructed rather differently, although there are obvious similarities in appearance. Firstly, the ozone statistic depicted by the isopleths is the mean, over the six-month summer period, of the early afternoon ozone concentrations calculated by the EMEP model. Secondly, in the version used here, ozone is shown as a function of the percentage reduction in emissions of $NO_x$ and VOC across Europe. Thus, the top right-hand corner of each diagram represents the base case without any reduction in precursor emissions.

In areas with sufficiently high emission densities, i.e., in the north-west of Europe, the isopleths form a ridge dividing the diagram into two areas (Figure 2.2b). On the left of the ridge, corresponding to the greatest reductions in $NO_x$ emissions, the system tends towards the $NO_x$ -limited case). On the right of the ridge, the $NO_x$ / VOC ratio is relatively high and the $NO_2$ concentrations are sufficiently great that $NO_2$ competes with VOC for reaction with the OH radical. In this region of the diagram, reducing VOC emissions results in lower ozone concentrations; to a large extent, ozone shows a linear dependence on VOC emission changes (Simpson, 1992). However, ozone concentrations may be increased, at least initially, by $NO_x$ reductions in the absence of concurrent reductions in VOC emissions.

For regions with lower emission densities, reductions in VOC emissions are seen to exert only a minor influence on mean ozone concentrations (Figure 2.2a). In these regions the $NO_x$ / VOC ratio is relatively low and there is an ample supply of peroxy radicals ($RO_2$ and $HO_2$) to convert NO to $NO_2$ and, thus, lead to ozone production. Decreasing the available $NO_x$ leads directly to a decrease in ozone. In these circumstances, ozone formation is limited by the availability of $NO_x$, and the atmospheric chemistry system is said to be $NO_x$-limited. In such regions, reductions in emissions of $NO_x$ are likely to be effective in reducing ozone concentrations, but ozone is relatively insensitive to reductions of VOC, and to changes in the VOC species distribution, at constant $NO_x$.

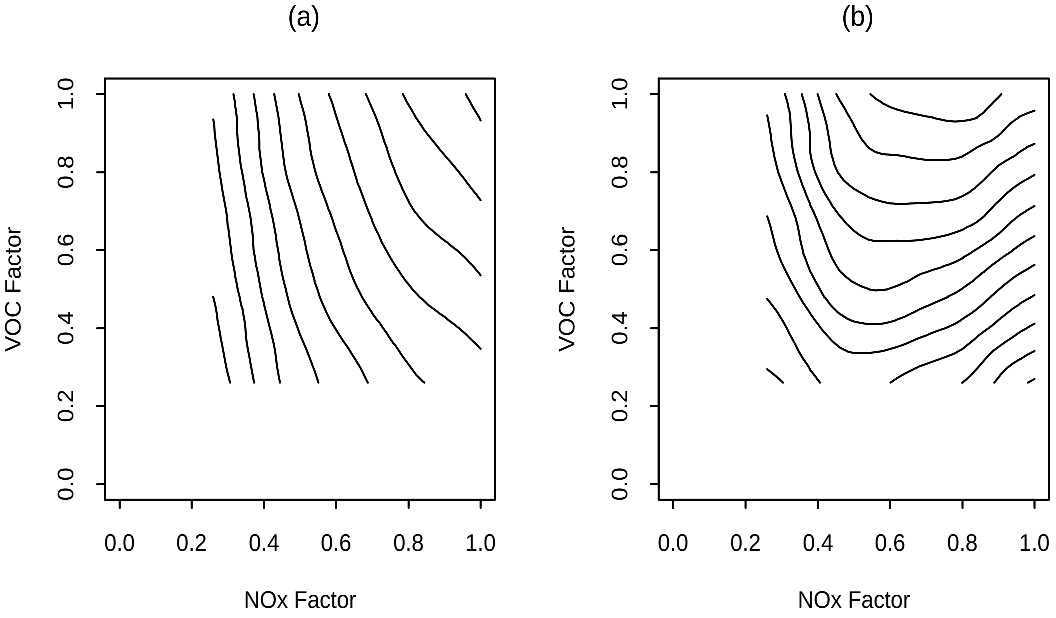

Figure 2.2: Typical patterns of ozone behaviour in Europe. The left isopleth sketches the situation for a NO$_x$ limited region’ in Europe, while the other illustrates the ‘ozone hill’ occurring in high-NO$_x$ areas.

### 2.5.3 A ‘Reduced Form’ Model of Ozone Formation

On the basis of the ideas outlined above a general formulation for the reduced-form "seasonal" model was developed. In subsequent sections the following abbreviations are used for model variables:

$v_i$ - annual national emissions of non-methane VOCs from emitter country i
$n_i$ - annual national emissions of NO$_x$ from emitter country i
$ev_j$ - "effective" emissions of VOCs, including natural sources, at receptor j
$en_j$ - "effective" emissions of NO$_x$, including natural sources, at receptor j
$evn_j$ - "effective" natural emissions of VOCs at receptor j
$enn_j$ - "effective" natural emissions of NO$_x$ at receptor j

The long-term ozone exposure at receptor *j*, $AOT_j$, is assumed to be a function of the non-methane VOC and NO$_x$ emissions, $v_i$ and $n_i$ respectively, from each emitter country *i*, and the mean "effective" emissions (of NO$_x$ and VOCs), $en_j$ and $ev_j$, experienced at the receptor over the period in question. The general model formulation adopted is:

$$AOT_{lj} = k_j + \sum_{i=1}^{M}( a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^{2}) + \alpha_j \overline{en}_j^{\,2} + g(\overline{en}_j, V) + \overline{en}_j \sum_{i=1}^{M} h_{ij}n_i \tag{1}$$

where *M* is the number of emitter countries considered,

$$V = \{v1, v2, ...., vM\}, \tag{2}$$

and the non-linear function *g()* is given either by:

$$g(\overline{en}_j, V) = \overline{en}_j \sum_{i=1}^{M} d_{ij} v_i \tag{3}$$

or by:

$$g(\overline{en}_j, V) = \beta_j \overline{en}_j \overline{ev}_j \tag{4}$$

The mean "effective" emissions are given by:

$$\overline{en}_j = \sum_{i=1}^{M} \overline{E_{ij}} n_i + \overline{enn_j} \tag{5}$$

$$\overline{ev}_j = \sum_{i=1}^{M} \overline{F_{ij}} v_i + \overline{evn_j} \tag{6}$$

where $E_{ij}$, $F_{ij}$ depend on the meteorology and are obtained from EMEP model calculations, and $enn_j$ and $evn_j$ represent the "effective" natural emissions of $NO_x$ and VOCs, respectively.

For the initial stages of evaluating this model, an heuristic approach was taken to decide which terms, if any, could be dropped from the model. Such experiments led to the conclusion that the following linear regression model contained sufficient information for the present purpose:

$$AOT_{lj} = k_j + \sum_{i=1}^{M} ( a_{ij} v_i + b_{ij} n_i + c_{ij} n_i^2 ) + \alpha_j \overline{en}_j^{\,2} + \overline{en}_j \sum_{i=1}^{M} d_{ij} v_i \tag{7}$$

In order to decide which emitter countries should be included in the model, the emitter countries were ranked (i) on the basis of their contribution to the "effective" $NO_x$ emissions experienced at each receptor *j*, and (ii) by how great an ozone reduction was achieved for a given fractional VOC reduction. The most influential twelve countries were included in the equation, i.e. *M* was set equal to 12. This choice was based on an assessment of the EMEP model results for a small number of receptor sites, in an attempt to include in the simplified model all the most influential emitter countries (for a given receptor) yet exclude those which had very little effect.

The formulation of the reduced-form model given in Equation 7 above has been used in the construction of models for 598 European receptor grids.

It is of interest to relate the terms of Equation 7 to the physical and chemical processes that determine ozone formation in the atmosphere. Possible interpretations are:

| | |
|---|---|
| $k_j$ | includes the effects of background concentrations of $O_3$ and its precursors, and natural VOC emissions; |
| $a_{ij}v_i$ | provides the linear country-to-grid contribution from VOC emissions in country *i*, allowing for meteorological effects; |
| $b_{ij}n_i$ | provides the linear country-to-grid contribution from $NO_x$ emissions in country *i*, allowing for meteorological effects; |
| $\alpha_j en_j^2$ | takes account of the average non-linearity (in the $O_3$ / $NO_x$ relationship) experienced along trajectories arriving at receptor *j* and any non-linear effects local to that receptor; |
| $c_{ij}n_i^2$ | serves essentially as a correction term to allow for non-linearities occurring close to high $NO_x$ emitter countries; |
| $d_{ij}en_jv_i$ | allows for interactions between $NO_x$ and VOCs along the trajectories. |

The coefficients $a_{ij}$, $b_{ij}$, $c_{ij,\,,}$ , $d_{ij}$ and $\alpha_I$ are estimated by the linear regression, and $n_i$, $v_i$ and $en_j$ are used as variables. The coefficients $a_{ij}$ and $b_{ij}$ may also be regarded as a composite source-receptor matrix.

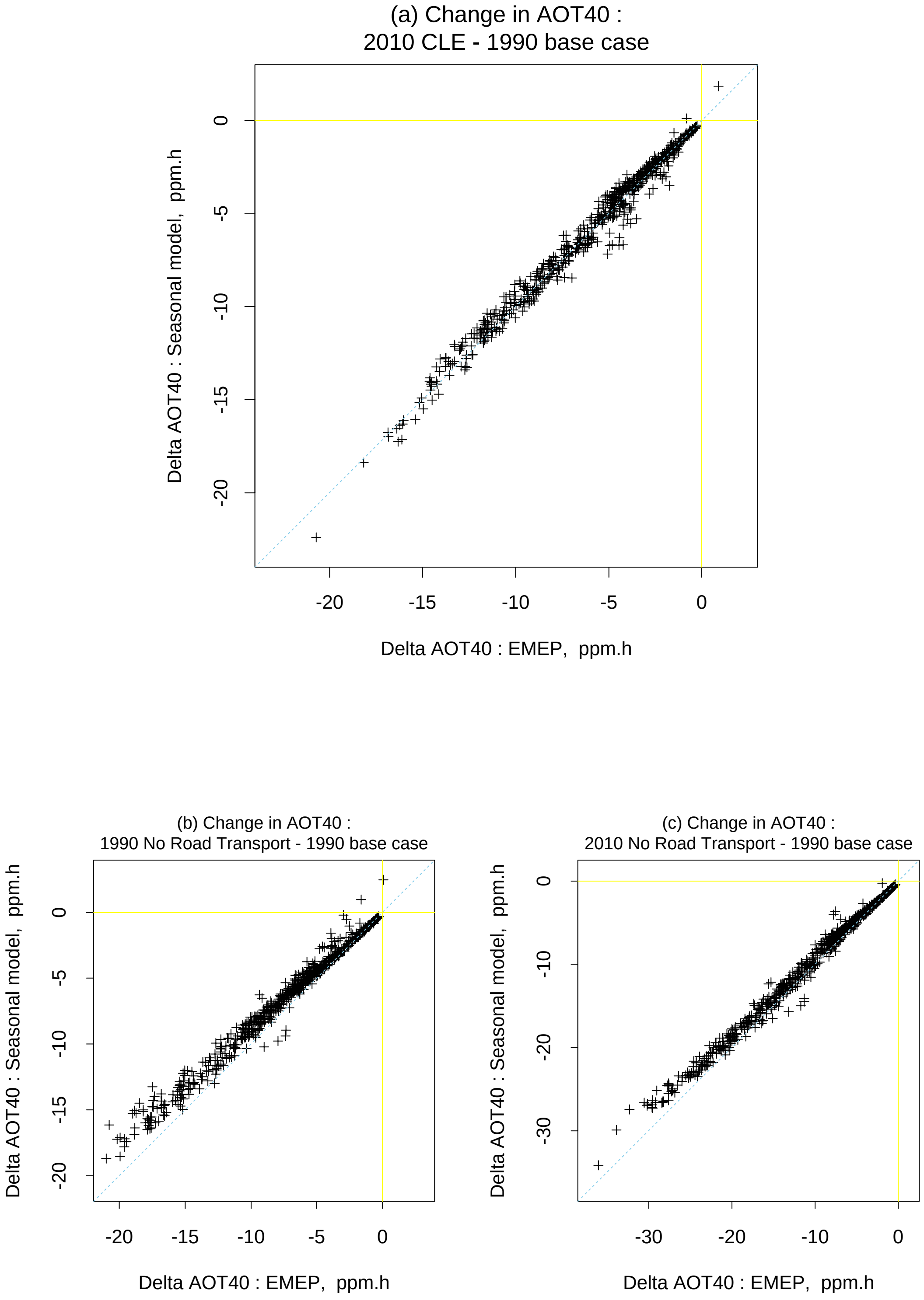

Figure 2.3: Comparison of the results from the reduced-form model for three scenarios with the corresponding EMEP model calculations

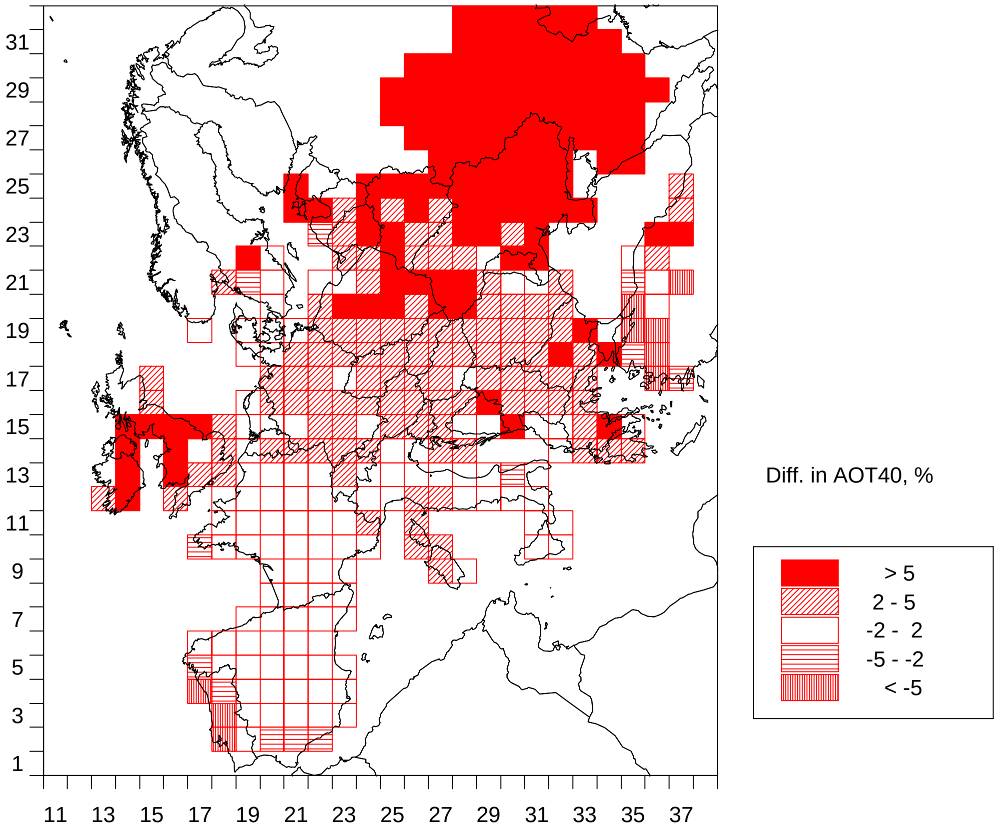

Figure 2.4: Spatial distribution of differences between a reduced-form and the full EMEP models for those receptor grids at which the 1990 base case AOT40 value for forests - as calculated using the 1995 version of the EMEP model - exceeds the critical level of 10 ppm.hours.

## *2.6 Optimization*

The optimization mode of integrated assessment models can be a powerful tool in the search for cost-effective solutions to combat an air pollution problem. In the RAINS-acidification model, optimization techniques have been used to identify the cost-minimal allocation of resources in order to reduce the gap between current sulfur deposition and the ultimate targets of full critical loads achievement.

In the case of tropospheric ozone, a systematic search for cost-effectiveness appears even more attractive. The facts that several pollutants ($NO_x$ and VOC emissions) are involved, and that important non-linearities between precursor emissions and ozone levels have been recognized, cut the likelihood of 'intuitive' solutions being identified in the scenario analysis mode.

Emissions are analyzed for sets of emitters that are located in a region, which is typically a country. $NO_x$ and VOC emitters are further subdivided into sectors in order to account for measures that can be applied for sources that belong to one sector. In such a case emitters that belong to a particular sector emit either $NO_x$ or VOC or a linear combination of them.

For simple cost-minimization, the optimization problem can be formulated as

$$\sum_{i=1}^{N} c_i(n_i, v_i) \longrightarrow \min \qquad (8)$$

The country cost curves $c_i(n_i,v_i)$ are constructed from the sectoral cost curves $c_{is}(e_{is})$.

$$c_i(n_i, v_i) = \min \sum_{s=1}^{S} c_{is}(e_{is}) \qquad (9)$$

constrained to

$$n_i = \sum_{s=1}^{S} n_{is} \qquad (10)$$

$$v_i = \sum_{s=1}^{S} v_{is} \qquad (11)$$

where *s* denotes the sector and :

$e_{is}$ … sectoral emissions
$n_{i1}=e_{i1}$
$v_{i1}=0$
$n_{i2}=0$
$v_{i2}=e_{i2}$
$n_{is}=e_{is}$ $\qquad s>2$
$v_{is}=\mu_{is} + ß_{is}\, e_{is}$

The ozone exposure is defined by

$$AOT_{lj} = k_j + \sum_{i=1}^{M}( a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^{2} ) + \alpha_j \overline{en}_j^{\,2} + \overline{en}_j \sum_{i=1}^{M} d_{ij}v_i \qquad (12)$$

and it is constrained at each receptor by

$$AOT_{lj} - y_{lj} \le AOT_{lj}^{\max} \qquad (13)$$

As will be shown later in ths report, a ’compensation mechanism has been developed allowing the optimization to exceed environmental targets at single grid cells as long as the excess is compensated by further reductions at other grids in the same country. Therefore, violations *y* of targets are constrained by corresponding lower and upper limits specified for each target type and for each grid:

$$y_{lj}^{\min} \le y_{lj} \le y_{lj}^{\max} \qquad (14)$$

A grid is only allowed to violate the target, if another grid j in the same country I is compensating for this violation. Therefore, violations of targets have to be balanced (over receptors belonging to the ith country) with over-achievements of targets:

$$\sum_{l=1}^{L} \sum_{j=1}^{J} wo_{ijl}\, y_{lj} \le 0 \qquad (15)$$

with $wo_{ijl}$ as the population or ecosystem densities in the grid.

### 2.6.1 Sectoral Cost Curves as Input to the Optimization

Inputs to the optimization package include cost curves (Equation 9) providing, for the various pollutants under consideration, the costs of reducing emissions at the different source regions for a selected year.

The current implementation of the RAINS model contains modules for estimating emission control costs for $SO_2$, $NO_x$, $NH_3$ and VOC. These estimates can be expressed in terms of cost curves, providing - for a given emission source (country) - the least costs for achieving increasingly stringent emission reductions. They are compiled by ranking the available abatement options according to their marginal costs. Consequently, this methodology produces piece-wise linear curves, consisting typically of about 30 segments.

For each of the pollutants ($NO_x$, VOC) and the countries, such piece-wise linear curves can be used as input to the optimization according to Equation 9. Although the solvers used for this exercise are capable of dealing with piece-wise linear constraints, for reasons of increased numerical stability a smoothed approximation of the cost curves has been developed and used. For this the original piece-wise linear information was smoothed at corners.

The selected functional form guarantees that the curve is, within the selected interval, convex and monotonically decreasing, and shows asymptotic behavior at the maximum control level. For $NO_x$, the maximum deviation from the piece-wise linear curve is typically within a range of ± five percent.

In December 1996 the cost curves for $NO_x$ and $NH_3$ have been submitted to the Parties of the Convention on Long-range Transboundary Air Pollution for review. The documentation of the VOC cost curves was distributed in early 1998. Comments received from the Parties will be fully incorporated into the cost curves in the near future. It is foreseen to present the cost curves for $_{SO2}$, together with a detailed documentation of the methodology used, to the Parties later in 1998.

### 2.6.2 Bounds to the Optimization

The sectoral emissions are implicitly bounded by a corresponding definition of the domain of the corresponding cost function that defines costs associated with reductions of emissions. This domain may be restricted by a specification of optional bounds (e.g., to take account of emission targets specified in the 'Current Reduction Plans). The total emissions of $NO_x$ or VOC are bounded by given upper and lower bounds:

$$n_i^{\min} \le n_i \le n_i^{\max} \tag{16}$$

$$v_i^{\min} \le v_i \le v_i^{\max} \tag{17}$$

Additionally, the definition of cost functions of the type given in Equation 9 may contain linear constraints for $n_i$ and $v_i$.. to reflect measures included in the Current Legislation scenario.

# 3 Data Sources

## 3.1 Energy Projections

Input to the RAINS model are projections of future energy consumption on a national scale up to the year 2010. For the purpose of this study, energy projections for the 15 EU member states have been provided by DG-XVII and have been incorporated into the RAINS database. These projections (Table 3.1) are extracted from the pre-Kyoto 'Business as usual' (BAU) scenario of the 'Energy 2020' Study (DG-XVII, 1996). For Denmark, however, the DG-XVII projections have been replaced by the forecast of the national energy plan recently adopted by the Danish Parliament. In the remainder of the report the resulting combination of energy scenarios (i.e., the official Danish energy scenario for Denmark and the 'Business as usual' scenario for the other 14 EU Member States) will be referred to as the 'Modified Business-as-usual' energy scenario.

The energy scenario selected for this study projects for the 15 EU countries an increase of total energy consumption of 20 percent between 1990 and 2010. The demand for coal decreases by 43 percent. This decline is mainly compensated by a rapid increase in the demand for natural gas (83 percent by 2010) and for other fuels (nuclear, hydropower, renewable energy) by 32 percent (Table 3.2). The transport sector is expected to grow further, which - in spite of continuing improvement in fuel economy of new cars and trucks - results in an increase in the demand for transport fuels by 36 percent.

For the non-EU countries considered in RAINS (Table 3.3), energy projections are based on data submitted by the governments to the UN/ECE and published in the UN/ECE Energy Data Base (UN/ECE, 1996a). Where necessary, missing forecast data have been constructed by IIASA based on a simple energy projection model. These forecasts (Table 3.3) are also the basis for the scenario calculations conducted for the negotiations of the Second $NO_x$ Protocol under the Convention on Long-range Transboundary Air Pollution.

For the non-EU countries, the scenario projects a five percent drop in total primary energy consumption (Table 3.4). This is due to a sharp decrease in primary energy demand that occurred in the period 1990 - 1995 in the countries of the former Soviet Union and in other central and east European countries with economies in transition. Processes of economic restructuring in those countries will allow further economic development while keeping the total primary energy demand until 2010 below the 1990 level. Consumption of coal and oil by stationary sources is predicted to decrease by 23 and 34 percent, respectively. Consumption of natural gas will increase (by 12 percent). As in the EU countries, the demand for transport fuels will increase (by 7 percent over the period 1990 - 2010). In spite of a fast increase in car ownership, the growth in the demand for fuels is modest because of a rapid decrease in material- and transport intensities of the former so-called planned economies. Thus, until 2010 the demand for goods transport will also remain below the 1990 level.

It must be stressed that the selected energy scenario is an exogenous input to the RAINS model and does not specifically change due to constraints on emissions imposed by RAINS calculations.

Table 3.1: Projections of total primary energy consumption for the countries of the EU-15 used for this study

| | 1990 [PJ] | 2010 [PJ] | *Change 1990-2010* | GDP growth [%/year] |
|---|---|---|---|---|
| Austria | 1235 | 1428 | 16% | 2.2% |
| Belgium | 1907 | 2454 | 29% | 2.1% |
| Denmark | 757 | 765 | 1% | 2.2% |
| Finland | 1207 | 1385 | 15% | 1.7% |
| France | 8792 | 11153 | 27% | 2.0% |
| Germany | 14534 | 15112 | 4% | 2.3% |
| Greece | 910 | 1398 | 54% | 2.8% |
| Ireland | 423 | 578 | 37% | 4.6% |
| Italy | 6560 | 8482 | 29% | 1.9% |
| Luxembourg | 122 | 129 | 6% | 2.3% |
| Netherlands | 2711 | 3556 | 31% | 2.5% |
| Portugal | 699 | 1113 | 59% | 3.0% |
| Spain | 3585 | 5238 | 46% | 2.6% |
| Sweden | 2317 | 2679 | 16% | 1.9% |
| UK | 8526 | 9899 | 16% | 2.3% |
| EU-15 | 54285 | 65371 | 20% | 2.2% |

Table 3.2: Energy projections for the EU-15 (Source: DG-XVII - Business as usual Scenario, Danish Energy Plan)

| Source category/fuel | 1990 [PJ] | 2010 [PJ] | *Change 1990-2010* |
|---|---|---|---|
| Stationary combustion sources: | | | |
| Total | 44253 | 51689 | 17% |
| - Coal | 11623 | 6665 | -43% |
| - Liquid fuels | 11768 | 12134 | 3% |
| - Gaseous fuels | 10424 | 19111 | 83% |
| - Other | 10439 | 13779 | 32% |
| Mobile sources - total | 10032 | 13682 | 36% |
| TOTAL | 54285 | 65371 | 20% |

Table 3.3: Projections of total primary energy consumption for the non-EU countries used for this study

| | 1990<br>[PJ] | 2010<br>[PJ] | *Change*<br>*1990-2010* | GDP growth<br>[%/year] |
|---|---|---|---|---|
| Albania | 128 | 143 | 12% | 1.5% |
| Belarus | 1762 | 1553 | -12% | 0.5% |
| Bosnia-H.. | 311 | 297 | -5% | -0.3% |
| Bulgaria | 1296 | 1262 | -3% | 1.0% |
| Croatia | 413 | 447 | 8% | 1.4% |
| Czech Republic | 1956 | 1837 | -6% | 1.6% |
| Estonia | 423 | 366 | -13% | 0.5% |
| Hungary | 1109 | 1350 | 22% | 1.7% |
| Latvia | 399 | 359 | -10% | -1.1% |
| Lithuania | 677 | 565 | -17% | -0.7% |
| Norway | 1612 | 1732 | 7% | 2.0% |
| Poland | 4202 | 4951 | 18% | 3.0% |
| R. of Moldova | 392 | 324 | -17% | -2.2% |
| Romania | 2425 | 2525 | 4% | 1.2% |
| Russia | 18237 | 16617 | -9% | -0.4% |
| Slovakia | 987 | 982 | 0% | 1.4% |
| Slovenia | 231 | 234 | 1% | 3.6% |
| Switzerland | 1119 | 1184 | 6% | 1.3% |
| FYR Macedonia | 151 | 138 | -9% | 0.5% |
| Ukraine | 9970 | 8559 | -14% | -1.0% |
| Yugoslavia | 790 | 725 | -8% | 0.6% |
| Non-EU | 48590 | 46151 | -5% | 0.6% |

Table 3.4: Energy projections for the non-EU countries (Sources: UN/ECE, 1996a, RAINS estimates)

| Source category/fuel | 1990<br>[PJ] | 2010<br>[PJ] | Change<br>1990-2010 |
|---|---|---|---|
| Stationary combustion sources: | | | |
| Total | 43986 | 41230 | -6% |
| - Coal | 11540 | 8888 | -23% |
| - Liquid fuels | 8545 | 5673 | -34% |
| - Gaseous fuels | 18198 | 20371 | 12% |
| - Other | 5704 | 6299 | 10% |
| Mobile sources - total | 4604 | 4921 | 7% |
| TOTAL | 48590 | 46151 | -5% |

Note: Energy use for air transport is not included.

## 3.2 Forecast of Activity Levels Used in the VOC Module

The future rate of emission generating activities, such as industrial production, fuel consumption or transport services, are derived in RAINS by modifying the present activity levels according to exogeneously provided projections, e.g., for the year 2010. In fact, reliable and consistent projections of future activity rates at the process level are hardly available; most economic long-term forecasts restrict themselves to a rather aggregated level of economic activities and rarely specify even the development of the main economic sectors. Therefore, a key question for modeling future abatement costs is which generally available long-term forecasts (such as energy projections, sectoral GDP development, etc.) could be used to derive the temporal changes of the activity rates employed for the emission calculation.

At present, RAINS applies four concepts for constructing forecasts of sectoral activity rates:

- The change of the activity rates for processing, distribution and combustion of fossil fuels is linked to changes in fuel consumption provided by the energy scenario input to RAINS. Internal consistency with the energy scenario used for calculation of $SO_2$ and $NO_x$ emissions is maintained.
- Some other activity rates (dry cleaning, use of solvents in households, vehicle treatment, food and drink industry) are assumed proportional to population development.
- The temporal development of a number of industrial activities (e.g., degreasing, paint use, solvent use in chemical industry, printing, other industrial solvent use) is related to changes in the sectoral gross domestic product (supplied with the energy scenario). In many cases statistics suggest that these activities grow more slowly than the GDP. To reflect this trend, sector-specific elasticities derived from statistics have been applied.
- In the absence of more information the activity rates for less important emission sectors are kept constant. This was typically done
    i. for sectors where current emissions estimates are very uncertain (e.g., agriculture, waste treatment),
    ii. where it is difficult to identify meaningful relations with other economic activities, and
    iii. for sectors where the increase in activity rates are expected to be offset by emission reductions induced by autonomous technical improvements.

The energy projections used are summarized in the previous section. Population forecasts and assumptions on the sectoral split of GDP development (as derived from the 'Business as usual' energy scenario) are provided Table 3.5.

Table 3.5: Population development and GDP growth between 1990 and 2010 used for this study

| | Population growth [million] | | | GDP growth [%/year] | | |
|---|---|---|---|---|---|---|
| | 1990 | 2010 | change [%] | Total country | Chemical industry | Other industry |
| Austria | 7.7 | 8.2 | 6.7 | 2.33 | 1.68 | 1.47 |
| Belgium | 10.0 | 10.0 | 0.0 | 1.91 | 1.81 | 1.20 |
| Denmark | 5.1 | 5.3 | 2.6 | 2.31 | 1.34 | 1.70 |
| Finland | 5.0 | 5.3 | 6.1 | 1.91 | 2.50 | 2.42 |
| France | 56.4 | 62.2 | 10.2 | 2.19 | 1.51 | 1.36 |
| Germany | 79.4 | 83.6 | 6.2 | 2.57 | 1.87 | 1.63 |
| Greece | 10.1 | 10.7 | 6.2 | 2.27 | 1.29 | 1.35 |
| Ireland | 3.5 | 3.6 | 2.2 | 3.62 | 2.92 | 2.30 |
| Italy | 57.7 | 57.8 | 0.2 | 1.90 | 1.19 | 1.56 |
| Luxembourg | 0.4 | 0.4 | 0.6 | 1.91 | 1.16 | 1.10 |
| Netherlands | 14.9 | 16.5 | 10.4 | 2.13 | 1.61 | 1.56 |
| Portugal | 9.4 | 9.5 | 1.3 | 2.57 | 1.07 | 1.20 |
| Spain | 39.0 | 40.6 | 4.1 | 2.39 | 1.31 | 1.35 |
| Sweden | 8.6 | 9.1 | 6.5 | 1.64 | 1.50 | 1.40 |
| UK | 57.4 | 60.2 | 4.9 | 2.00 | 2.35 | 1.32 |
| EU-15 | 364.6 | 383.0 | 5.0 | - | - | - |

## 3.3 Changes in the Database Since the Third Interim Report

Since the Third Interim Report of this study a number of changes have been made to the database of the RAINS model. The most important updates are as follows:

- The 'Conventional Wisdom' energy scenario used for the Third Interim Report has been replaced by the latest pre-Kyoto 'Business as usual' scenario of DG-XVII. National energy projections received from Finland and Austria arrived too late to be incorporated into the analysis of this Fourth Interim Report. They will be used for the Fifth Report.
- Revised projections on agricultural livestock were supplied by a number of countries. Since acidification - and therefore also the control of ammonia emissions - is outside the scope of the Fourth Report, they will be considered for the Fifth Report.
- Based on updated information received from the UN/ECE, energy projections for some non-EU countries were slightly revised.
- The 'Common Position' on the Auto/Oil 1 programme and the Directive on Off-road vehicles were introduced into the 'Current Legislation' scenario.
- Following suggestions from experts of some countries, the combined emission control efficiency of the available measures for retrofitting existing boilers in the power plant sector (combustion modification and selective catalytic reduction) has been decreased to 80 percent. The implied differentiation in control efficiencies between new boilers and retrofit application takes into account that in practice retrofits are often subject to a number of limitations, e.g., caused by space availability.

- Based on information provided in the 'Common Position' on the Auto/Oil 1 program, provisional cost estimates were attributed to the emission control options reflecting the 'indicative 2005 emission standards' of Auto/Oil 1.
- An improved version of the RAINS VOC emission/cost module has been used. A detailed documentation of the methodology and data sources was recently submitted to the Parties of the Convention on Long-range Transboundary Air Pollution for review. All material (for all countries) is provided electronically on IIASA's WorldWideWeb site (http://www.iiasa.ac.at/~klimont/main-review.html).
- The approach for modeling the emission reduction potential in the transport sector has been revised. Four main sectors (four-stroke gasoline engines in passenger and light dusty vehicles, diesel engines in passenger and light duty vehicles, heavy duty vehicles, other transport) are distinguished. The new methodology allows the combined $NO_x$ and VOC reductions of a number of control options in these sectors to be considered and treated differently from the 'single pollutant' measures.

Updated information on emission factors, removal efficiencies and current legislation were incorporated into the model, leading to minor adjustments of base year and 2010 emissions.

# 4 The Situation in 1990, the Expected Impacts of the Current Policies and the Maximum Technically Feasible Reductions

## *4.1 Emissions*

To establish a reference line against which the emission control scenarios of this report can be compared, the likely impacts of current emission abatement policies and regulations for the year 2010 are explored first. In order to capture the 'dual-track' approach adopted in Europe (regulations on emission standards for specific source categories and ceilings for national total emissions), two alternative scenarios were constructed that mimicked the implications of these approaches. While the 'Current Reduction Plans' (CRP) scenario incorporates officially adopted or internationally announced ceilings on national emissions, the 'Current Legislation' (CLE) scenario relies on an inventory of (present and already accepted future) legally binding emission control legislation for the European countries. Finally, for the further analysis a 'Reference' (REF) scenario was constructed that selected the more stringent emission ceiling for each country.

### 4.1.1 The Current Reduction Plans (CRP) Scenario for the Year 2010

The 'Current Reduction Plans' (CRP) scenario is based on an inventory of officially declared national emission ceilings. Such declarations of envisaged future emissions result from the various protocols of the Convention on Long-range Transboundary Air Pollution and are collected on a routine basis by the Secretariat of the Convention. The analysis in this study uses the recent data published in EMEP (1997). In cases where no projections were supplied by a country for the target year 2010, the following rules, which are in accordance with the practice used for modeling work under the Convention, have been applied:

- If a future projection is available, the latest number has been used for the year 2010;
- if the country has signed the $NO_x$ or VOC protocol, the resulting obligation (e.g., standstill or 30 percent cut in emissions relative to a base year) has been extended to the year 2010;
- if neither applies, the results from the RAINS estimate of the Current Legislation scenario has been used.

The CRP emissions used for this study are provided in Table 4.4. For the EU-15, the CRP emissions of $NO_x$ are 25 percent below the 1990 level, those of VOC 36 percent.

### 4.1.2 The Current Legislation (CLE) Scenario for the Year 2010

The Current Reduction Plans (CRP) scenario, which projects future emission levels in Europe based on officially announced national emission caps, e.g., as laid down in the Second Sulfur Protocol, is contrasted by a Current Legislation (CLE) scenario, which explores the impacts of adopted national and international legislation for emission control, based on projections of future energy consumption.

The starting point for the analysis is a detailed inventory of regulations on emission controls. Thereby it takes into account the legislation in the individual European countries, the relevant Directives of the European Union (in particular the ‘Large Combustion Plant Directive’ (OJ, 1988) and the Directive on Sulfur Content of Gas Oil (Johnson & Corcelle, 1995)), as well as the obligatory clauses regarding emission standards from the protocols under the Convention on Long-range Transboundary Air Pollution (for instance, the Second Sulfur Protocol (UN/ECE, 1994a) requires emission control according to ‘Best Available Technology’ (BAT) for new plants). The measures for controlling $NO_x$ emissions from stationary sources are summarized in Table 4.1

For the control of $NO_x$ emissions from mobile sources, the scenario considers the implementation of the current EU standards for all new cars, light duty trucks and heavy duty vehicles (i.e., the Directives 94/12/EC, 70/220/EEC and 88/77/EEC; see McArragher, 1994) in the Member States of the European Union. Additionally, the scenario assumes for all EU countries after the year 2000 the implementation of the measures outlined in the 'Common Position' of the Auto/Oil 1 program. They include vehicle-related measures like improved catalytic converters, engine modifications and on-board diagnostic systems. Furthermore, the impacts of the proposed 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.

For VOC, the CLE scenario assumes the implementation of the Solvent Directive of the EU (COM(96)538) as proposed by the Commission. Furthermore, the obligations of the VOC Protocol of the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1994d) were incorporated. For mobile sources, the measures proposed under Auto/Oil 1 and the regulations on carbon canisters of the Directive 91/441/EEC are assumed to be fully implemented. Emissions from off-road vehicles are subject to the Commission’s proposal COM(95)350. It was further assumed that VOC emissions from gasoline distribution will be controlled through the Stage-I measures in all the EU countries (reflecting the Directive 94/63/EC), unless there already exist more stringent regulations requesting Stage-II control.
VOC control measures assumed in the CLE scenario are presented in Table 4.2.

For constructing the CLE scenario the emission control measures listed above were combined with the future level of energy consumption as projected by the Modified Business as usual energy scenario. Table 4.4 compares the emission estimates for the year 1990 with the CRP and the CLE scenarios. There is clear evidence that official long-term emission targets presented to international organizations are not always consistent with what could be expected to be achieved through current legislation. In particular, the longer-term dynamics of technology-related emission limit values induced by the turnover of the capital stock often seem to be underestimated, so that frequently technology- and activity-based forecasts yield higher emission reductions. However, most of the differences in the estimates for the EU countries can be explained by the stricter emission standards for mobile sources resulting from the Auto/Oil program. Whereas these new plans are considered in the CLE scenario, they are not yet taken into account in the official country submissions to the UN/ECE used for the CRP scenario.

Table 4.1: Measures assumed for the ’Current Legislation’ (CLE) scenario for $NO_x$ emissions

**Stationary sources:**

- Emission standards for new plant and emission ceilings for existing plant from the Large Combustion Plant Directive (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 in force in each European country – if stricter than the international legislation. Inventory of current national legislation can be found in Bouscaren and Boucherau (1996) as well as in McConville (1997). Because of the stringency of national standards in some countries, add-on controls (SCR) were assumed for those countries. The control measures for stationary sources included in the CLE scenario for individual countries are shown in Table 4.3.

**Mobile sources:**

- EU standards for cars and light duty trucks (Directive 94/12/EC, 93/59/EEC, 91/441/EEC)
- EU standards for heavy duty vehicles according to the ‘Clean Lorry Directive’ (91/542/EEC)
- EU standards for off-road vehicles, agricultural tractors COM(95)350, as well as for mopeds and motorcycles (Common Position No 23/96, Bouscaren and Boucherau, 1996)
- UN/ECE and national emission standards on mobile sources for non-EU countries (Bouscaren and Boucherau, 1996)
- From 2000 - fuel quality and emission standards resulting from the Auto/Oil Program (COM(96) 248. These standards are assumed to be implemented in the EU-15 as well as in Norway and in Switzerland.

Table 4.2: Measures assumed for the 'Current Legislation' (CLE) scenario for VOC emissions

**Stationary sources:**

- Emission ceilings and standards from the Solvent Directive COM(96)538.
- Stage I and Stage II controls on gasoline distribution - Directive 94/63/EC (EC, 1994)

**Mobile sources:**

- All directives and legislation acts aimed at a reduction of emissions form mobile sources mentioned for $NO_x$ also apply to NMVOC
- Passenger cars – small carbon canister according to the Directive 91/441/EEC (EC, 1991)

Table 4.3: $NO_x$ emission control measures in the EU-15 for stationary sources in the CLE scenario

| Country<br>Capacity class, $MW_{th}$ | New plants<br>Coal | <br>Oil | <br>Gas | Existing plants<br>Coal | <br>Oil | <br>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 |
| **Netherlands:** | | | | | | |
| <300(3) | SCR | SCR | SCR | CM | CM | CM |
| >300 | SCR | SCR | SCR | CM/SCR | CM | CM |
| Industrial processes: | | Stage 2 | | | Stage 2 | |

Table 4.3: $NO_x$ emission control measures in the EU-15 for stationary sources in the CLE scenario, continued

| Country<br>Capacity class, $MW_{th}$ | New plants<br>Coal | <br>Oil | <br>Gas | Existing plants<br>Coal | <br>Oil | <br>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 | - |

Lignite/hard coal
- Standard slightly below of what is achievable with CM
- Includes also sources below 50 MWth
- Only in the power plant sector

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

Table 4.4: $NO_x$ emissions for 1990, the current reduction plans for the year 2010 and the current legislation scenario (CLE) for the year 2010 (in kilotons)

| | $NO_x$ (kt)<br>1990 | <br>CRP | <br>CLE | VOC (kt)<br>1990 | <br>CRP | <br>CLE |
|---|---|---|---|---|---|---|
| Austria | 236 | 155 | 115 | 427 | 305 | 325 |
| Belgium | 362 | 309 | 209 | 343 | 232 | 196 |
| Denmark | 271 | 192 | 128 | 165 | 134 | 92 |
| Finland | 279 | 224 | 155 | 206 | 108 | 118 |
| France | 1620 | 1276 | 811 | 2144 | 1675 | 1171 |
| Germany | 2644 | 2130 | 1296 | 3116 | 1750 | 1397 |
| Greece | 392 | 357 | 324 | 302 | 205 | 246 |
| Ireland | 107 | 105 | 74 | 111 | 138 | 46 |
| Italy | 1998 | 2060 | 1166 | 1846 | 1456 | 1079 |
| Luxembourg | 21 | 19 | 10 | 18 | 13 | 8 |
| Netherlands | 539 | 270 | 271 | 481 | 204 | 203 |
| Portugal | 208 | 221 | 196 | 217 | 144 | 184 |
| Spain | 1159 | 892 | 903 | 1062 | 795 | 794 |
| Sweden | 344 | 254 | 220 | 432 | 287 | 289 |
| United Kingdom | 2664 | 1186 | 1163 | 2661 | 1276 | 1354 |
| Total | 12843 | 9650 | 7040 | 13531 | 8722 | 7502 |

### 4.1.3 The Reference (REF) Scenario for the Year 2010

A Reference scenario has been constructed in order to assess the likely environmental impacts of the current emission control strategies. Taking into account national and international legislation as well as commitments made within the framework of the Convention on Long-range Transboundary Air Pollution, the Reference (REF) scenario selects, for each country individually, the more stringent outcome of the Current Reduction Plans- and the Current Legislation-scenarios.

Emissions and control costs of this scenario are presented in Table 4.5. For EU-15 as a whole, the REF scenario results in a 45 percent cut of $NO_x$ and 46 percent cut of VOC emissions. Emission control costs for $NO_x$ and VOC emissions amount to at 33 billion ECU/year.

Table 4.5: Emissions and control costs for $NO_x$ and VOC for 1990 and the Reference (REF) scenario (emissions in kilotons, costs in million ECU/year).

| | $NO_x$ | | | VOC | | | Costs |
|---|---|---|---|---|---|---|---|
| | 1990 | REF | Change | 1990 | REF | Change | of REF |
| Austria | 236 | 115 | -51% | 427 | 305 | -29% | 613 |
| Belgium | 362 | 209 | -42% | 343 | 196 | -43% | 905 |
| Denmark | 271 | 128 | -53% | 165 | 92 | -44% | 443 |
| Finland | 279 | 155 | -44% | 206 | 108 | -48% | 440 |
| France | 1620 | 811 | -50% | 2144 | 1171 | -45% | 5412 |
| Germany | 2644 | 1296 | -51% | 3116 | 1397 | -55% | 7651 |
| Greece | 392 | 324 | -17% | 302 | 205 | -32% | 600 |
| Ireland | 107 | 74 | -31% | 111 | 46 | -59% | 200 |
| Italy | 1998 | 1166 | -42% | 1846 | 1079 | -42% | 5032 |
| Luxembourg | 21 | 10 | -52% | 18 | 8 | -56% | 50 |
| Netherlands | 539 | 270 | -50% | 481 | 203 | -58% | 1404 |
| Portugal | 208 | 196 | -6% | 217 | 144 | -34% | 911 |
| Spain | 1159 | 892 | -23% | 1062 | 794 | -25% | 3601 |
| Sweden | 344 | 220 | -36% | 432 | 287 | -34% | 746 |
| UK | 2664 | 1163 | -56% | 2661 | 1276 | -52% | 4888 |
| EU-15 | 12843 | 7029 | -45% | 13531 | 7311 | -46% | 32896 |

### 4.1.4 Full Implementation of Current Control Technologies

A further scenario, the Maximum Feasible Reductions (MFR) scenario, has been constructed to illustrate the potential of a full application of current control technology and to quantify possible progress towards the ultimate target of full achievement of the long-term environmental targets discussed within the context of the EU ozone strategy.

The MFR scenario simulates the complete implementation of currently available emission control technologies taking into account constraints imposed by current legislation and historically observed turnover rates of the capital stock when determining the application potential of the presently available emission control options.

By definition, changes to the structure and the levels of economic activities and energy consumption, e.g., as reactions to excessive emission control costs or the effects of non-technical instruments to control emissions, are excluded.

It is important to mention that, for the first time, the analysis presented in this Fourth Interim Report includes the potential for further emission reductions from mobile sources beyond measures agreed upon in the Auto/Oil 1 programme. Unfortunately, at the present time the in-depth analysis of the Auto/Oil 2 programme has not yet reached the phase where definite findings could be presented. Given this situation, the emission control potential and the costs assumed in this report for these measures have to be considered as purely illustrative and should in no way prejudge the outcome of the ongoing Auto-Oil 2 activities.

In principle there is a methodological problem to avoid double-counting of costs for measures that reduce simultaneously $NO_x$ and VOC emissions, if conventional ’single pollutant’ cost curves are used. Over the last few months the RAINS model and its optimization module were extended to handle ’multi-pollutant’ cost curves (see Equation 9 in Section 2.6), which enable a correct treatment of those emission control options most important in the transport sector.

Table 4.6: Emissions and control costs (on top of REF) for REF and the Maximum technically feasible redcutions (MFR). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | REF | | MFR | | REF | | MFR | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | *-51%* | 75 | *-68%* | 305 | *-29%* | 243 | *-43%* | 617 |
| Belgium | 209 | *-42%* | 105 | *-71%* | 196 | *-43%* | 98 | *-71%* | 1045 |
| Denmark | 128 | *-53%* | 78 | *-71%* | 92 | *-44%* | 63 | *-62%* | 349 |
| Finland | 155 | *-44%* | 82 | *-71%* | 108 | *-48%* | 85 | *-59%* | 399 |
| France | 811 | *-50%* | 496 | *-69%* | 1171 | *-45%* | 814 | *-62%* | 3454 |
| Germany | 1296 | *-51%* | 829 | *-69%* | 1397 | *-55%* | 885 | *-72%* | 5590 |
| Greece | 324 | *-17%* | 207 | *-47%* | 205 | *-32%* | 173 | *-43%* | 621 |
| Ireland | 74 | *-31%* | 32 | *-70%* | 46 | *-59%* | 30 | *-73%* | 213 |
| Italy | 1166 | *-42%* | 669 | *-67%* | 1079 | *-42%* | 684 | *-63%* | 4172 |
| Luxembourg | 10 | *-52%* | 5 | *-76%* | 8 | *-56%* | 5 | *-72%* | 52 |
| Netherlands | 270 | *-50%* | 162 | *-70%* | 203 | *-58%* | 134 | *-72%* | 1319 |
| Portugal | 196 | *-6%* | 113 | *-46%* | 144 | *-34%* | 122 | *-44%* | 600 |
| Spain | 892 | *-23%* | 470 | *-59%* | 794 | *-25%* | 499 | *-53%* | 2791 |
| Sweden | 220 | *-36%* | 124 | *-64%* | 287 | *-34%* | 248 | *-43%* | 682 |
| UK | 1163 | *-56%* | 588 | *-78%* | 1276 | *-52%* | 746 | *-72%* | 4641 |
| EU-15 | 7029 | *-45%* | 4035 | *-69%* | 7311 | *-46%* | 4829 | *-64%* | 26545 |

Table 4.6 lists the resulting emissions for the REF and MFR scenarios. For the EU-15 as a whole, the MFR scenario produces a 69 percent cut of $NO_x$ emissions relative to 1990, and a 64 percent decline in VOC emissions. Costs on top of REF amount to more than 26 billion ECU/year. For the interpretation of model results in the following sections it is important to realize that in the Mediterranean countries Greece, Portugal and Spain the full application of control technology will result in significantly smaller emission reductions (about 45 percent

instead of 70 percent) compared to 1990 than in the other EU countries. This is due to the higher economic growth assumed in the Business as usual energy scenario.

The MFR scenario for the year 2010 considers the historically observed turnover of the capital stock. This means that the scenario assumes for the year 2010 a certain fraction of the emission sources (car fleet, etc.) equipped with emission controls according to the regulations of the time when they entered into service. This is of particular relevance for the transport sector, where cars adhering to the Auto/Oil 1 emission standards fixed for the year 2000/2005 will still be in operation. The potential for more stringent controls is therefore limited only to cars built after 2005. As a consequence, emission levels could be even lower in later years when the most advanced control options penetrate the entire car fleet.

## 4.2 Health-related Ozone Exposure

Following the revised WHO Air Quality Guidelines for Europe, the Draft Position Paper on Ozone prepared by the Commission's Services proposes a maximum eight-hour average concentration of 60 ppb (120 μg) as the long-term environmental objective for the EU ozone strategy[15]. The ultimate goal would be to eliminate all excess of this criterion.

The modeling of European abatement strategies for individual days over a multi-month period is a rather ambitious task and is not entirely feasible at the moment. In order to simplify the modeling task, and particularly to find a manageable approach for the reduced-form model implemented in the RAINS optimization, the target of no-exceedance of the WHO criterion (60 ppb as maximum eight hours mean concentrations) was converted into an AOT index, which could be handled in a similar way to the AOT40 for vegetation. As a result, an AOT60 (i.e., the cumulative excess exposure over 60 ppb, for practical reasons over a six-month period) of zero is considered as equivalent to the full achievement of the WHO criterion. Any violation of this WHO guideline will consequently result in an AOT60 of larger than zero.

It is important to stress that this AOT60 surrogate indicator has been introduced purely for practical modeling reasons. Given the current knowledge on health effects it is not possible to link any AOT60 value larger than zero with a certain risk to human health. The only possible interpretation is that if the AOT60 is above zero, the WHO criterion is exceeded at least once during the six-month period.

It is documented elsewhere that actual ozone concentrations are strongly influenced (a) by the concentrations of the precursor emissions and (b) by the actual meteorological conditions. Excluding for the moment the meteorological influence, the following figures portray the anticipated (from the REF scenario) and the possible (from the MFR scenario) changes in AOT60 between 1990 and 2010. In doing so, the analysis uses the mean meteorological conditions of the five years 1989, 1990, 1992, 1993 and 1994. Obviously, the data displayed in the maps cannot be directly compared with real observations, since these incorporate the specific meteorological conditions for the selected year.

Figure 4.1 illustrates that for the emissions of 1990 and assuming the five year mean meteorology, the highest (rural) AOT60 of more than 6 ppm.hours occurred in northern

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[15] The maximum is calculated from running eight-hour averages of the one-hour mean concentrations.

France, Belgium and Germany. In many other parts of France, Germany the AOT60 was modeled in a range of 5-6 ppm.hours. Typical rural values in the UK and Austria were between 2 and 3 ppm.hours, while the highest AOT60 in Spain and Greece was between 1 and 2 ppm.hours. Portugal is estimated at 3 ppm.hours, while Scandinavia did not experience significant excess of the AOT60.

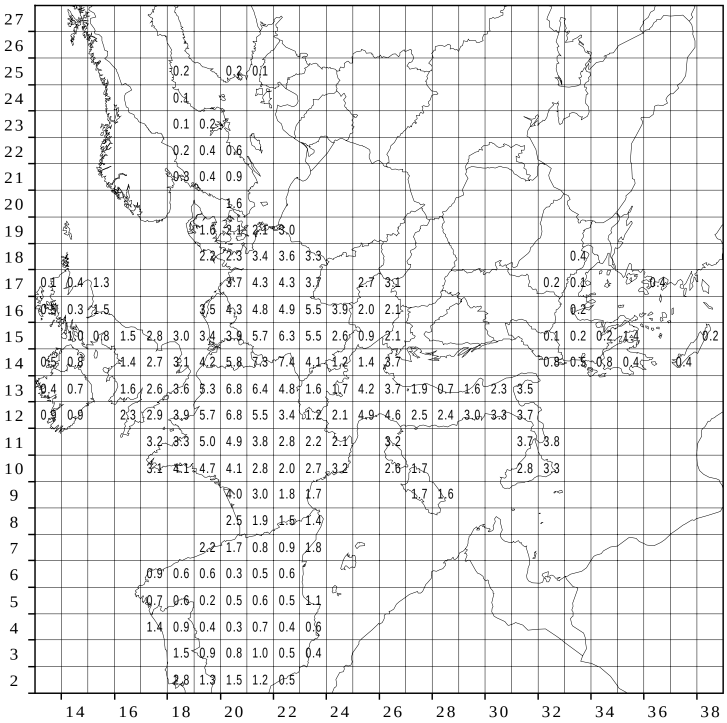

Figure 4.1: Mean AOT60 for the emissions of 1990 taking into account the meteorological conditions of five years (in ppm.hours)

The emission controls calculated for the REF scenario for the year 2010 ($NO_x$ -45%, VOC -46% compared to 1990) are expected to have profound impacts on ozone exposure (Figure 4.2). Assuming mean meteorological conditions, the highest AOT60 in Europe would decline to about 3 ppm.hours, i.e., by about 50 percent. In many other regions there would be even higher improvements, leading to an average drop of the AOT60 by 60 percent.

Even further cuts in the AOT60 could be achieved by the maximum feasible emission reductions (Figure 4.3). A 70 percent decline of $NO_x$ and VOC emissions would bring highest AOT60 levels in Europe to about 1.5 ppm.hours, which is 70-80 percent below the 1990 levels. Since most of Europe would be able to achieve the WHO guideline, the average AOT60 would be 83 percent lower than in 1990.

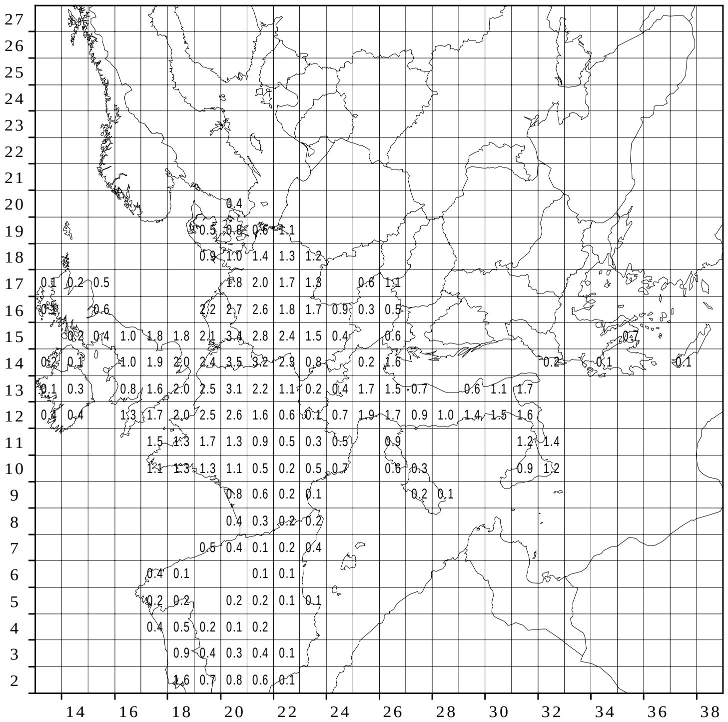

Figure 4.2: Mean AOT60 for the emissions of the REF scenario, taking into account the meteorological conditions of five years (in ppm.hours)

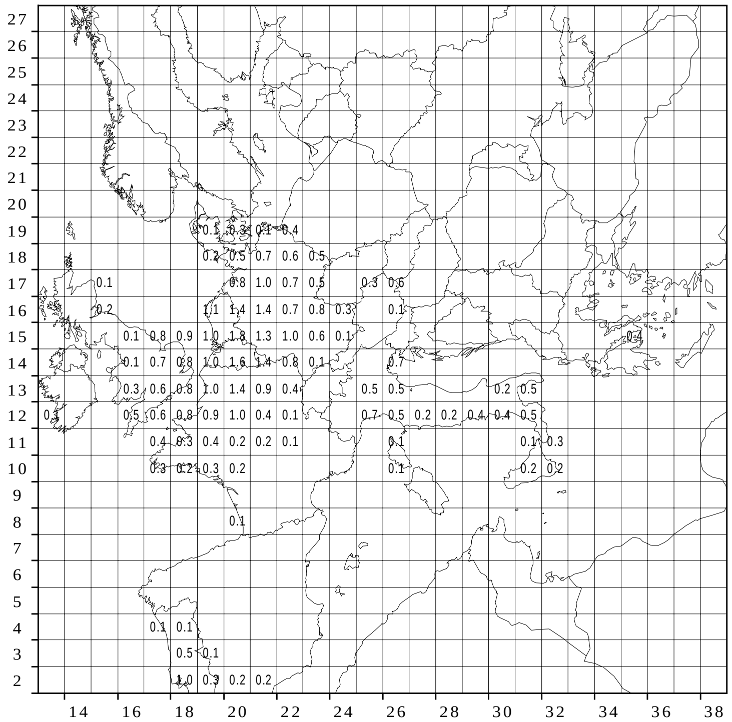

Figure 4.3: Mean AOT60 for the emissions of the MFR scenario, taking into account the meteorological conditions of five years (in ppm.hours)

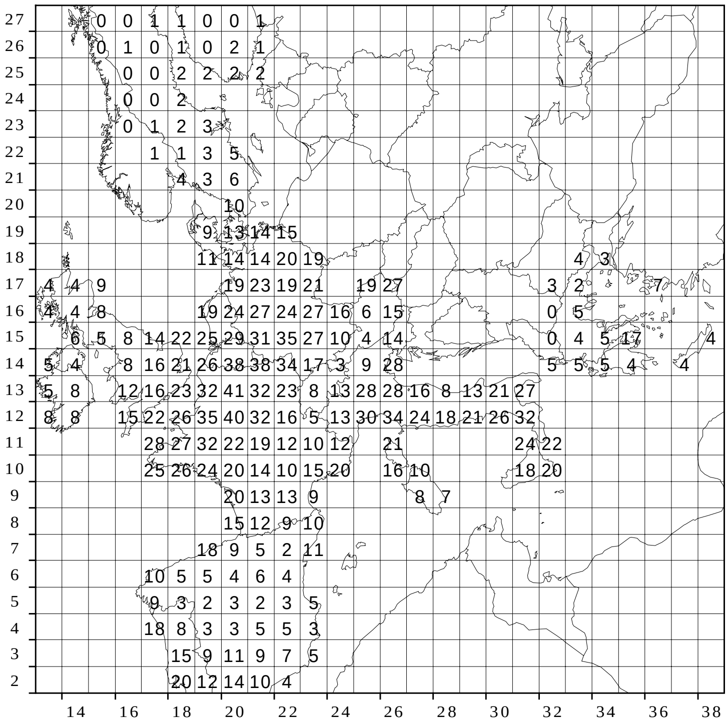

Figure 4.4: Number of days exceeding the WHO ozone guideline value (60 ppb eight hour mean) for the emissions of the REF scenario. The map displays the second highest occurrence out of the meteorological conditions of five years

Although the AOT60 is a convenient index to model, it might be a difficult one to interpret and to link with generally understandable notions. A better measure in this respect is obviously the number of days on which the WHO criterion is exceeded. Figure 4.4 displays (for the mean meteorology) the regional distribution of the "excess days" for the emissions of the REF scenario. It is interesting to note that there is not a 1:1 relationship between the AOT60 and the number of days across all regions in Europe, indicating that the amount by which the 60 ppb criterion is exceeded varies over Europe. Whereas the highest AOT60 is expected for the northern part of Europe (France/Belgium/Germany), large numbers of days exceeding the 60 ppb threshold are also found in Italy, where the AOT60 is typically 20 to 30 percent lower than in northern Europe. This phenomenon underlines the observation that ozone exposure shows different temporal characteristics in different parts of Europe, a fact which is important to take into account when designing emission control strategies.

Table 4.7 presents two different types of population exposure for the AOT60. The cumulative index reflects the total exposure of a population and is expressed in person.ppm.hours. This index is the result of the average exposure per person multiplied with the total population. The RAINS model calculates these indices on a grid basis (using gridded data on AOT60 and population); in a second step these grid values are aggregated to the country level. The indices presented in this report use the AOT60 concentrations per grid, representing the rural ozone concentrations, and the total population per grid in 1990. Inaccuracies may occur for grids with major urban areas, where the rural ozone concentrations used for these analysis present an upper bound for the concentrations in the cities, and are lower than the concentrations occurring in the city plumes. The 'average' indicator reflects the average exposure of a person in a country, calculated from gridded data. It is important to stress that these indices may not be used to derive estimates of health damage, for which more detailed information is deemed necessary. In the context of this report, these indices provide relative measures to enable a comparison of different scenarios.

Table 4.7: Population exposure indices (AOT60) for 1990, the Reference (REF) scenario and the maximum feasible emission reductions (MFR), using the five year mean meteorology. The table presents the cumulative population exposure for each country (in million person.ppm.hours) and the average exposure per person in each country (in ppm.hours). Note that the environmental long-term target is proposed at a level of zero.

| | Cumulative population exposure (million person. ppm.hours) | | | Average population exposure (ppm.hours) | | |
|---|---|---|---|---|---|---|
| | 1990 | REF | MFR | 1990 | REF | MFR |
| Austria | 15 | 3 | 1 | 2.0 | 0.4 | 0.2 |
| Belgium | 63 | 35 | 17 | 5.8 | 3.2 | 1.5 |
| Denmark | 8 | 3 | 1 | 1.6 | 0.6 | 0.1 |
| Finland | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| France | 264 | 90 | 31 | 4.7 | 1.6 | 0.5 |
| Germany | 362 | 149 | 67 | 4.6 | 1.9 | 0.8 |
| Greece | 7 | 3 | 2 | 0.7 | 0.3 | 0.2 |
| Ireland | 2 | 1 | 0 | 0.7 | 0.3 | 0.0 |
| Italy | 157 | 60 | 15 | 2.7 | 1.0 | 0.3 |
| Luxembourg | 3 | 1 | 1 | 7.6 | 3.2 | 1.4 |
| Netherlands | 65 | 39 | 20 | 4.4 | 2.6 | 1.4 |
| Portugal | 16 | 8 | 4 | 1.7 | 0.8 | 0.4 |
| Spain | 32 | 8 | 1 | 0.9 | 0.2 | 0.0 |
| Sweden | 3 | 0 | 0 | 0.4 | 0.0 | 0.0 |
| UK | 123 | 76 | 24 | 2.2 | 1.3 | 0.4 |
| EU-15 | 1122 | 477 | 182 | 3.1 | 1.3 | 0.5 |

As shown in the table, in 1990 the average exposure was highest in France, Luxembourg, Belgium and Germany; the highest cumulative exposure (due to the large population) occurred in Germany, France, Italy and the UK. The cumulative exposure of the population in the EU-15 countries is expected to decline by 57 percent as a result of the current policy. Larger improvements occur in Austria (-71 percent) and the Scandinavian countries (60-70 percent), while for the UK and Netherlands a decrease in AOT60 by about 40 percent could be expected. The maximum feasible emission reductions would reduce the exposure indices by 84 percent.

It is important to mention that there are some areas where, despite - or because of - the anticipated emission reductions of the REF scenario, for individual years the AOT60 is expected to slightly increase as a result of current policy. Using mean meteorology, however, masks the increase occurring in individual years.

The explanation for this increase is related to the ozone formation chemistry. Put in a rather simplistic way, very high NO concentrations (in areas with high $NO_x$ emissions) have, i.a., two effects: (a) they lead to the titration of ozone, i.e., the conversion of ozone and NO into $NO_2$, and (b) they cause a (partial) depletion of OH radicals. This resulting shortage of OH radicals at such high $NO_x$ levels limits ozone production. Reducing $NO_x$ emissions from such a high level will increase the available OH radicals, and more ozone will be produced, until $NO_x$ emissions are so low that the ozone production will be limited by the available $NO_2$ molecules. As indicated in Section 2.5.2, reducing $NO_x$ will lead for some time to increased ozone. Beyond a certain $NO_x$ reduction level, however, ozone will decline again.

Figure 4.5 supports this explanation by illustrating the emission densities in 1990. It is important to realize that the emissions in the areas where the increase occurs (UK, Belgium, Netherlands, etc.) are up to a factor of 10 higher than in other industrialized European regions (compare e.g., southern Germany).

It is also important to realize that this ozone increase disappears for the maximum feasible emission reductions. This means that sufficiently high $NO_x$ reductions (which are considered as technically feasible) can overcome the temporary ozone increase everywhere.

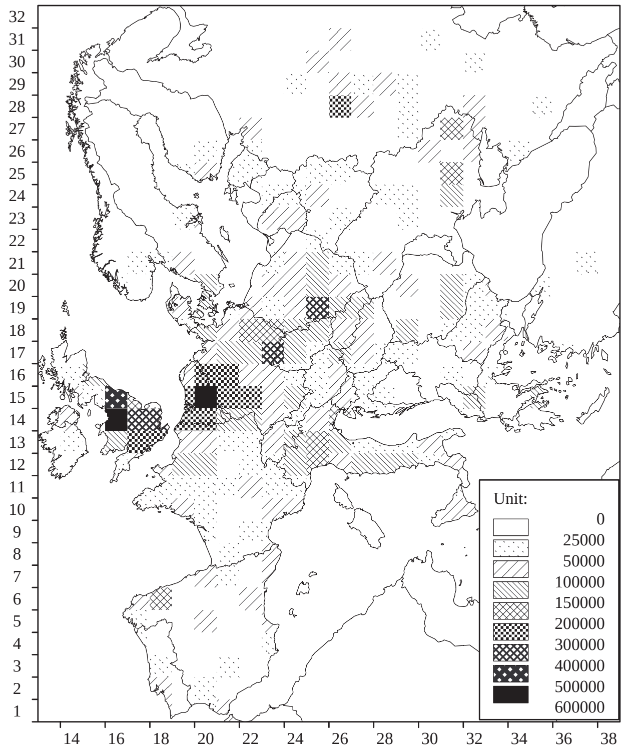

Figure 4.5: $NO_x$ emissions per EMEP grid cell in 1990 (in tons)

## 4.3 Vegetation-related Ozone Exposure

The following analysis explores important features of strategies aimed at reducing the risk of ozone-induced damage on vegetation. In the absence of accepted dose-response curves applicable at the large scale, the analysis uses the concept of critical thresholds as developed within the framework of the UN/ECE Convention on Long-range Transboundary Air Pollution. The Working Group on Effects of this Convention established two long-term related critical levels:

- For agricultural crops and herbaceous plant communities (natural vegetation), the critical level is set at an AOT40 of 3 ppm.hours for the growing season and daylight hours, over a five-year period;
- For forest trees, a critical level of 10 ppm.hours for daylight hours, accumulated over a six-month growing season, is proposed.

The AOT40 is calculated as the sum of the differences between the hourly ozone concentrations in ppb and 40 ppb for each hour when the concentration exceeds 40 ppb, using daylight hours only.

It has been shown elsewhere that for the currently prevailing European ozone regime the critical level for crops and natural vegetation is stricter than the critical level for forest trees; in other words, while the critical levels for forest trees are usually met when the critical level for crops and vegetation is achieved, the opposite statement does not hold. Based on this finding it has been decided to restrict the scenario analysis to the critical levels for crops and natural vegetation. If considered necessary, however, there are no methodological problems to prevent exploring scenarios for the achievement of the critical levels for forest trees separately.

Before assessing the potential for further improvement of the AOT40 exposure in Europe, the situation in 1990 and the possible range of future development is outlined.

Figure 4.6 displays the excess AOT40 (over the critical level of 3 ppm.hours) calculated for the emissions of the year 1990 using the five years mean meteorology. The map clearly shows that in most countries of the EU-15 the critical level for vegetation was exceeded. The only exceptions are parts of the Scandinavian countries. In an area extending from Paris over Belgium and Netherlands to Germany the excess AOT40 reached 16 ppm.hours, i.e., it exceeded the critical level by more than a factor of five. It is important to note that ozone levels in many areas, which do not experience significant excess of the AOT60, exceed the AOT40 criterion significantly. This applies particularly to the Mediterranean countries and some Alpine regions.

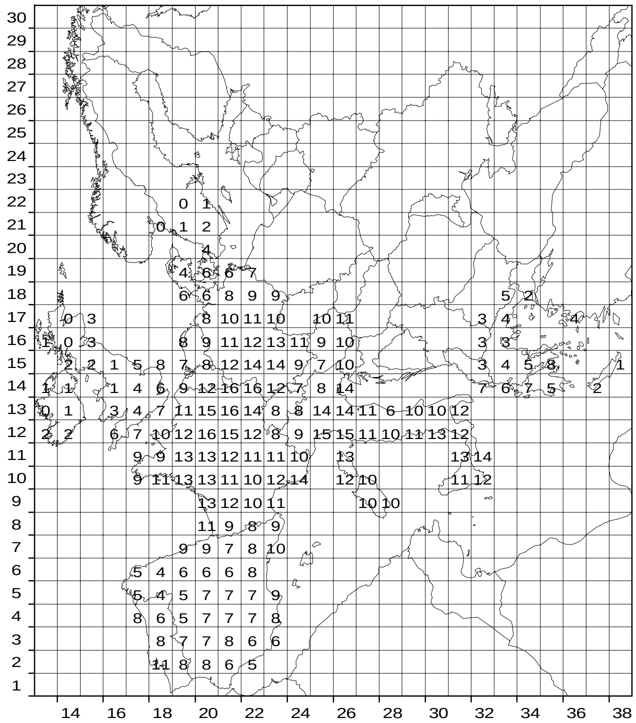

Figure 4.6: Excess AOT40 above the critical level of 3 ppm.hours for the year 1990 (using five years mean meteorology), in ppm.hours. Land area left blank had no excess in 1990 (or does not belong to the EU).

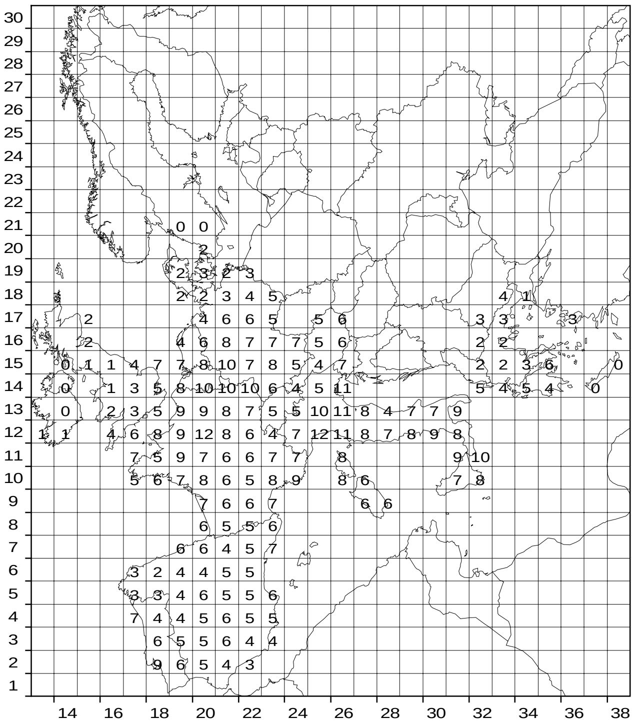

Figure 4.7: Excess AOT40 above the critical level of 3 ppm.hours for the Reference scenario in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario or do not belong to the EU.

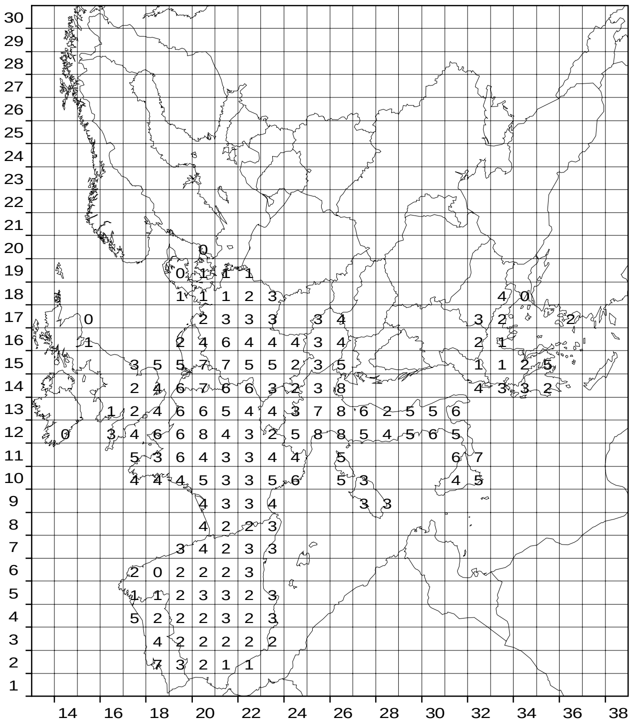

Figure 4.8: Excess AOT40 above the critical level of 3 ppm.hours for the maximum feasible emission reductions in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario or do not belong to the EU.

The emission reductions of the Reference scenario will generally lead to a decline of the excess AOT40, but will not significantly increase the protected area (Figure 4.7). Peak levels are in a range of 10-12 ppm.hours. The maximum feasible emission reductions are expected to achieve a 50 percent and higher cut of the excess AOT40 in most regions (Figure 4.8).

Table 4.8 introduces two vegetation-related exposure indices. The cumulative vegetation exposure index is calculated as the excess AOT40 (i.e., the AOT40 in excess of the critical level of 3 ppm.hours) multiplied by the area of ecosystems which are exposed to the excess concentration. The index is calculated on a grid resolution, considering agricultural land, natural vegetation and forest areas. The average vegetation exposure index reflects the average excess AOT40 (over all grids in a country). The estimate of these indices is based on rural ozone concentrations.

Table 4.8: Vegetation exposure indices for 1990, the Reference Scenario in 2010 and the maximum feasible emission reductions

| | Cumulative vegetation exposure index (million hectares.excess ppm.hours) | | | Average vegetation exposure index (excess ppm.hours) | | |
|---|---|---|---|---|---|---|
| | 1990 | REF | MFR | 1990 | REF | MFR |
| Austria | 459 | 264 | 169 | 8.9 | 5.1 | 3.3 |
| Belgium | 172 | 143 | 104 | 11.1 | 9.2 | 6.7 |
| Denmark | 131 | 54 | 15 | 4.4 | 1.8 | 0.5 |
| Finland | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| France | 3948 | 2346 | 1357 | 12.2 | 7.3 | 4.2 |
| Germany | 2216 | 1268 | 754 | 10.4 | 6.0 | 3.6 |
| Greece | 225 | 154 | 108 | 4.1 | 2.8 | 2.0 |
| Ireland | 26 | 8 | 1 | 1.1 | 0.3 | 0.0 |
| Italy | 1673 | 1164 | 782 | 10.6 | 7.4 | 5.0 |
| Luxembourg | 24 | 14 | 9 | 15.8 | 9.7 | 5.9 |
| Netherlands | 105 | 82 | 59 | 8.0 | 6.3 | 4.6 |
| Portugal | 380 | 288 | 179 | 6.6 | 5.0 | 3.1 |
| Spain | 2019 | 1377 | 619 | 6.6 | 4.5 | 2.0 |
| Sweden | 106 | 21 | 2 | 0.4 | 0.1 | 0.0 |
| UK | 206 | 154 | 85 | 2.5 | 1.9 | 1.0 |
| EU-15 | 11689 | 7336 | 4244 | 6.3 | 3.9 | 2.3 |

In 1990, France, Germany, Spain and Italy experienced the highest cumulative indices, while, for instance, the UK had a significantly lower value. On average, the highest exposure was experienced in France, Luxembourg, Belgium, Germany and Italy. The current reduction measures are expected to decrease the indices for the EU-15 by 36 percent, which is significantly lower than the expected decline of the health-related exposure indices (- 57 percent). While areas with already low indices achieve a 60 - 85 percent reduction (Ireland, Sweden, etc.), the expected improvement in Belgium, the Netherlands and the UK ranges only between five and 15 percent. Again, as for the AOT60 this low improvement is caused by the features of the ozone chemistry in high-$NO_x$ regions. The maximum feasible reductions would overcome these effects and lead to a 63 percent reduction for the EU-15 as a whole.

# 5 Targets for Ozone Reduction in Europe

Based on the finding that current policies will not be sufficient to fully achieve the environmental long-term targets for ozone, it seems obvious that further measures will be necessary to move closer towards these objectives. In such a situation it is a key task for an ozone strategy to find an appropriate rationale for shaping the next step towards the long-term targets.

It is clear from the analysis in the preceding section that the full achievement of the ultimate targets everywhere will be difficult, if not impossible, to attain within the time horizon of this analysis, given the technical and economic restrictions for emission abatement measures. Consequently, a realistic strategy could only establish an interim target on the way towards the ultimate objective.

It is in the nature of the matter that the choice of the interim target will crucially determine the extent of required emission controls, the associated costs and the environmental benefits and will decide their distribution across regions and economic sectors in Europe. A number of alternative concepts for establishing interim targets could be imagined:

- Further emission controls could be selected solely on the basis of their technical and/or economic properties. Such technology-related approaches were, and still are, frequently employed and are useful for guaranteeing minimum environmental standards without causing unjustified distortions for individual emission sources. A major disadvantage, however, is that they do not establish a relation to the specific environmental situation and that they might require measures which are not justified by actual environmental improvements.

In order to overcome this shortcoming, the ’effect-based’ approach was developed, which selects the measures to be taken on the basis of their cost-effectiveness for improving the environmental situation. In practice, the cost-effectiveness analysis starts from given environmental targets and identifies the least-cost combination of measures for achieving these targets. This means that the effect-based approach assists in identifying measures leading to effective environmental improvements. However, it does not provide guidance for selecting the targets themselves (and their spatial distribution). It remains a matter of preference whether priority should be given

- to the improvement of the situation in areas with largest ozone problems (hot-spots), e.g., by establishing a uniform target exposure value to be achieved everywhere, or
- to a general move towards the long-term targets, possibly by postulating uniform relative improvements in relation to the situation in a base year (the ’gap closure’ concept).

By gradually tightening the targets (e.g., the target value or the gap closure percentage), both strategies would eventually lead to full achievement of the environmental long-term target.

It has been demonstrated in the preceding section that the present ozone exposure shows strong regional differences over Europe. Even after implementation of the current legislation, significant parts of the European Union will face large-scale ozone exposure in excess of the environmental long-term targets:

- Highest large-scale excess of the environmental long-term targets is expected in northern France, the Benelux countries and in Germany;
- Additional ’hot-spots’ are expected to remain in and around urban areas in Mediterranean countries;
- For Ireland and Scandinavia, only relatively little excess exposure is anticipated.

Given these distinct regional differences of the ozone characteristics over Europe, it is to be expected that the two alternative principles of target setting (priority to 'hot spots' versus uniform 'gap closure') will result in rather different (spatial) allocations of emission reductions, abatement costs and environmental improvements:

- Priority for reducing the highest excess exposure will select measures solely on the basis of their contribution to ozone levels in these 'hot spots'. Since the absolute excess is highest in a confined region in the north-west of Europe (Benelux countries, northern France, Germany), emission controls are targeted to this limited region. All other areas with lower ozone would not experience an improvement of their situation, unless their ozone chemistry is strongly interconnected via the atmospheric long-range transport to the 'hot spots'. To some degree, measures are proportional to the severity of the ozone problem in the region.
- Emphasis on a general move towards the environmental long-term target ('closing the gap between current excess and the ultimate goal) would allocate measures more evenly over the entire area where these final targets are not yet achieved. However, this principle would not necessarily impose stricter requirements on 'hot spots' (even if they could be easily accomplished), but it could possibly imply heavy burdens for comparatively 'clean' areas, where further improvements are difficult to attain.

It is important to mention that both principles are presently applied for air quality management on the European scale: The Air Quality Framework Directive of the European Union uses the concept of spatially uniform 'target values' for prescribing desired environmental conditions and triggering actions in the case of non-achievement. The concept of 'closing the gap' between present excess exposure and the long-term target was practically applied in more strategic environmental accords, such as the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution and the Acidification Strategy of the European Union.

The following sections will discuss these two principles in more detail and illustrate their implications for emission reductions, costs and environmental effects. The analysis is carried out in parallel for health-related (optimizations using the AOT60 as a surrogate health indicator) and for vegetation-related ozone exposure.

# 6 Interim Targets for Health-related Ozone Exposure

## 6.1 *Optimized Emission Controls to Bring the AOT60 Everywhere Below a Common Target Value*

One possible rationale for selecting environmental interim targets is to establish one common target value to be attained throughout Europe. For practical reasons, this value must be set at a high enough level to be achievable even in the areas with currently highest ozone. In the European context this means that this value will necessarily be above the current exposure in many other regions in Europe. Strategies for achieving this goal will focus emission reductions on the sources contributing to the highest excess, and will per se not imply further actions to improve areas with lower exceedences of the long-term target. As a logical outcome of this approach, the distribution of abatement costs will be largely proportional to the severity of the ozone problem.

As listed in Table 6.1, for the emissions of 1990 the highest AOT60 occurred, according to model calculations, in the region of northern France, Belgium, Netherlands and Germany with typical values between 10 and 12 ppm.hours. The emission reductions of the REF scenario are expected to bring the peak AOT60 below 6 ppm.hours (Table 6.2); the MFR scenario would still leave the area around Maastricht (grid 20/15) above 3.2 ppm.hours. This means that any strategy, in order to be feasible, could only select a target value of more than 3.2 ppm.hours, a value which is achieved already by the REF scenario for the clear majority of grid cells in Europe (see also Figure 4.2).

Table 6.1: The highest occurrences of the AOT60 for the emissions of 1990

| Grid cell<br>EMEP coordinates | Country/region | Meteorology | AOT60 for emissions of 1990 (ppm.hours) |
|---|---|---|---|
| 21/14 | LUX/BEL/FRA/GER | 1994 | 12.7 |
| 22/14 | FRA/GER | 1994 | 11.1 |
| 21/15 | GER | 1994 | 10.8 |
| 22/14 | FRA/GER | 1990 | 9.8 |
| 22/15 | GER | 1994 | 10.5 |
| 20/12 | FRA | 1990 | 9.9 |
| 19/12 | FRA | 1989 | 9.7 |
| 20/12 | FRA | 1989 | 9.6 |

Table 6.2: The highest occurrences of the AOT60 for the emissions of the REF scenario

| Grid cell<br>EMEP coordinates | Country/region | Meteorology | AOT60 for emissions of 1990 (ppm.hours) |
|---|---|---|---|
| 20/15 | NL/BEL/GER | 1994 | 6.0 |
| 21/14 | LUX/BEL/FRA/GER | 1994 | 6.0 |
| 21/15 | GER | 1994 | 5.4 |
| 19/12 | FRA | 1989 | 5.2 |
| 20/14 | BEL/FRA | 1994 | 5.0 |
| 20/13 | FRA | 1989 | 4.8 |
| 20/12 | FRA | 1989 | 4.6 |
| 20/14 | FRA | 1989 | 4.6 |

Table 6.3: The highest occurrences of the AOT60 for the emissions of the MFR scenario

| Grid cell<br>EMEP coordinates | Country/region | Meteorology | AOT60 for emissions of 1990 (ppm.hours) |
|---|---|---|---|
| 20/15 | NL/BEL/GER | 1994 | 3.2 |
| 21/14 | LUX/BEL/FRA/GER | 1994 | 2.8 |
| 21/15 | GER | 1994 | 2.7 |
| 21/16 | GER | 1994 | 2.6 |
| 20/14 | FRA | 1989 | 2.4 |
| 19/12 | FRA | 1989 | 2.4 |
| 18/2 | POR | 1989 | 2.4 |
| 20/16 | NL/GER | 1990 | 2.3 |
| 20/13 | FRA | 1989 | 2.3 |

Another important aspect illustrated by these three tables is the fact that ozone concentrations are not only determined by the surrounding emissions, but are also strongly influenced by the meteorological conditions. It is shown that, while keeping the emissions constant, the AOT60 maxima occur in different regions in different meteorological years. The implications of the inter-annual meteorological variability on the optimized allocation of emission reductions were a major theme of the Third Interim Report of this study (Amann *et al.*, 1997). Assessing the meteorological variations over five years, in this report it was concluded that:

- for constant emissions, the AOT60 typically varies by a factor of plus/minus two as a result of meteorology;
- optimized reduction requirements for $NO_x$/VOC emissions of individual countries may differ by up to 40 percentage points, depending on the meteorological conditions assumed for the analysis;
- preparing for the worst case is expensive, and
- the worst case/year is not identical over all of Europe.

As a consequence, a methodology was developed to simultaneously optimize emission reductions for the meteorological conditions of multiple years (the ’composite optimization’). In practice it was suggested to ignore, for each grid cell separately, the meteorological conditions of the year in which the environmental target is most difficult to achieve, and to aim at a strategy which would attain the (interim) targets in all of the remaining four years.

Keeping to this 'four out of five' principle, for this Fourth Interim Report a number of optimization runs have been performed with increasingly stringent restrictions on the maximum AOT60. Analysis showed that the starting point of the optimization, i.e., the REF scenario, would result in a maximum AOT60 of about 3.5 ppm.hours (ignoring the worst of the five years). On the other hand, the maximum technically feasible reductions would still leave some grids in the Benelux countries with an AOT60 of about 2.6 ppm.hours, again if the worst year is excluded from consideration. Consequently, the series of optimization runs explored the reduction requirements for gradually reducing the AOT60 ceiling from 3.25 to 3.0 to 2.75 ppm.hours.

Table 6.4 illustrates the outcomes of the optimization runs. For the EU-15, $NO_x$ reductions (compared to the level of 1990) increase from 45 percent in the REF scenario to 48 and 50 percent in the most stringent case. While this reflects a 9 percent reduction of $NO_x$ emissions below REF, VOC emissions are further reduced by 17 percent. Abatement costs on top of REF increase from 2.5 billion ECU/year for the 3.25 ppm.hours ceiling to 5.5 billion for the 2.75 ppm.hours target. The cumulative population exposure index declines between 24 percent and 37 percent compared to the REF case.

Figure 6.1 compares the additional abatement costs involved with the three scenarios with the improvement in the cumulative population exposure index. As to be expected on theoretical grounds, stricter targets result in diminishing returns. It is interesting, however, to note that the graph does not reveal an obvious 'knuckle point', i.e., a point from where on the costs experience a steep increase.

Table 6.5 presents the emissions and the costs for the 'central' 3.0 ppm.hours AOT60 ceiling scenario (D1/2). The table clearly indicates that emission reductions are geared towards the high-ozone areas in the north-west of Europe; highest costs would occur in Germany, Belgium, UK, and France. Only little action would be required in Scandinavia, Ireland and in the Mediterranean countries. Due to the chemical (high-$NO_x$) regime prevailing in the high-ozone region, introducing an absolute AOT60 ceiling for all of Europe puts stronger emphasis on further measures for VOC emissions. Most notably, largest additional reductions (on top of REF) occur for Belgium (-28 percentage points), Germany (-14 percent), UK (-13 percent), Luxembourg (-11 percent) and Netherlands (-9 percent). Significant $NO_x$ reductions occur only in regions with a need (and a potential) for overcoming the '$NO_x$ hill' of the non-linear ozone response (see also the explanation in Section 2.5.2), i.e., in Belgium (-28 percent), France (-9 percent) and Luxembourg (-10 percent).

Table 6.4: Emissions, control costs and population exposure indices for the 'AOT60 ceiling' scenarios D1/1 to D1/3. Percentage changes relate to the year 1990.

| AOT60 ceiling<br>Scenario | -<br>REF | 3.25<br>D1/1 | 3.0<br>D1/2 | 2.75<br>D1/3 | -<br>MFR |
|---|---|---|---|---|---|
| $NO_x$ emissions [kt] | 7029<br>(-45%) | 6693<br>(-48%) | 6661<br>(-48%) | 6406<br>(-50%) | 4035<br>(-69%) |
| VOC emissions [kt] | 7311<br>(-46%) | 6551<br>(-52%) | 6303<br>(-53%) | 6048<br>(-55%) | 4828<br>(-64%) |
| Costs (on top of REF), [million ECU/yr] | 0 | 2514 | 3590 | 5541 | 26545 |
| Cumulative population exposure index | 477<br>(-57%)- | 363<br>(-68 %) | 330<br>(-71 %) | 302<br>(-73 %) | 182<br>(-84 %) |

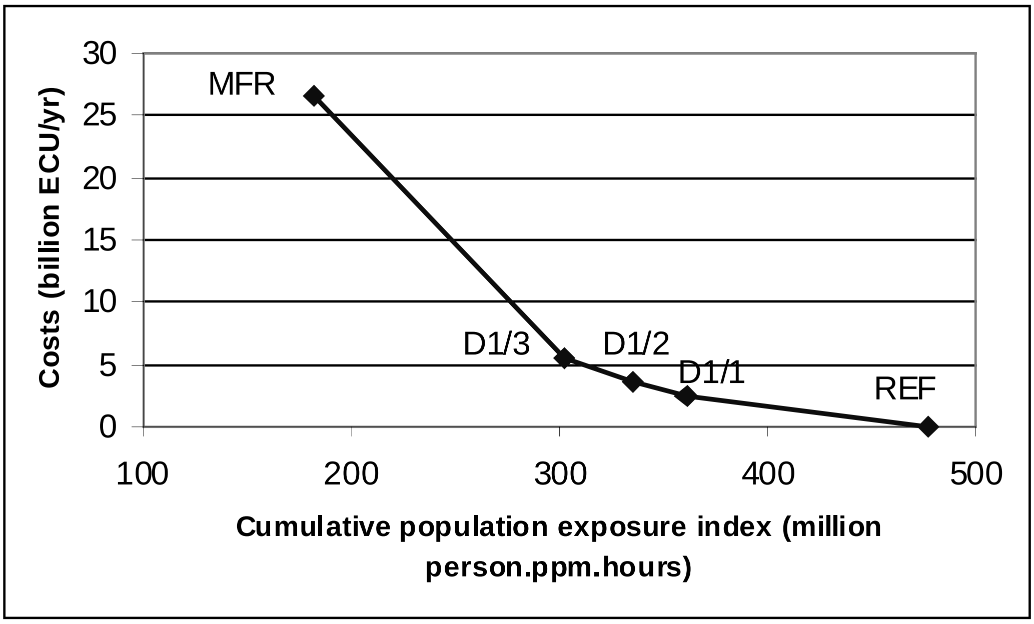

Figure 6.1: Cost-effectiveness of the AOT60-ceiling scenarios

Table 6.5: Emissions and control costs for REF and the 3.0 ppm.hours AOT60-ceiling scenario (D1/2). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| Scenario | REF | | D1/2 | | REF | | D1/2 | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | *-51%* | 110 | *-53%* | 305 | *-29%* | 290 | *-32%* | 41 |
| Belgium | 209 | *-42%* | 108 | *-70%* | 196 | *-43%* | 101 | *-71%* | 907 |
| Denmark | 128 | *-53%* | 128 | *-53%* | 92 | *-44%* | 92 | *-44%* | 0 |
| Finland | 155 | *-44%* | 155 | *-44%* | 108 | *-48%* | 108 | *-48%* | 0 |
| France | 811 | *-50%* | 662 | *-59%* | 1171 | *-45%* | 1090 | *-49%* | 383 |
| Germany | 1296 | *-51%* | 1208 | *-54%* | 1397 | *-55%* | 979 | *-69%* | 1405 |
| Greece | 324 | *-17%* | 324 | *-17%* | 205 | *-32%* | 205 | *-32%* | 0 |
| Ireland | 74 | *-31%* | 74 | *-31%* | 46 | *-59%* | 46 | *-59%* | 0 |
| Italy | 1166 | *-42%* | 1166 | *-42%* | 1079 | *-42%* | 1079 | *-42%* | 0 |
| Luxembourg | 10 | *-52%* | 8 | *-62%* | 8 | *-56%* | 6 | *-67%* | 15 |
| Netherlands | 270 | *-50%* | 270 | *-50%* | 203 | *-58%* | 157 | *-67%* | 147 |
| Portugal | 196 | *-6%* | 196 | *-6%* | 144 | *-34%* | 140 | *-35%* | 18 |
| Spain | 892 | *-23%* | 892 | *-23%* | 794 | *-25%* | 783 | *-26%* | 10 |
| Sweden | 220 | *-36%* | 197 | *-43%* | 287 | *-34%* | 287 | *-34%* | 24 |
| UK | 1163 | *-56%* | 1163 | *-56%* | 1276 | *-52%* | 940 | *-65%* | 640 |
| | | | | | | | | | |
| EU-15 | 7029 | *-45%* | 6661 | *-48%* | 7311 | *-46%* | 6303 | *-53%* | 3590 |

Figure 6.2 to Figure 6.4 illustrate the resulting AOT60 of the optimized D1/2 scenario (with an AOT60 ceiling of 3.0 ppm.hours, to be achieved in four out of five years). shows the mean AOT60 over the meteorological conditions of the five years (1989, 1990, 1992, 1993 and 1994). Not surprisingly, averaged over the meteorologies of the five years, the AOT60 is everywhere lower than the target value of 3.0 ppm.hours used as a constraint for the optimization.

Figure 6.3 displays the highest AOT60 for the ’four out of five’ situation, i.e., for the situation as the optimization sees it (where the ’most difficult’ year is excluded for each grid). The map shows clearly that three grids (20/14, 20/16 and 21/14; all of them in the Benelux region) end up with an AOT60 of exactly 3.0 ppm.hours, i.e., that they ’drive’ the solution for entire Europe. Everywhere else the optimized AOT60 is significantly lower than the target value.

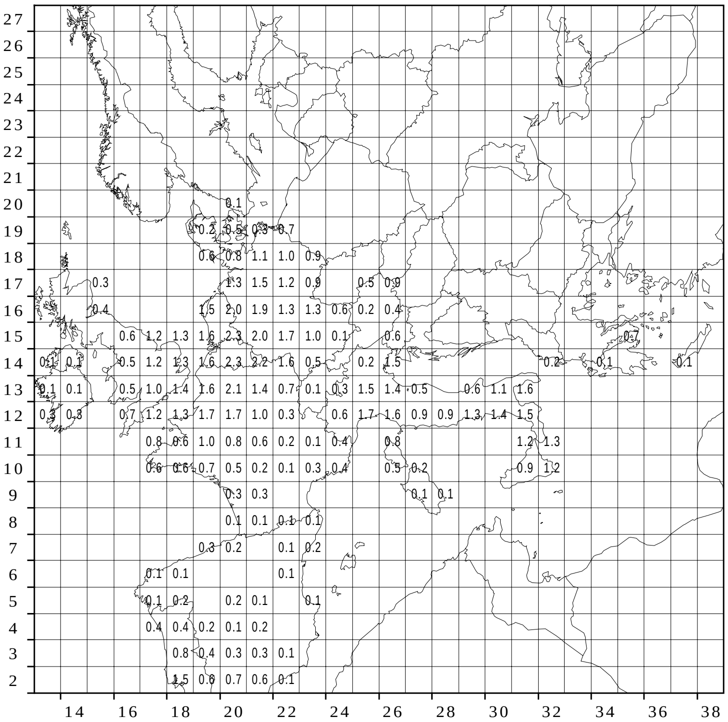

Figure 6.2: Mean AOT60 over the meteorologies of five years for the emissions of the 3 ppm.hours ceiling (D1/2) scenario, in ppm.hours.

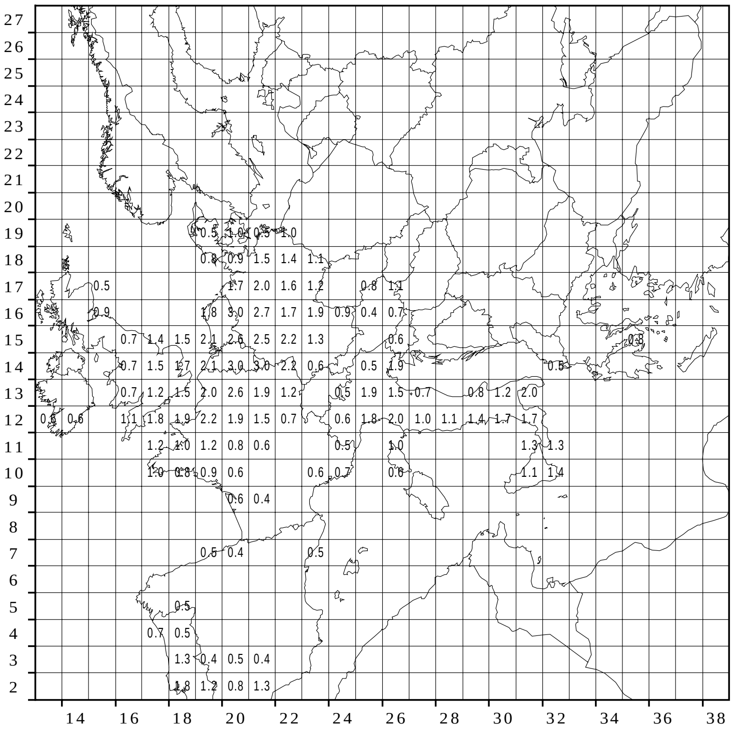

Figure 6.3: ’Second highest’ AOT60 for the emissions of the D1/2 (3.0 ppm.hours ceiling, to be met in four out of five years), in ppm.hours

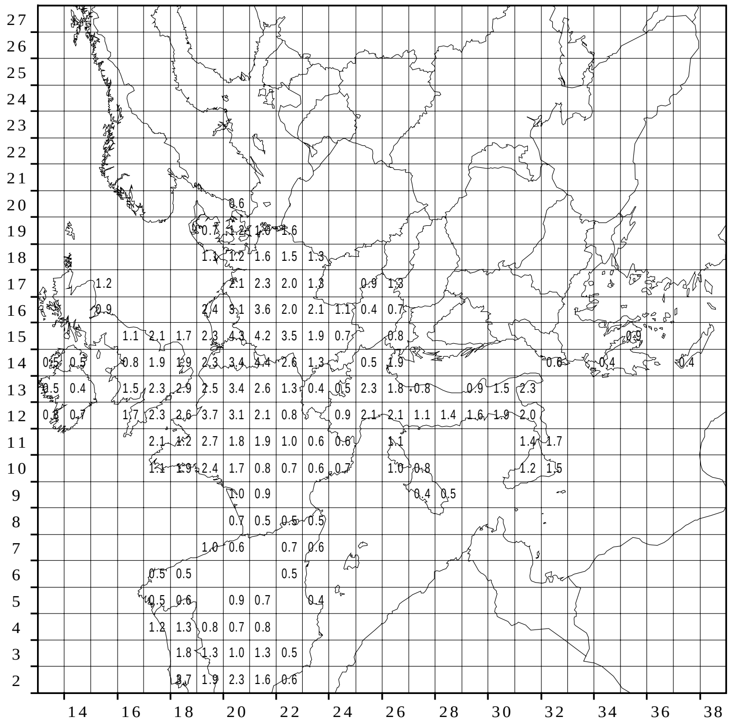

Figure 6.4: Highest AOT60 for the emissions of the D1/2 scenario, i.e., the AOT60 in the year which was ignored as a target; in ppm.hours

For comparison, Figure 6.4 shows the highest AOT60 resulting from the emissions of the D1/2 scenario including the most difficult year. The target level of 3 ppm.hours is exceeded in ten grids (in the north-west of Europe), with highest values of 4.4 ppm.hours. It must be stressed, however, that this map is of only academic value, since these peak concentrations do not occur simultaneously, but for the individual grids distributed over five years.

Table 6.6 compares the cumulative population exposure indices of the D1/2 scenario with the REF case. The table illustrates clearly that the improvement in ozone exposure resulting from such a uniform ’ceiling’ target is confined to the region with the highest ozone in Europe. Countries without contributions to these areas remain virtually unaffected (e.g., Ireland, Portugal, Austria, Greece).

Table 6.6: Cumulative population exposure index for the REF and the D1/2 (3.0 ppm.hours AOT60 ceiling) scenario, in million persons.ppm.hours

| | REF | | D1/2 | |
|---|---|---|---|---|
| | Million Person. ppm.hours | Change to 1990 | Million. Person. ppm.hours | Change to 1990 |
| Austria | 3 | -80% | 3 | -80% |
| Belgium | 35 | -44% | 23 | -63% |
| Denmark | 3 | -63% | 2 | -75% |
| Finland | 0 | -100% | 0 | -100% |
| France | 90 | -66% | 56 | -79% |
| Germany | 149 | -59% | 105 | -71% |
| Greece | 3 | -57% | 3 | -57% |
| Ireland | 1 | -50% | 1 | -50% |
| Italy | 60 | -62% | 41 | -74% |
| Luxembourg | 1 | -67% | 1 | -67% |
| Netherlands | 39 | -40% | 27 | -58% |
| Portugal | 8 | -50% | 8 | -50% |
| Spain | 8 | -75% | 10 | -69% |
| Sweden | 0 | -100% | 1 | -67% |
| UK | 76 | -38% | 49 | -60% |
| EU-15 | 477 | -57% | 330 | -71% |

## 6.2 Optimized Emission Controls to Cut the AOT60 Everywhere by 60 Percent

As an alternative concept for moving towards the environmental long-term target, a strategy could aim at environmental improvements everywhere where the ultimate targets are not yet achieved, without allowing progress to be limited by the situation at the most difficult areas. A practical example is the 'gap closure' concept, which calls for equal relative improvements of the excess exposure, starting from the situation in a base year. In the international context, this principle has been applied before for the negotiations on the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution and for the EU Acidification Strategy.

### 6.2.1 A Mechanism for Compensating Violations of Environmental Targets

Earlier analysis (see, e.g., Amann *et al.*, 1997) demonstrated that the optimal allocation of emission controls may be strongly influenced by the need to exactly meet specified targets at a few single grid cells, while for the majority of grid cells the targets are usually over-achieved. The sensitivity of the optimization results to modifications of the environmental targets of these 'binding grids' was the subject of numerous discussions in the past. It was argued that the requirement to achieve stringent isolated targets could possibly imply unbalanced high costs without yielding adequate benefits. This concern is even more pronounced when the targets are not related to absolute levels of exposure or damage (as is the case with the absolute AOT60 ceilings in Section 6.1), but to some interim targets on the way towards the ultimate environmental objective.

In response to a request of the Council Conclusions on the Acidification Strategy (8387/97 ENV 146 PRO-COOP45 - COM(97) 88 final), attempts were made to explore mechanisms to decrease the influence of single environmental targets on optimization results while preserving the overall level of the environmental objective. To this end a 'compensation approach' was developed, which allows the violation of environmental targets at single grid cells as long as this excess is compensated by additional improvements at other grid cells within the same country.

In order to accommodate proposals to consider differences in the stock at risk over grid cells (i.e., to put more relative emphasis on densely populated areas), a population weighting was introduced in the national compensation balances. This means that excess AOT60 must be compensated on a population-adjusted basis, e.g., a small excess of AOT60 in a big city by larger improvements in less populated rural areas. In practice, this population-weighting mechanism assures that for each country the population exposure index of the optimized solution (applying the compensation mechanism) may not exceed the index resulting from the original targets.

In practice, the 'gap closure' optimization with compensation proceeds along the following steps:

- For each grid cell, a 'soft' target is determined. This soft target is either the AOT60 of the base year (1990) reduced by *x* percent (for a *x* percent gap closure) or the AOT60 resulting from the REF scenario, whichever is lower.
- The AOT60 after the optimization may exceed the soft target in a grid, if the excess AOT60 (weighted by the population in the grid) is fully compensated by over-achievements of the soft targets at other grids in the same country (again population-weighted).
- For the AOT60, the country balances (of the excess population exposure indices) extend not only over all grids of a country, but also over all five meteorological years. This means (a) that for the gap closure approach also the worst meteorological year is considered in the optimization, and (b) that excess in some years may be compensated by additional improvements in other years.
- In addition, a lower cut-off for the AOT60 of 0.4 ppm.hours is introduced[16]. This means that grid cells with targets below 0.4 ppm.hours are excluded from the optimization, and that improvements below the level of 0.4 ppm.hours are not allowed to compensate violations at other grids. The major argument for this cut-off is the fact that the regression model used for calculating the AOT60 (see Section 2.5.1) is not valid below this level. Model artifacts should not be allowed to drive the optimization solution, nor should they justify violations of environmental targets at other grid cells.

In practice, the country balances ensure that for each country the population excess exposure indices will be reduced at least by the percentage of the selected gap closure, or phrased differently, that the desired 'gap closure' is achieved for the country population exposure indices rather than for individual grid cells.

The mathematical formulation of the optimization problem is provided in Section 2.6.

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- [16] For the calculations of the Third Interim Report, the cut-off level of 1 ppm.hours was related to the 1990 situation. In this report, the cut-off of 0.4 ppm.hours is applied to the actual target level. For a 60 percent gap closure the outcome is identical.

### 6.2.2 Optimized AOT60 Gap Closure Scenarios

Analysis of the REF scenario shows that the currently envisaged emission control measures will achieve for all countries at least a 40 percent reduction of the population exposure index, i.e., a 40 percent gap closure compared to the situation in the year 1990. On the other hand, the possible improvements as indicated by the MFR scenario are lowest in Greece, Portugal and the Benelux countries, ranging at about 70 percent compared to 1990. A realistic interim gap closure must therefore target somewhere between 40 and 70 percent.

A series of scenarios was calculated to assess the costs and emission reductions for a range of interim targets. In practice, optimizations were performed for a 55, 60 and 65 percent gap closure, respectively (Scenarios D2/1 to D2/3). Overall results of these optimizations are presented in Table 6.7. It is interesting to note that, in comparison to the AOT60 ceiling scenarios (D1), the gap closure approach involves more $NO_x$ reductions (from 45 percent of REF to a 56 percent reduction of $NO_x$ for theD2/3 scenario).

Table 6.7: Emissions, control costs and population exposure indices for the 'AOT60 gap closure' scenarios D2/1 to D2/3. Percentage changes relate to the year 1990.

| AOT60 gap closure | - | 55% | 60% | 65% | - |
|---|---|---|---|---|---|
| Scenario | REF | D2/1 | D2/2 | D2/3 | MFR |
| $NO_x$ emissions [kt] | 7029<br>(-45%) | 6654<br>(-48%) | 6175<br>(-52%) | 5591<br>(-56%) | 4035<br>(-69%) |
| VOC emissions [kt] | 7311<br>(-46%) | 6382<br>(-53%) | 5682<br>(-58%) | 5205<br>(-62%) | 4828<br>(-64%) |
| Costs (on top of REF), [million ECU/yr] | 0 | 2685 | 5643 | 11354 | 26545 |
| Cumulative population exposure index | 477 | 360 | 296 | 240 | 182 |

Figure 6.5 plots the costs of the gap closure scenarios D2/1 to D2/3 versus their population exposure indices and compares them with the AOT60 ceiling scenarios D1/1 to D1/3. It is interesting to realize that the overall shape of the cost-effectiveness curves for these two alternative target setting concepts is rather similar over wide ranges, and that also for the gap closure scenarios a clear 'knuckle point' seems to be absent.

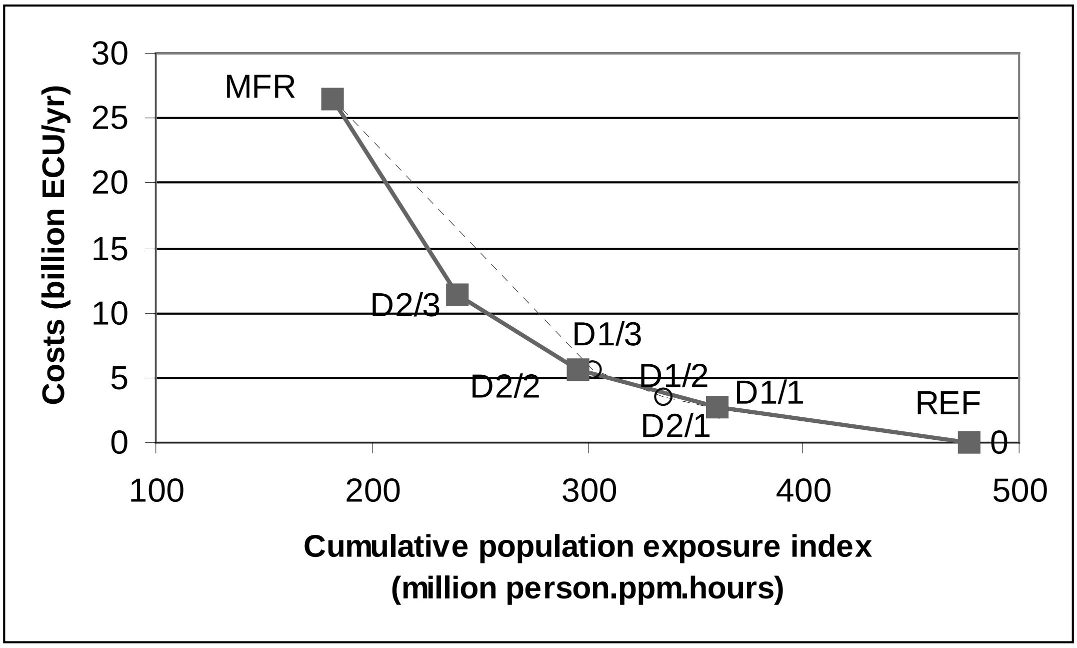

Figure 6.5: Cost-effectiveness of the optimized AOT60 scenarios. The solid line connects the points for the gap closure scenarios D2/1-3, while the dotted line indicates the AOT60 ceiling scenarios (D1/1-3)

Despite the similarities in the overall costs and exposure indices between the gap closure and the AOT60 ceiling scenarios, the spatial distribution of measures, costs and environmental benefits is different. Table 6.8 lists the country results for the 'central' 60 percent gap closure scenario D2/2. Highest costs occur in Germany, followed by France, Italy, UK and Belgium. It is important to note that the target to also improve lower levels of ozone exposure requires certain measures in Mediterranean countries (Portugal, Spain, Italy and Greece). There are major needs for further $NO_x$ reductions in Portugal, Belgium, Ireland, Spain and Italy, while VOC emissions should be further controlled in Belgium (-26 percent), Spain, Portugal, Germany, UK, Italy and France. The higher involvement of $NO_x$ reductions clearly illustrates that the more wide-spread environmental targets of a gap closure concept (due to the consideration of low- and high-$NO_x$ regions) yields a more balanced approach towards $NO_x$ and VOC reductions. This is in sharp contrast to a 'ceiling' strategy, which is strongly determined by the chemical regime prevailing in the 'worst ozone' region.

Figure 6.6 displays the grids where for the D2/2 scenario the 'soft' environmental targets, i.e., the 60 percent cut of the AOT60 calculated for the emissions of 1990, are violated at least in one of the five years. Excess ozone exposure at these grids is compensated by further ozone reductions in other years (Belgium, Netherlands) or at other grids in the same country. The map clearly indicates that such re-balancing is an important large-scale mechanism in the North-west of Europe (the Benelux countries, northern France and Germany, southern UK, and that it occurs for the large cities in Mediterranean countries (around Rome, Lisbon, Athens). In-depth analysis of the optimized solution reveals that for the 60 percent gap closure scenario the 'country balances ' are fully exhausted for the Netherlands, Belgium, Greece and Portugal.

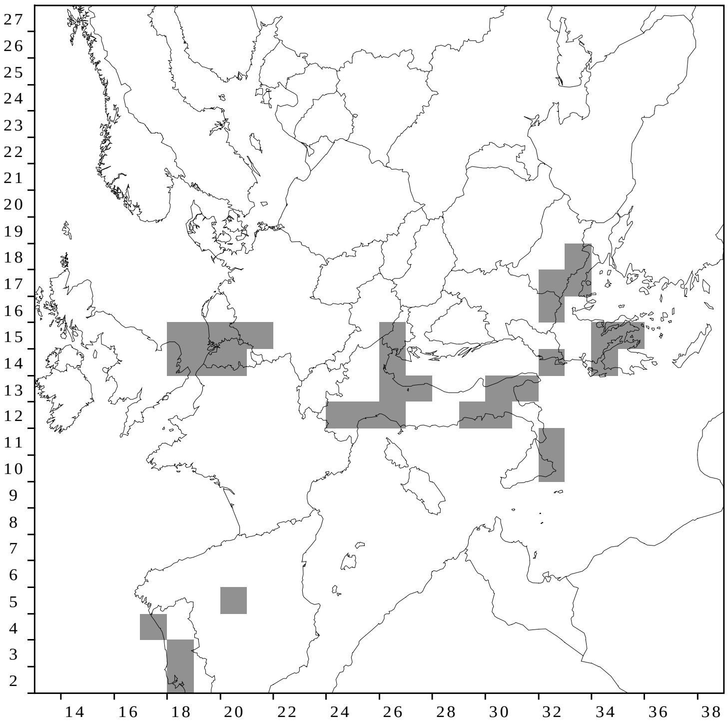

Figure 6.6: Grids where the 'soft targets' of the 60 percent gap closure (Scenario D2/2) are violated and where the excess in single years is compensated by additional reductions in other years or at other grid cells in the same country

It is interesting to note that in the optimized solution Portugal shows up with substantial emission reductions (mainly for $NO_x$). It is mentioned above that for Portugal the optimal solution is steered by its own 'country balance', i.e., by the need to reduce the population exposure index for the entire country. There are several important reasons for these optimization results:

- According to model calculations, the area around Lisbon experiences relatively high AOT60 (in 1990 about 3ppm.hours). Available monitoring data support these estimates (de Leeuw & van Zantvoort, 1997; Sluyter & van Zantvoort, 1997).
- Compared to other countries, Portugal expects a much higher economic growth leading to a strong increase of energy consumption and transport activities. As a result, the technical potential for emission reductions - compared to 1990 - is significantly lower than in all other EU countries.
- ($NO_x$) emissions from ship lanes along the Portuguese coast make a contribution to ozone, but no emission reductions are considered in this study for these sources.
- The relative share of 'background' ozone versus anthropogenic (controllable) ozone is higher on the Atlantic coast than inside the continent.

While all these arguments are valid explanations for the higher demand on Portuguese emission reductions posed by a gap closure target, the determination of a robust and acceptable magnitude for such reductions remains a subject for further analysis.

Table 6.8: Emissions and control costs for REF and the AOT60 60% gap closure scenario (D2/2). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D2/2 | | REF | | D2/2 | | $10^6$ |
| | kt | *Change* | kt | *Change* | Kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -51% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 133 | -63% | 196 | -43% | 105 | -69% | 562 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 78 | -53% | 25 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 623 | -62% | 1171 | -45% | 943 | -56% | 958 |
| Germany | 1296 | -51% | 1227 | -54% | 1397 | -55% | 976 | -69% | 1370 |
| Greece | 324 | -17% | 322 | -18% | 205 | -32% | 177 | -41% | 183 |
| Ireland | 74 | -31% | 56 | -48% | 46 | -59% | 46 | -59% | 4 |
| Italy | 1166 | -42% | 960 | -52% | 1079 | -42% | 833 | -55% | 740 |
| Luxembourg | 10 | -52% | 10 | -52% | 8 | -56% | 8 | -56% | 0 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 149 | -69% | 216 |
| Portugal | 196 | -6% | 114 | -45% | 144 | -34% | 124 | -43% | 486 |
| Spain | 892 | -23% | 679 | -41% | 794 | -25% | 613 | -42% | 423 |
| Sweden | 220 | -36% | 220 | -36% | 287 | -34% | 287 | -34% | 0 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 930 | -65% | 675 |
| EU-15 | 7029 | -45% | 6175 | -52% | 7311 | -46% | 5682 | -58% | 5643 |

Table 6.9 presents the cumulative population exposure indices for all countries for the 60 percent gap closure scenario (D2/2) and contrasts them with those of the REF scenario. Compared to 1990, the index declines as a result of the gap closure scenario by 74 percent (instead of 57 percent for the REF case). It is clear from this table that such a scenario reduces the exposure index in all countries, except in the cases where REF already results in full achievement of the ultimate target. This is much in contrast to the AOT60 ceiling scenario (D1/2, see Table 6.6), where the improvement is centered on the north-west of Europe, while other countries on the periphery of the EU (e.g., Austria, Ireland, Portugal) remain unaffected.

Figure 6.7 presents the AOT60 of the D2/2 scenario.

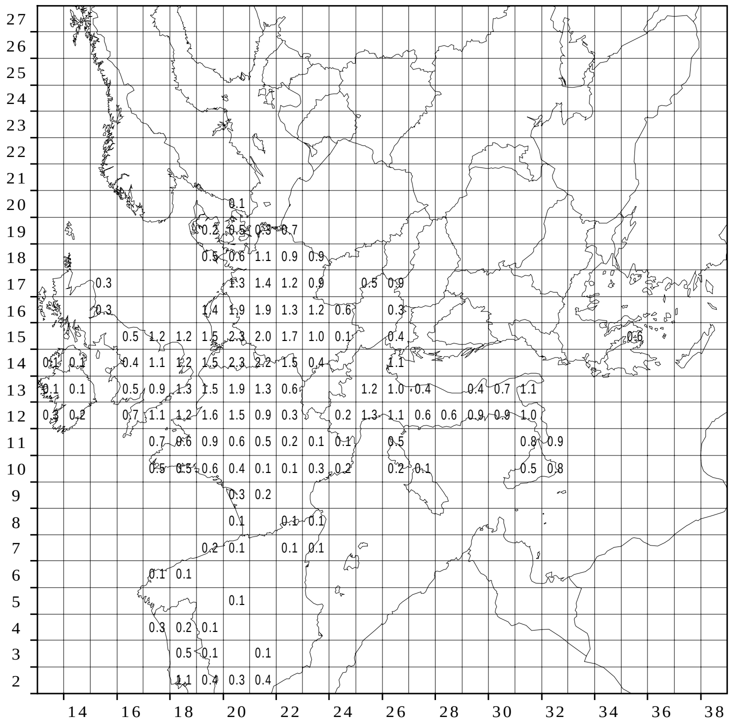

Figure 6.7: AOT60 of the 60% gap closure scenario (mean over the five years meteorology)

Table 6.9: Cumulative population exposure index for the REF and the D2/2 (60% gap closure) scenario, in million persons.ppm.hours

| | REF | | D2/2 | |
|---|---|---|---|---|
| | Million person. ppm.hours | Change to 1990 | Million. person. ppm.hours | Change to 1990 |
| Austria | 3 | -80% | 2 | -87% |
| Belgium | 35 | -44% | 23 | -63% |
| Denmark | 3 | -63% | 1 | -88% |
| Finland | 0 | -100% | 0 | -100% |
| France | 90 | -66% | 49 | -81% |
| Germany | 149 | -59% | 101 | -72% |
| Greece | 3 | -57% | 2 | -71% |
| Ireland | 1 | -50% | 0 | -100% |
| Italy | 60 | -62% | 36 | -77% |
| Luxembourg | 1 | -67% | 1 | -67% |
| Netherlands | 39 | -40% | 26 | -60% |
| Portugal | 8 | -50% | 5 | -69% |
| Spain | 8 | -75% | 2 | -94% |
| Sweden | 0 | -100% | 0 | -100% |
| UK | 76 | -38% | 42 | -66% |
| | | | | |
| EU-15 | 477 | -57% | 292 | -74% |

## 6.3 A Combination of the AOT60 Ceiling and Gap Closure Targets

The above analysis clearly illustrates the general advantages and disadvantages of the two alternative concepts for setting environmental interim targets in an international context. Stated in brief, the AOT60 ceiling approach concentrates on the most polluted areas and derives the priority of international measures based on their contribution to the ozone problem in these regions. The gap closure approach results in spatially wide spread environmental improvements, but attributes relatively less attention to areas where the problem is worst. Although individual countries might favor the one or the other approach based on a particular distribution of costs and benefits for their territory, it is difficult to decide about the superiority of either one in the European situation. Ultimately, it will remain a matter of political judgement whether priority should be restricted to 'hot spots' or extended to a general move towards the environmental long-term targets.

To this end, an attempt was made to combine these two target setting principles into one single optimization problem. It is the hope that this combination would merge the advantages of both approaches, i.e., put higher pressure on heavily polluted areas while also keeping a certain momentum towards the environmental long-term target in regions where the problem is less severe.

Based on the target ranges illustrated in the preceding sections (AOT60 ceilings between 3.25 and 2.75 ppm.hours, AOT60 gap closures between 55 and 65 percent), a large number of combinations of these two criteria could be imagined. In order to keep the analysis manageable and the presentation of the results understandable to the reader, a choice has been made to center the analysis around a combination of the AOT 60 ceiling of 3.0 ppm.hours and the 60 percent gap closure (Scenario D3). Sensitivity analyses explored the response behavior of the optimization towards changes in these two target parameters.

Table 6.10 presents the aggregated results for the 'central' combination of 60 percent gap closure and 3.0 ppm.hours ceiling as well as the responses to variations in these targets. There is clear evidence that the combined optimization is dominated by the gap closure target. Variations of this target result in cost changes of -30/+90 percent and changes in the exposure index of -18/+14 percent. On the other hand, modifying the ceiling target has a -2/+22 percent influence on costs and a -5/+1 percent influence on the index.

Table 6.11 provides the country emissions and costs (on top of REF) of the central combined scenario. Costs are highest in Germany, France, Italy, the UK and Belgium, and measures are distributed over most countries. The scenario results in a further decline of $NO_x$ emissions of seven percentage points below REF, and of 12 percentage points for VOC. Relative highest $NO_x$ reductions emerge for Portugal and Belgium (-39 and -22 percent, respectively). For France, Ireland, Italy and Spain, further cuts in $NO_x$ range between 10 and 17 percent. Most stringent VOC measures are required for Belgium (-26 percent), while a large group of countries (Denmark, France, Germany, Greece, Italy, Netherlands, Spain and UK) end up with VOC reductions between 10 and 15 percent.

Table 6.12 displays the cumulative population exposure indices for the combined D3 scenario. As to be expected from the 'overlay' of the ceiling and the gap closure targets (i.e., due to the requirements of the gap closure target), improvements in the population exposure index occur in all countries.

Table 6.10: Emissions, costs and population exposure indices for the combined AOT60 ceiling/gap closure scenarios

| | AOT60 ceiling (ppm.hours) | | |
|---|---|---|---|
| | 3.25 | 3.00 | 2.75 |
| 55% gap closure | | $NO_x$= 6582 kt<br>VOC = 6200 kt<br>Costs = 4066 MECU<br>Index = 330 | |
| 60% gap closure | $NO_x$= 6148 kt<br>VOC = 5685 kt<br>Costs = 5758 MECU<br>Index = 292 | $NO_x$= 6140 kt<br>VOC = 5672 kt<br>Costs = 5877 MECU<br>Index = 290 | $NO_x$= 5966 kt<br>VOC = 5614 kt<br>Costs = 7194 MECU<br>Index =276 |
| 65% gap closure | | $NO_x$= 5583 kt<br>VOC = 5205 kt<br>Costs = 11427 MECU<br>Index = 239 | |

Table 6.11: Emissions and control costs for REF and the combined AOT60 3.0 ppm.hours ceiling/ 60% gap closure scenario (D3). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D3 | | REF | | D3 | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -51% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 129 | -64% | 196 | -43% | 105 | -69% | 605 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 79 | -52% | 23 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 592 | -63% | 1171 | -45% | 938 | -56% | 1118 |
| Germany | 1296 | -51% | 1224 | -54% | 1397 | -55% | 975 | -69% | 1384 |
| Greece | 324 | -17% | 322 | -18% | 205 | -32% | 177 | -41% | 183 |
| Ireland | 74 | -31% | 57 | -47% | 46 | -59% | 46 | -59% | 4 |
| Italy | 1166 | -42% | 960 | -52% | 1079 | -42% | 837 | -55% | 725 |
| Luxembourg | 10 | -52% | 10 | -52% | 8 | -56% | 8 | -56% | 0 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 149 | -69% | 217 |
| Portugal | 196 | -6% | 114 | -45% | 144 | -34% | 124 | -43% | 483 |
| Spain | 892 | -23% | 682 | -41% | 794 | -25% | 615 | -42% | 411 |
| Sweden | 220 | -36% | 219 | -36% | 287 | -34% | 287 | -34% | 1 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 919 | -65% | 722 |
| EU-15 | 7029 | -45% | 6140 | -52% | 7311 | -46% | 5672 | -58% | 5877 |

Table 6.12: Cumulative population exposure index for the REF and the D3 (combined 60% gap closure/3 ppm.hours ceiling) scenario, in million persons.ppm.hours

| | REF | | D3 | |
|---|---|---|---|---|
| | Million person. ppm.hours | Change to 1990 | Million. person. ppm.hours | Change to 1990 |
| Austria | 3 | -80% | 2 | -87% |
| Belgium | 35 | -44% | 22 | -65% |
| Denmark | 3 | -63% | 1 | -88% |
| Finland | 0 | -100% | 0 | -100% |
| France | 90 | -66% | 49 | -81% |
| Germany | 149 | -59% | 100 | -72% |
| Greece | 3 | -57% | 2 | -71% |
| Ireland | 1 | -50% | 0 | -100% |
| Italy | 60 | -62% | 36 | -77% |
| Luxembourg | 1 | -67% | 1 | -67% |
| Netherlands | 39 | -40% | 26 | -60% |
| Portugal | 8 | -50% | 5 | -69% |
| Spain | 8 | -75% | 2 | -94% |
| Sweden | 0 | -100% | 0 | -100% |
| UK | 76 | -38% | 42 | -66% |
| | | | | |
| EU-15 | 477 | -57% | 290 | -74% |

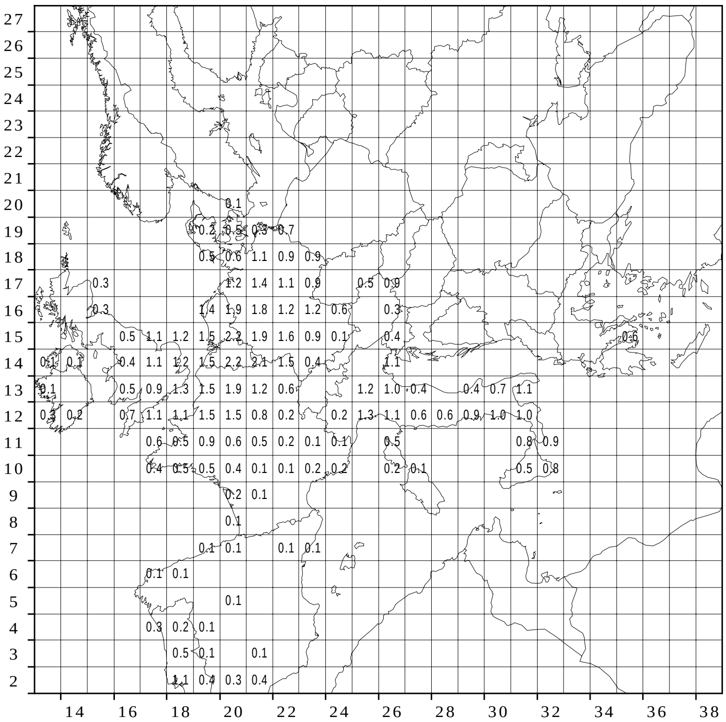

Figure 6.8: Mean AOT60 for the combined 60% gap closure/3 ppm.hours ceiling (D3) scenario (in ppm.hours)

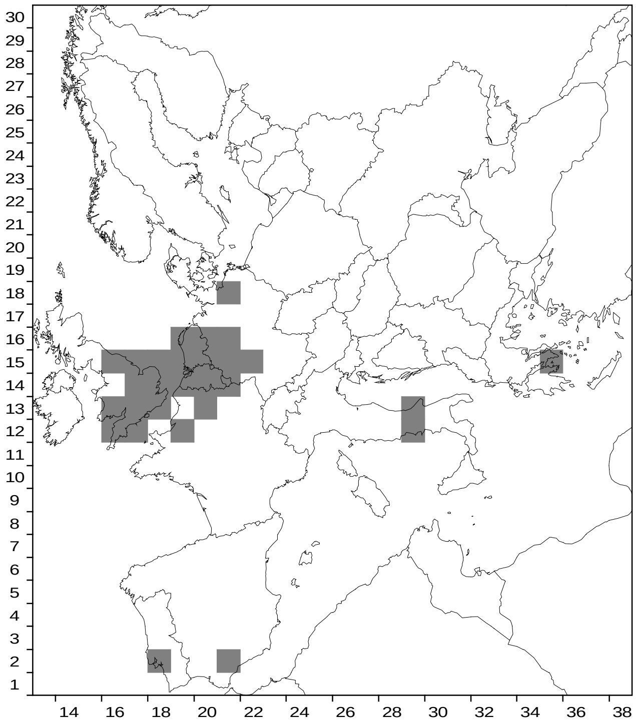

Figure 6.9: Grid cells where the AOT60 in the D3 scenario violates the ’soft targets’ and where the excess in single years is compensated by additional reductions in other years or at other grid cells in the same country ’

# 7 Ozone Reductions Targeted at Vegetation Protection

It has been shown in earlier reports (e.g., Amann, 1997) that optimized strategies aimed at health- and vegetation-related criteria result in different allocations of emission reductions, particularly in different relationships between $NO_x$ and VOC reductions.

The following section examines the implications of the two target setting concepts (’hot spots’ versus ’gap closure’) for vegetation oriented emission control strategies. As explained in Section 4.3, the assessment focuses on the ’AOT40’ criterion for natural vegetation and crops.

The definition of the critical level for vegetation protection is based on five years mean exposure (Kärenlampi L., Skärby L., 1996). Consequently, the scenario analysis carried out for this study could restrict itself to one set of source-receptor relationships, reflecting the accumulated excess AOT40 over the five available meteorological years.

## *7.1 Optimized Emission Controls to Bring the AOT40 Everywhere Below a Common Target Value*

Figure 4.7 in Section 4.3 shows that in the REF case the highest AOT40 in excess of the critical levels for natural vegetation are expected to occur in northern Italy (up to 12 ppm.hours) and in the Benelux region with excess values of around 10 ppm.hours. For all other areas the scenario results in lower excess exposure. With maximum feasible emission reductions the highest excess could be reduced to 8 - 9 ppm.hours (Figure 4.8).

In order to find possible interim targets, three optimization runs have been performed for AOT40 ceilings of 10.5, 10.0 and 9.5 ppm.hours of excess exposure (scenarios D4/1 to D4/3). Table 7.1 presents the main results of these optimizations. With costs ranging from 1.1 to 3.4 billion ECU/year (on top of REF), the cumulative vegetation exposure index would decline between 8 and 17 percent compared to REF. The scenarios suggest similar overall reductions of $NO_x$ and VOC emissions.

Table 7.2 provides for the 'central' scenario, i.e., the scenario with an AOT40 ceiling of 10.0 ppm.hours, the emission reductions for $NO_x$ and VOC on a country basis. As to be expected from the REF case, measures are focussed almost exclusively on the two areas where the AOT40 of the REF scenario is above the target; this means that highest costs occur in France for a 15 percent $NO_x$ reduction and in Italy for 15 percent cuts in $NO_x$ and VOC emissions, respectively.

A map with the remaining excess AOT40 of the D4/2 scenario is displayed in Figure 7.2. Most parts of the European Union are expected to still face excess exposure above the long term targets (with the exception of Scandinavia and Ireland), and the maximum excess occurs in northern Italy and France. Table 7.3 presents the cumulative vegetation exposure indices for the central 10.0 ppm.hours AOT40 ceiling scenario (D4/2). The table illustrates that, although the measures are confined to a small number of countries, transboundary effects lead to improvements in ozone exposure throughout all EU countries.

Table 7.1: Emissions, control costs and vegetation exposure indices for the 'AOT40 ceiling' scenarios D4/1 to D4/3. Percentage changes relate to the year 1990

| AOT40 ceiling (ppm.hours) | - | 10.5 | 10.0 | 9.5 | - |
|---|---|---|---|---|---|
| Scenario | REF | D4/1 | D4/2 | D4/3 | MFR |
| $NO_x$ emissions [kt] | 7029<br>(-45%) | 6565<br>(-49%) | 6357<br>(-50%) | 6259<br>(-51%) | 4035<br>(-69%) |
| VOC emissions [kt] | 7311<br>(-46%) | 7112<br>(-47%) | 6938<br>(-49%) | 6556<br>(-52%) | 4828<br>(-64%) |
| Costs (on top of REF), [million ECU/yr] | 0 | 1077 | 1992 | 3391 | 26545 |
| Cumulative vegetation exposure index | 7336<br>(-37%) | 6732<br>(-42%) | 6438<br>(-45%) | 6113<br>(-48%) | 4243<br>(-64%) |

Figure 7.1 compares for the AOT40 ceiling scenarios the costs (on top of REF) with the vegetation exposure indices (ecosystems area x excess AOT40). Again, as in the AOT60 related scenarios, there is no distinct 'knuckle point' on these curves.

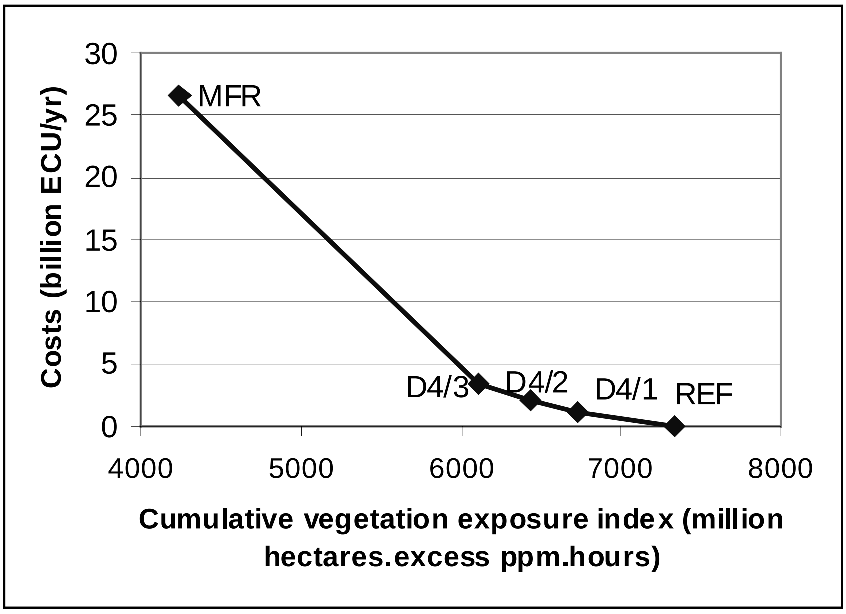

Figure 7.1: Cost-effectiveness of the AOT40-ceiling scenarios

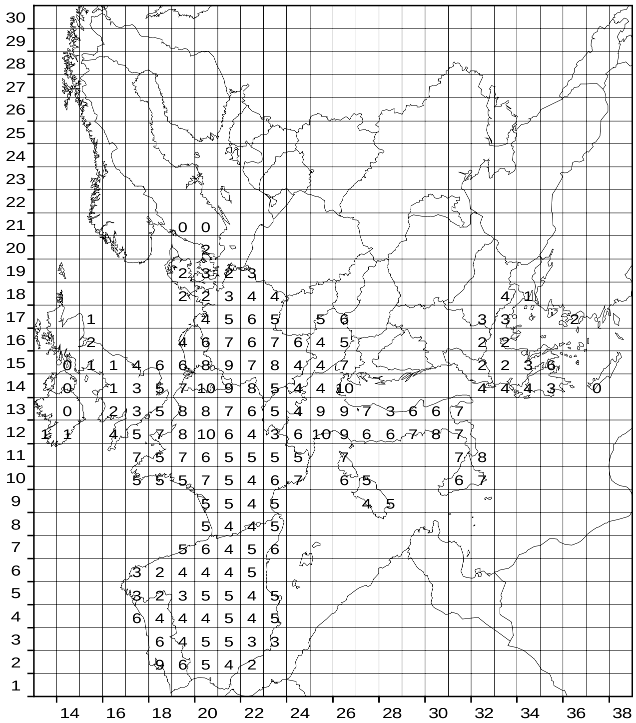

Figure 7.2: Excess AOT40 over the critical levels for the AOT40 10.0 ppm.hours ceiling scenario (in ppm.hours)

Table 7.2: Emissions and control costs for REF and the 10.0 ppm.hours AOT40-ceiling scenario (D4/2). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D4/2 | | REF | | D4/2 | | $10^6$ |
| | Kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -52% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 209 | -42% | 196 | -43% | 171 | -50% | 22 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 92 | -44% | 0 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 559 | -65% | 1171 | -45% | 1028 | -52% | 1059 |
| Germany | 1296 | -51% | 1296 | -51% | 1397 | -55% | 1397 | -55% | 0 |
| Greece | 324 | -17% | 324 | -17% | 205 | -32% | 205 | -32% | 0 |
| Ireland | 74 | -31% | 74 | -31% | 46 | -59% | 46 | -59% | 0 |
| Italy | 1166 | -42% | 859 | -57% | 1079 | -42% | 874 | -53% | 884 |
| Luxembourg | 10 | -52% | 10 | -52% | 8 | -56% | 8 | -56% | 0 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 203 | -58% | 0 |
| Portugal | 196 | -6% | 196 | -6% | 144 | -34% | 144 | -34% | 0 |
| Spain | 892 | -23% | 781 | -33% | 794 | -25% | 794 | -25% | 27 |
| Sweden | 220 | -36% | 220 | -36% | 287 | -34% | 287 | -34% | 0 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 1276 | -52% | 0 |
| | | | | | | | | | |
| EU-15 | 7029 | -45% | 6357 | -50% | 7311 | -46% | 6938 | -49% | 1992 |

Table 7.3: Cumulative vegetation exposure index for the REF and the D4/2 (10.0 ppm.hours AOT40 ceiling) scenario, in million hectares.excess ppm.hours

| | REF | | D4/2 | |
|---|---|---|---|---|
| | Million hectares. excess. ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 |
| Austria | 264 | -43% | 243 | -47% |
| Belgium | 143 | -17% | 132 | -23% |
| Denmark | 54 | -58% | 52 | -60% |
| Finland | 0 | -100% | 0 | -100% |
| France | 2346 | -41% | 1926 | -51% |
| Germany | 1268 | -43% | 1189 | -46% |
| Greece | 154 | -32% | 144 | -36% |
| Ireland | 8 | -71% | 6 | -76% |
| Italy | 1164 | -30% | 990 | -41% |
| Luxembourg | 14 | -39% | 13 | -46% |
| Netherlands | 82 | -22% | 78 | -26% |
| Portugal | 288 | -24% | 278 | -27% |
| Spain | 1377 | -32% | 1223 | -39% |
| Sweden | 21 | -81% | 19 | -82% |
| UK | 154 | -26% | 145 | -30% |
| EU-15 | 7336 | -37% | 6439 | -45% |

## 7.2 Optimized Emission Controls to Cut the AOT40 Everywhere by 35 Percent

As an alternative approach to the uniform AOT40 ceilings, the implications of ’gap closure’ targets have also been explored for vegetation related scenarios. Within the range spanned by the REF scenario and the maximum technically feasible reductions, optimization runs explored the emission reductions for a 30, 35 and 40 percent cut of the excess AOT40 calculated for the emissions of the year 1990 , respectively.

Following the same concept as for the AOT60 gap closure, the analysis allowed for a compensation of excess exposure at individual grids by additional improvements in other grid cells within the same country. Since the environmental endpoint of this analysis is directed at vegetation protection, the compensation must be accomplished on a ecosystems-area adjusted basis (i.e., the exposure in each grid is weighted by the ecosystems area, taking into account natural and agricultural ecosystems).

Table 7.4 presents the aggregated results for the three gap closure scenarios (D5/1 to D5/3). For the EU-15 as a whole, costs (on top of the Reference scenario) range between 2.3 and 7.9 billion ECU/year. $NO_x$ emissions would be reduced below REF between three and nine percentage points (related to 1990), VOC emissions between six and 18 percentage points. This results in a decline of the cumulative vegetation exposure index between 15 and 28 percent. Figure 7.3 compares the costs of these scenarios with the vegetation indices.

Table 7.4: Emissions, control costs and vegetation exposure indices for the 'AOT40 ceiling' scenarios D5/1 to D5/3. Percentage changes relate to the year 1990.

| AOT40 gap closure<br>Scenario | -<br>REF | 30%<br>D5/1 | 35%<br>D5/2 | 40%<br>D5/3 | -<br>MFR |
|---|---|---|---|---|---|
| $NO_x$ emissions [kt] | 7029<br>(-45%) | 6634<br>(-48%) | 6419<br>(-50%) | 5957<br>(-54%) | 4035<br>(-69%) |
| VOC emissions [kt] | 7311<br>(-46%) | 6533<br>(-52%) | 6161<br>(-54%) | 5714<br>(-58%) | 4828<br>(-64%) |
| Costs (on top of REF), [million ECU/yr] | 0 | 2334 | 4037 | 7900 | 26545 |
| Cumulative vegetation exposure index | 7336<br>(-37%) | 6235<br>(-47%) | 5864<br>(-50%) | 5284<br>(-55%) | 4243<br>(-64%) |

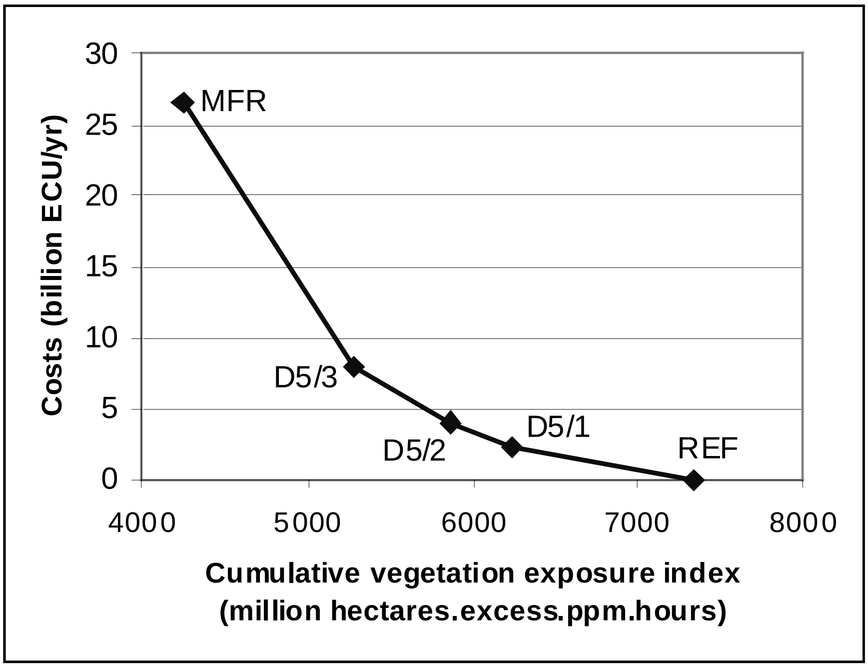

Figure 7.3: Cost-effectiveness of the AOT40 gap closure scenarios (D5/1 to D5/2)

Table 7.5 presents costs and emission reductions of the gap closure scenario on a country basis. While for achieving a uniform AOT40 ceiling measures are confined to few countries, the gap closure target allocates further emission controls to ten EU Member States. Highest costs occur in France (for $NO_x$ and VOC reductions) and in Germany and the UK for VOC control measures.

Table 7.5: Emissions and control costs for REF and the 35 percent AOT40 gap closure scenario (D5/2). Percentage changes relate to the year 1990.

| | NO$_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D5/2 | | REF | | D5/2 | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -51% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 209 | -42% | 196 | -43% | 108 | -69% | 298 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 92 | -44% | 0 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 553 | -66% | 1171 | -45% | 936 | -56% | 1391 |
| Germany | 1296 | -51% | 1296 | -51% | 1397 | -55% | 979 | -69% | 1223 |
| Greece | 324 | -17% | 291 | -26% | 205 | -32% | 205 | -32% | 16 |
| Ireland | 74 | -31% | 74 | -31% | 46 | -59% | 46 | -59% | 0 |
| Italy | 1166 | -42% | 1053 | -47% | 1079 | -42% | 1060 | -43% | 112 |
| Luxembourg | 10 | -52% | 6 | -71% | 8 | -56% | 6 | -67% | 35 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 156 | -68% | 154 |
| Portugal | 196 | -6% | 132 | -37% | 144 | -34% | 134 | -38% | 142 |
| Spain | 892 | -23% | 754 | -35% | 794 | -25% | 794 | -25% | 44 |
| Sweden | 220 | -36% | 220 | -36% | 287 | -34% | 287 | -34% | 0 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 945 | -64% | 623 |
| EU-15 | 7029 | -45% | 6419 | -50% | 7311 | -46% | 6161 | -54% | 4037 |

The environmental achievements of the gap closure scenario are presented in Figure 7.4 and Table 7.6. It is clear that the wide geographical distribution of emission controls results in large-scale environmental improvements throughout the EU region. It is of special interest, however, to note that the highest AOT40 excess is larger than in the AOT40 ceiling scenario (D4/2). The table also indicates where the 35 percent gap closure target is most difficult to attain on a country basis. Even after full utilization of the compensation potential for individual grids, the improvements in Portugal (35 percent), Greece and Belgium (36 percent) are at or very close to the target and drive therefore the solution.

Figure 7.5 marks the grid cells where the optimization results in a violation of the ’soft’ gap closure targets. Excess exposure at these grids is compensated by additional reductions in other grid cells within the same country.

Table 7.6: Cumulative vegetation exposure index for the REF and the D5/2 (35 percent gap closure) scenario, in million hectares.excess,ppm.hours

| | REF | | D5/2 | |
|---|---|---|---|---|
| | Million hectares. excess. ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 |
| Austria | 264 | -43% | 234 | -49% |
| Belgium | 143 | -17% | 111 | -36% |
| Denmark | 54 | -58% | 41 | -68% |
| Finland | 0 | -100% | 0 | -100% |
| France | 2346 | -41% | 1720 | -56% |
| Germany | 1268 | -43% | 1002 | -55% |
| Greece | 154 | -32% | 143 | -36% |
| Ireland | 8 | -71% | 3 | -89% |
| Italy | 1164 | -30% | 1068 | -36% |
| Luxembourg | 14 | -39% | 11 | -55% |
| Netherlands | 82 | -22% | 62 | -41% |
| Portugal | 288 | -24% | 246 | -35% |
| Spain | 1377 | -32% | 1115 | -45% |
| Sweden | 21 | -81% | 14 | -87% |
| UK | 154 | -26% | 95 | -54% |
| | | | | |
| EU-15 | 7336 | -37% | 5864 | -50% |

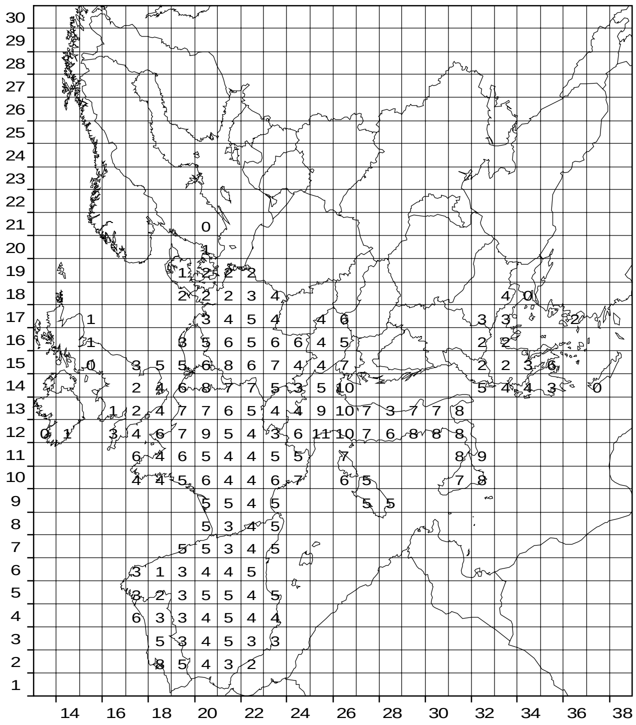

Figure 7.4: Excess AOT40 of the 35 percent gap closure scenario D5/2 (in ppm.hours)

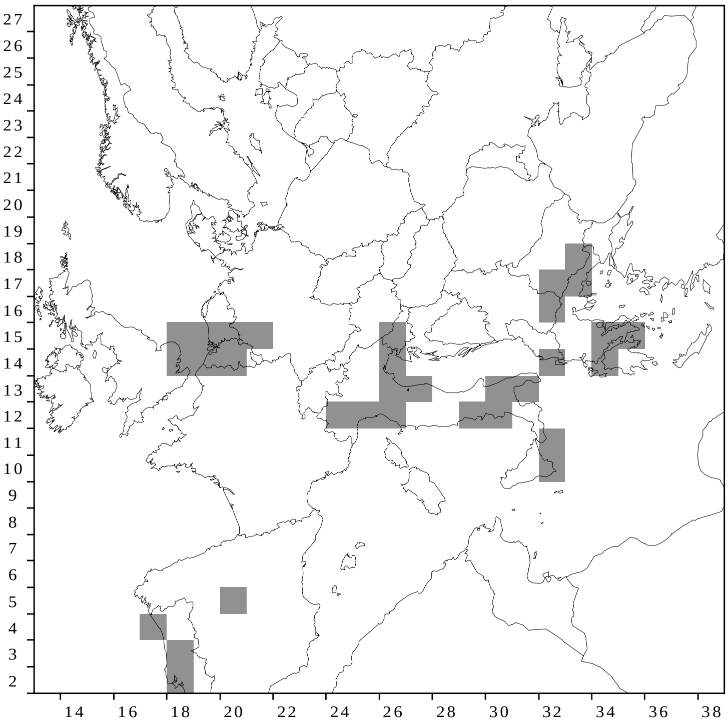

Figure 7.5: Grid cells where the 'soft' gap closure targets are violated and compensated by additional reductions in other grids (Scenario D5/2)

## 7.3 A Combination of the AOT40 Ceiling and Gap Closure Targets

As a third option the analysis explored the interaction of the ceiling- and gap closure-targets, if both are introduced simultaneously in the optimization. From a large number of possible combinations of these two targets, the analysis was restricted to one central case targeted at a 35 percent gap closure and a 10.0 ppm.hours excess AOT40 ceiling. (i.e., a combination of the targets of the D4/2 and D5/2 scenarios).

Aggregated results for the central scenario (D6) and for variations in the gap closure or ceilings targets are provided in Table 7.7. Accommodating both the gap closure and the ceiling targets increases the overall costs by about 10 percent, compared to the 'gap closure only' case. The optimization puts some higher emphasis on further VOC reductions (from 46 to 55 percent; $NO_x$ from 45 to 51 percent). However, the combination of the targets achieves a lower vegetation index for the EU-15 as a whole (5.7 instead of 6.2 billion hectares.excess ppm.hours, see Table 7.9).

Table 7.8 presents country results. The strategy would emphasize $NO_x$ reductions in Portugal, Spain, France and Luxembourg, and further VOC controls in Belgium, Germany, UK, Italy and in the Netherlands. The resulting AOT40 on a grid basis is presented in Figure 7.6.

The comparison of the costs with the improvements in the vegetation exposure indices clearly indicates that, despite the higher costs, the 'combined target' scenario D6 (Figure 7.7) yields an equal (compared to the gap closure targets) or better (compared to the ceiling targets) cost effectiveness.

Table 7.7: Emissions, costs and vegetation exposure indices for the combined AOT40 ceiling/gap closure (D6) scenarios.

| | AOT40 ceiling (excess.ppm.hours) | | |
|---|---|---|---|
| AOT40 gap closure | 10.5 | 10.0 | 9.5 |
| 30% | | $NO_x$= 6340 kt<br>VOC = 6330 kt<br>Costs = 3091 MECU<br>Index = 6023 | |
| 35% | $NO_x$= 6330 kt<br>VOC = 6197 kt<br>Costs = 4037 MECU<br>Index =5833 | $NO_x$= 6272 kt<br>VOC = 6033 kt<br>Costs = 4442 MECU<br>Index = 5732 | $NO_x$= 6095 kt<br>VOC = 5976 kt<br>Costs = 5177 MECU<br>Index = 5601 |
| 40% | | $NO_x$= 5957kt<br>VOC = 5714 kt<br>Costs = 7900 MECU<br>Index = 5284 | |

Table 7.8: Emissions and control costs for REF and the combined AOT40 35 percent gap closure/10 ppm.h ceiling scenario (D6). Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D6 | | REF | | D6 | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -51% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 209 | -42% | 196 | -43% | 109 | -68% | 298 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 92 | -44% | 0 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 553 | -66% | 1171 | -45% | 935 | -56% | 1392 |
| Germany | 1296 | -51% | 1225 | -54% | 1397 | -55% | 1002 | -68% | 1246 |
| Greece | 324 | -17% | 319 | -19% | 205 | -32% | 205 | -32% | 1 |
| Ireland | 74 | -31% | 74 | -31% | 46 | -59% | 46 | -59% | 0 |
| Italy | 1166 | -42% | 952 | -52% | 1079 | -42% | 895 | -52% | 555 |
| Luxembourg | 10 | -52% | 6 | -71% | 8 | -56% | 7 | -61% | 34 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 157 | -67% | 144 |
| Portugal | 196 | -6% | 132 | -37% | 144 | -34% | 136 | -37% | 136 |
| Spain | 892 | -23% | 751 | -35% | 794 | -25% | 794 | -25% | 46 |
| Sweden | 220 | -36% | 220 | -36% | 287 | -34% | 287 | -34% | 0 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 955 | -64% | 591 |
| EU-15 | 7029 | -45% | 6272 | -51% | 7311 | -46% | 6033 | -55% | 4442 |

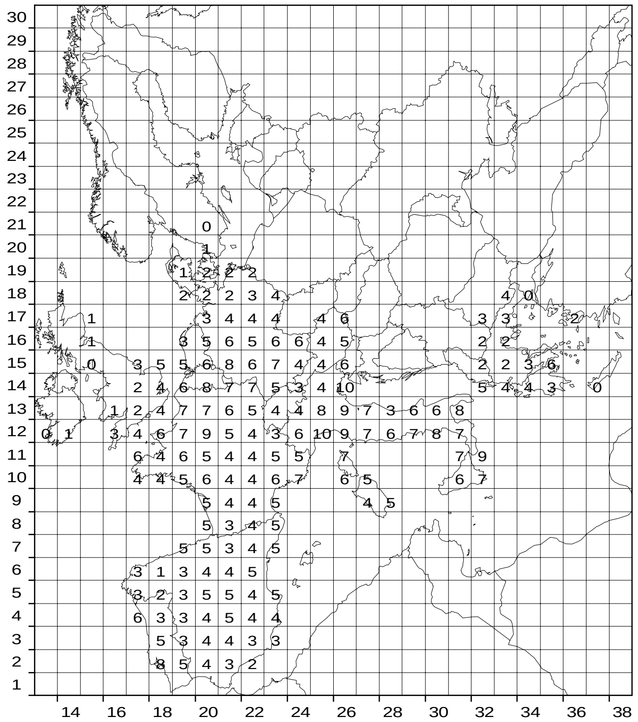

Figure 7.6: AOT40 of the combined 35% gap closure/10 ppm.hours ceiling scenario (D6)

Table 7.9: Cumulative vegetation exposure index for the three 'central' AOT40 scenarios (the 10 ppm.hours ceiling scenario (D4/2), the 35 percent gap closure scenario (D5/2), and the combined scenario (D6), in million hectares.excess ppm.hours

| Scenario | 10.0 ppm.hours ceiling D4/2 | | 35% gap closure D5/2 | | Combined D6 | |
|---|---|---|---|---|---|---|
| | Million. hectares. excess ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 |
| Austria | 243 | -47% | 234 | -49% | 226 | -51% |
| Belgium | 132 | -23% | 111 | -36% | 111 | -36% |
| Denmark | 52 | -60% | 41 | -68% | 40 | -70% |
| Finland | 0 | -100% | 0 | -100% | 0 | -100% |
| France | 1926 | -51% | 1720 | -56% | 1705 | -57% |
| Germany | 1189 | -46% | 1002 | -55% | 975 | -56% |
| Greece | 144 | -36% | 143 | -36% | 143 | -36% |
| Ireland | 6 | -76% | 3 | -89% | 3 | -88% |
| Italy | 990 | -41% | 1068 | -36% | 993 | -41% |
| Luxembourg | 13 | -46% | 11 | -55% | 11 | -55% |
| Netherlands | 78 | -26% | 62 | -41% | 62 | -41% |
| Portugal | 278 | -27% | 246 | -35% | 246 | -35% |
| Spain | 1223 | -39% | 1115 | -45% | 1109 | -45% |
| Sweden | 19 | -82% | 14 | -87% | 12 | -88% |
| UK | 145 | -30% | 95 | -54% | 96 | -53% |
| EU-15 | 6439 | -45% | 5864 | -50% | 5733 | -51% |

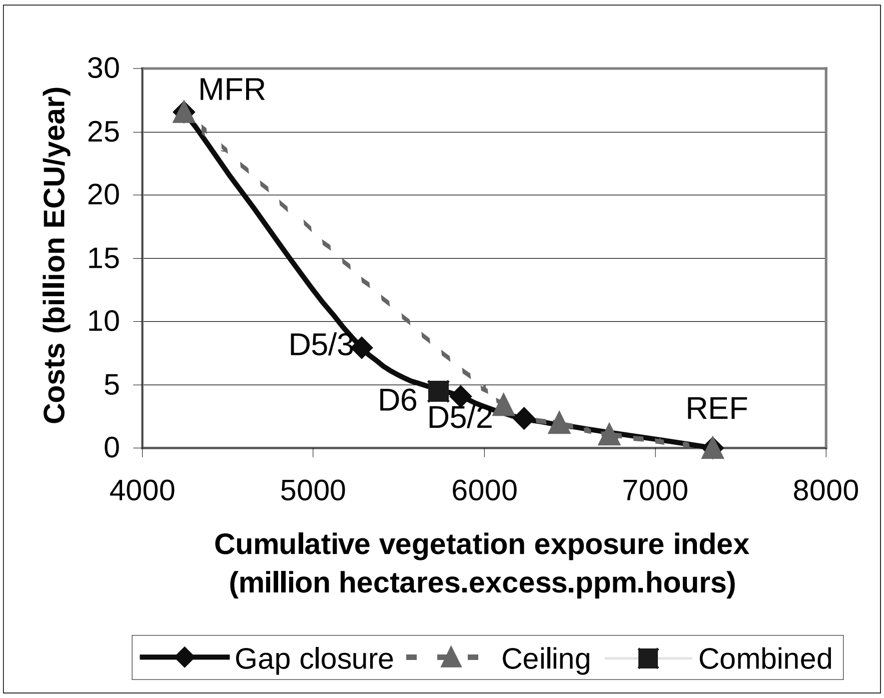

Figure 7.7: Comparison of costs and vegetation indices for the AOT40 optimized scenarios

# 8 Optimized Emission Reductions for a Combined AOT60/ AOT40 Target

As a last subject the combined optimization for health (AOT60) and vegetation (AOT40) related targets has been analyzed. Again, in principle there is a large number of combinations possible, and the challenging task for an ozone strategy will be to find the appropriate balances between (i) vegetation- and health-related targets, and (ii) improvement at 'hot spots' and a large-scale move towards the environmental long-term targets.

In order to keep the analysis manageable, at this point in time the assessment is focussed on a combination of targets of the two central health (D3) and vegetation (D6) related scenarios discussed in the preceding sections. Thereby, the new scenario D7 aims for the attainment of the following targets:

- Bring the highest AOT60 everywhere below 3 ppm.hours (in four out of five years),
- reduce the AOT60 everywhere by at least 60 percent compared to 1990 (allowing for a compensation of excess exposure on a country basis),
- limit the maximum excess of the critical levels for natural vegetation to 10.0 ppm.hours in terms of AOT40, and
- cut the excess AOT40 by 35 percent compared to 1990 (allowing for compensation of excess exposure at individual grids).

Phrased differently, the scenario will

- cut health-relevant excess ozone generally by 60 percent,
- vegetation-relevant excess ozone generally by 35 percent,
- while assuring the maximum possible improvement for areas with the highest exposure.

Table 8.1 presents the key results for the central D7 scenario and illustrates the implications of modifying gap closure and/or ceiling targets. At costs of 5.9 billion ECU/year (i.e., an 18 percent addition to the costs of the Reference scenario), the central scenario D7 proposes increased reductions of $NO_x$ emissions from 45 to 52 percent and of VOC emissions from 46 to 58 percent. Thereby it achieves a 74 percent improvement of the population exposure index and a 52 percent enhancement of the vegetation index compared to 1990.

The table also illustrates that the combined scenario is mainly driven by the gap closure targets: While at the selected point modifications of the gap closure percentages may result in major changes of required emission controls, the optimization results are rather robust against variations in the AOT ceiling targets. Of course this behavior is specific to the particular combination of targets and depends crucially on the relative severity of the various objectives. A comparison with the individual results for health- and vegetation-related scenarios reveals that the given constellation puts prime weight on health-related aspects, while assuring certain improvements for vegetation protection.

Table 8.1: Emissions, costs and exposure indices for the combined AOT60/AOT40 ceiling/gap closure scenarios

| Gap closure | AOT60/40 ceiling (ppm.hours) | | |
|---|---|---|---|
| | 3.25/10.5 | 3.0/10.0 | 2.75/9.5 |
| AOT60=0%/<br>AOT40=0% | | $NO_x$= 6304 kt<br>VOC = 6105 kt<br>Costs = 4415 MECU<br>Population index = 330<br>Vegetation index= 5996 | |
| AOT60=55%/<br>AOT40=30% | | $NO_x$= 6152 kt<br>VOC = 6006 kt<br>Costs = 4818 MECU<br>Population index = 302<br>Vegetation index= 5756 | |
| AOT60=60%/<br>AOT40=35% | $NO_x$= 6135 kt<br>VOC = 5689 kt<br>Costs = 5823 MECU<br>Population index =290<br>Vegetation index=5478 | **Scenario D7**<br>**$NO_x$= 6129 kt**<br>**VOC = 5683 kt**<br>**Costs = 5892 MECU**<br>**Population index = 289**<br>**Vegetation index=5484** | $NO_x$= 5780 kt<br>VOC = 5650 kt<br>Costs = 7539 MECU<br>Population index=288<br>Vegetation index=5271 |
| AOT60=65%/<br>AOT40=40% | | $NO_x$= 5580 kt<br>VOC = 5220 kt<br>Costs = 11682 MECU<br>Population index = 235<br>Vegetation index =4725 | |

Table 8.2 presents country results for the combined D7 scenario. In order to achieve the set of environmental targets at least costs, the optimization allocates further measures for $NO_x$ control in high ozone areas (Belgium -22 percent, France -14 percent, Luxembourg -5 percent), to Mediterranean countries (Italy -12 percent, Spain -15 percent, Portugal -39 percent), and to sources up-wind of problem areas (Ireland -13 percent). Further cuts of VOC emissions should take place in the high ozone area in the North-west of Europe (Belgium -26 percent, France and Netherlands -11 percent, UK -13 percent, Germany -14 percent) and in Mediterranean countries (Italy -13 percent, Greece and Portugal -9 percent, Spain -17 percent).

The AOT60 and AOT40 exposure maps are provided in Figure 8.1 and Figure 8.2.

Table 8.2: Emissions and control costs for REF and the combined AOT40/AOT60 scenario D7. Percentage changes relate to the year 1990.

| | $NO_x$ emissions | | | | VOC emissions | | | | Costs |
|---|---|---|---|---|---|---|---|---|---|
| | REF | | D7 | | REF | | D7 | | $10^6$ |
| | kt | *Change* | kt | *Change* | kt | *Change* | kt | *Change* | ECU/yr |
| Austria | 115 | -51% | 115 | -51% | 305 | -29% | 305 | -29% | 0 |
| Belgium | 209 | -42% | 131 | -64% | 196 | -43% | 105 | -69% | 582 |
| Denmark | 128 | -53% | 128 | -53% | 92 | -44% | 87 | -47% | 8 |
| Finland | 155 | -44% | 155 | -44% | 108 | -48% | 108 | -48% | 0 |
| France | 811 | -50% | 579 | -64% | 1171 | -45% | 937 | -56% | 1188 |
| Germany | 1296 | -51% | 1224 | -54% | 1397 | -55% | 976 | -69% | 1380 |
| Greece | 324 | -17% | 322 | -18% | 205 | -32% | 177 | -41% | 183 |
| Ireland | 74 | -31% | 58 | -46% | 46 | -59% | 46 | -59% | 3 |
| Italy | 1166 | -42% | 959 | -52% | 1079 | -42% | 837 | -55% | 724 |
| Luxembourg | 10 | -52% | 9 | -57% | 8 | -56% | 8 | -56% | 1 |
| Netherlands | 270 | -50% | 270 | -50% | 203 | -58% | 149 | -69% | 216 |
| Portugal | 196 | -6% | 114 | -45% | 144 | -34% | 124 | -43% | 483 |
| Spain | 892 | -23% | 682 | -41% | 794 | -25% | 616 | -42% | 409 |
| Sweden | 220 | -36% | 220 | -36% | 287 | -34% | 287 | -34% | 0 |
| UK | 1163 | -56% | 1163 | -56% | 1276 | -52% | 921 | -65% | 713 |
| | | | | | | | | | |
| EU-15 | 7029 | -45% | 6129 | -52% | 7311 | -46% | 5683 | -58% | 5892 |

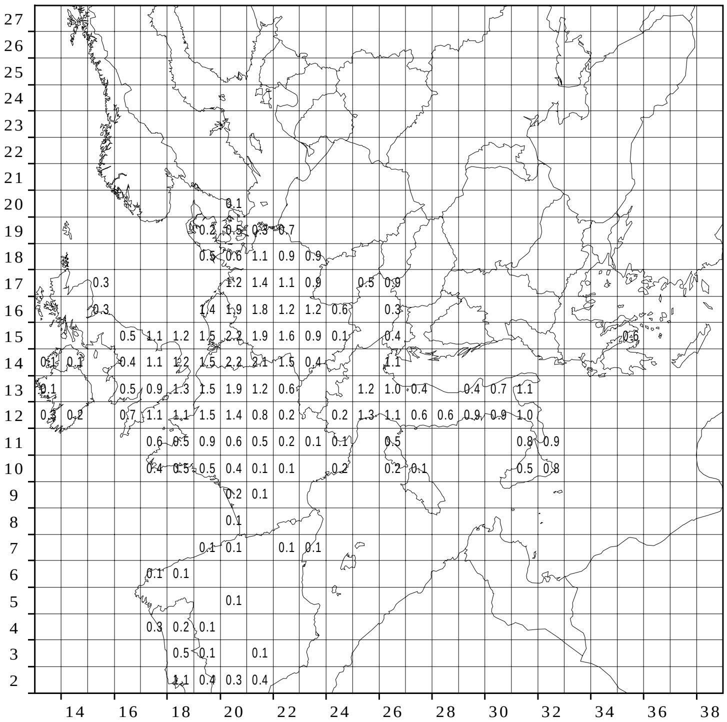

Figure 8.1: AOT60 of the combined AOT40&AOT60 scenario D7 (mean over five years), in ppm.hours

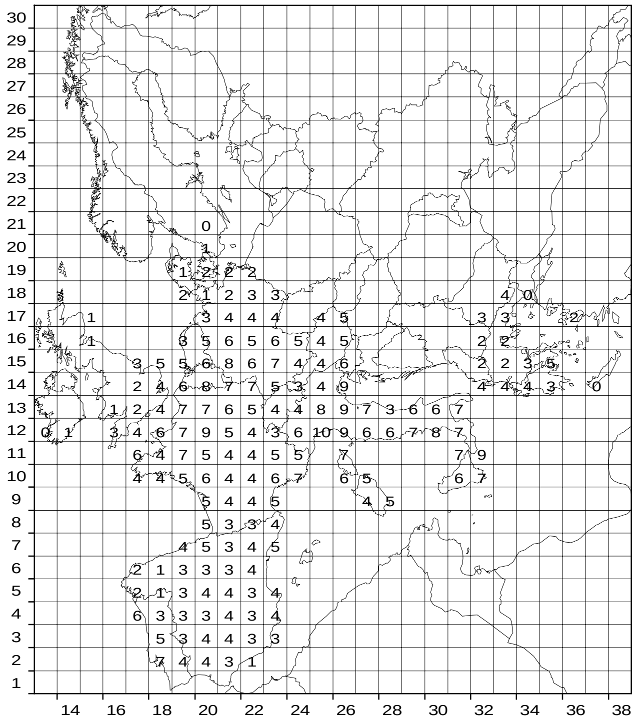

Figure 8.2: Excess AOT40 of the combined AOT40&AOT60 scenario D7 in ppm.hours

Table 8.3: Comparison of the cumulative population exposure indices for the combined scenarios

| Scenario | Combined AOT60 D3 | | Combined AOT40 D6 | | D7 | |
|---|---|---|---|---|---|---|
| | Million. persons. ppm.hours | Change to 1990 | Million. persons ppm.hours | Change to 1990 | Million. persons. ppm.hours | Change to 1990 |
| Austria | 2 | -87% | 2 | -87% | 2 | -87% |
| Belgium | 22 | -65% | 23 | -63% | 22 | -65% |
| Denmark | 1 | -88% | 1 | -88% | 1 | -88% |
| Finland | 0 | -100% | 0 | -100% | 0 | -100% |
| France | 49 | -81% | 49 | -81% | 48 | -82% |
| Germany | 100 | -72% | 103 | -72% | 100 | -72% |
| Greece | 2 | -71% | 2 | -71% | 2 | -71% |
| Ireland | 0 | -100% | 0 | -100% | 0 | -100% |
| Italy | 36 | -77% | 38 | -76% | 36 | -77% |
| Luxembourg | 1 | -67% | 1 | -67% | 1 | -67% |
| Netherlands | 26 | -60% | 27 | -58% | 26 | -60% |
| Portugal | 5 | -69% | 7 | -56% | 5 | -69% |
| Spain | 2 | -94% | 4 | -88% | 2 | -94% |
| Sweden | 0 | -100% | 0 | -100% | 0 | -100% |
| UK | 42 | -66% | 44 | -64% | 42 | -66% |
| | | | | | | |
| EU-15 | 290 | -74% | 303 | -73% | 289 | -74% |

Table 8.4: Comparison of the cumulative vegetation exposure indices for the combined scenarios

| Scenario | Combined AOT60 D3 | | Combined AOT40 D6 | | D7 | |
|---|---|---|---|---|---|---|
| | Million. hectares. excess ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 | Million. hectares. excess ppm.hours | Change to 1990 |
| Austria | 224 | -51% | 226 | -51% | 224 | -51% |
| Belgium | 111 | -35% | 111 | -36% | 111 | -36% |
| Denmark | 37 | -72% | 40 | -70% | 38 | -71% |
| Finland | 0 | -100% | 0 | -100% | 0 | -100% |
| France | 1708 | -57% | 1705 | -57% | 1691 | -57% |
| Germany | 963 | -57% | 975 | -56% | 962 | -57% |
| Greece | 140 | -38% | 143 | -36% | 140 | -38% |
| Ireland | 3 | -90% | 3 | -88% | 3 | -90% |
| Italy | 979 | -41% | 993 | -41% | 977 | -42% |
| Luxembourg | 11 | -55% | 11 | -55% | 11 | -55% |
| Netherlands | 61 | -42% | 62 | -41% | 61 | -42% |
| Portugal | 212 | -44% | 246 | -35% | 212 | -44% |
| Spain | 952 | -53% | 1109 | -45% | 950 | -53% |
| Sweden | 11 | -89% | 12 | -88% | 12 | -89% |
| UK | 94 | -55% | 96 | -53% | 93 | -55% |
| EU-15 | 5506 | -53% | 5733 | -51% | 5485 | -53% |

According to Table 8.3, the largest improvements of the population exposure index (compared to the REF scenario) occur in the UK (-27 percentage points) and Denmark (-25 percentage points). Most other countries experience a decline of the excess index between 10 and 20 percent points. A similar pattern occurs also for the vegetation index, where the D7 scenario achieves in the UK an additional cut of almost 30 percent. For most other countries, the indices decline between 10 and 20 percentage points.

As mentioned in Section 2.6.1, the RAINS optimization distinguishes emission control measures in a number of sectors with characteristic differences in their $NO_x$/VOC abatement efficiency. An initial analysis of the sectoral reductions selected by the optimization reveals a preference for further control of VOC emissions from stationary sources, although in some countries $NO_x$ controls for stationary sources also have a role to play. In the high ozone area in the North-west of Europe and in Mediterranean countries, further measures are also adopted in the transport sector. In particular, stricter emission controls for heavy duty vehicles and off-road machinery are identified as important elements in a strategy aimed at the control of ground-level ozone in Europe. As a rough indication, the D7 scenario allocates about 60 percent of total costs to further VOC control for stationary sources, 20 percent to $NO_x$ control at stationary sources, and 20 percent to $NO_x$/VOC control at mobile sources. Detailed analyses of country- and sector-specific reduction requirements are planned for the next Interim Report.

# 9 Conclusions

## 9.1 Summary of the Scenario Results

### 9.1.1 Reference Case and Maximum Feasible Reductions

The current (emission) reduction plans and legislation (the Reference case) are expected to significantly reduce ground-level ozone concentrations in the EU. Model calculations suggest that the excess population exposure (above the World Health Organization guidelines) will decline by about 55 percent between 1990 and 2010. For vegetation, the cumulative excess exposure over the critical levels is estimated to decline by 35 percent in the year 2010. In the absence of further measures, the environmental long-term targets for ground-level ozone will still be exceeded in large parts of the European Union.

The analysis also shows that, assuming energy consumption levels and economic development of the pre-Kyoto 'Business as usual' scenario, the remaining potential for technical emission control measures will not be sufficient to achieve the environmental long-term goals by the year 2010. Consequently, a practical ozone strategy aimed at these long-term objectives could either rely on non-technical to achieve the required emission reductions, or establish for the given time horizon realistic environmental interim targets.

In an 'effect-based' approach, emission reductions are selected on the basis of their cost- and environmental effectiveness for the desired air quality levels. The choice of the interim target will be crucial in determining both the distribution of emission reductions over economic sectors and countries and the environmental benefits.

This Interim Report attempts to highlight the features of two alternative principles for determining environmental interim targets for ground-level ozone:

- One approach would give priority to improving the worst polluted areas in Europe and direct measures to the emission sources contributing to these 'hot spots'. Other, less polluted, regions would not be a target for improvement.
- An alternative approach could emphasize a general, possibly proportional, environmental improvement everywhere towards the ultimate long-term targets. Such a strategy would not necessarily put largest efforts to improve the most polluted areas, but could require stricter measures in cleaner regions, if at these places effective improvements are difficult to attain (e.g., due to a larger influence of natural sources or in cases where the increase in emissions due to strong economic growth limits the relative emission reduction potential).

### 9.1.2 Absolute AOT Ceilings

The analysis illustrates that the highest ozone in excess of the WHO health guidelines (expressed in terms of the AOT60) occurs in the Benelux region. Consequently, a strategy asking for the attainment of a uniform 'AOT60 ceiling' will prioritize ozone improvements in this area and thus suggest measures to be taken mainly in the Benelux and surrounding countries. It is not surprising that, due to the chemical regime of ozone formation prevailing in this high-$NO_x$ region, priority is given to VOC reductions (e.g., for the 3 ppm.hours ceiling target, 7 percent overall VOC reduction versus 3 percent $NO_x$ reduction, if compared to the Reference case).

Focusing on vegetation protection, the largest excess exposure (excess AOT40) is observed in northern France and northern Italy. A general AOT40 ceiling target over Europe will therefore concentrate emission reductions around these two countries. In contrast to the health related strategy, stronger control measures are suggested for $NO_x$ emissions (e.g., for the 10 ppm.hours ceiling, 5 percent overall $NO_x$ reduction versus 3 percent for VOC).

### 9.1.3 Proportional Improvements

In contrast to limiting the highest excess, a proportional reduction of the excess exposure observed in a base year (the ’gap closure’ approach) allocates further emission controls to most EU countries where the long-term targets for ozone are not yet achieved.

In response to the Council Conclusions on the EU Acidification Strategy, a mechanism was developed which allows the optimization to violate environmental targets at individual grid cells as long as the excess above the target is compensated by additional (population or vegetation area adjusted) improvements at other grid cells in the same country. This compensation mechanism, employed for the gap closure scenarios, diminishes the influence of extreme situations at isolated grid cells and achieves a more balanced allocation of measures.

For the AOT60, the gap closure target entails fewer measures in the high-ozone area (control costs in Belgium are 30 percent lower than for the ceiling strategy) and more in other countries, notably in the Mediterranean region. A similar response pattern occurs for the AOT40, where lower emphasis is put on the maximum levels occurring in Italy, but significantly higher emission reductions are attributed to other areas. Consequently, environmental improvements are spread over the entire area of the European Union. Emission reductions are balanced between $NO_x$ and VOC (e.g., for an AOT60 60 percent gap closure, 7 percent $NO_x$ and 12 percent VOC; for an AOT40 35 percent gap closure, 5 percent $NO_x$ and 12 percent VOC).

A particular feature of the gap closure approach is the fact that, for some Mediterranean countries (where undoubtedly serious ozone problems exist), it often results in larger economic burdens than for other EU Member States, where the excess ozone might be higher. The major reason for this effect is the ’grandfathering’ principle underlying the gap closure concept, which determines the environmental target for the year 2010 in relation to a historical situation. Obviously, it is more demanding to achieve such relative targets with a fast developing economy, where the emission generating activities (energy consumption, traffic, industrial production) experience higher growth, than in a less dynamic economic situation.

### 9.1.4 Combined Targets

The analysis clearly illustrates the existence of advantages and disadvantages of the two fundamental principles for selecting interim targets. Although individual countries might favor the one or the other approach based on a particular distribution of costs and benefits for their territory, it is difficult to decide objectively about the superiority of either one in the European context. Consequently, an attempt was made to combine these two target types into one optimization problem, i.e., to identify the optimal allocation of emission reductions satisfying a combination of both sets of targets.

In principle, there is an infinite number of possible combinations of health-related (AOT60) and vegetation-related (AOT40) strategies with AOT ceilings and gap closure types of targets. In order to keep the analysis and the presentation of the results manageable, a sequential approach was selected in which, for each type of target, a range of optimization scenarios with progressively more stringent targets was calculated. In a second step, the central cases from each of these four scenario samples were then combined into one target set for a simultaneous optimization. Thereby, the combined optimization aimed

- for the improvement of the health-related excess exposure at an AOT60 ’gap closure’ of at least 60 percent compared to 1990, and
- in the interest of vegetation protection at a minimum 35 percent ’gap closure’ of the AOT40

In addition, stronger demands were specified for the areas with highest ozone:

- The maximum AOT60 should decline below 3 ppm.hours everywhere, and
- the highest excess AOT40 should not exceed 10 ppm.hours.

At costs of 5.9 billion ECU/year (on top of the costs of the Reference case), the least-cost allocation of emission reductions attaining these targets would cut the $NO_x$ emissions in the EU-15 by 7 percent and the VOC emissions by 12 percent below the Reference case. About 60 percent of the costs occur for the control of VOC emissions from stationary sources; 20 percent are allocated to $NO_x$ emissions from stationary sources, and 20 percent to further measures in the transport sector (mainly for heavy duty trucks).

It has to be mentioned that the described rationale for combining the individual targets results in this particular case in a dominance of the health-oriented scheme. Over the entire area of the EU-15 the cumulative population exposure index improves by 74 percent compared to 1990 (in the Netherlands by only 60 percent). For vegetation, the overall excess exposure is reduced by 52 percent.

## *9.2 Caveats*

The assessment in this report is based on the currently available data sets and models. There are certainly some critical aspects (estimates of maximum feasible reductions, review of the VOC cost curves, quantification of the non-linear effect of ozone formation, influence of possible changes in the global background concentration of ozone in the free troposphere) where substantially different findings could possibly modify quantitative model results presented in this report.

It must be stressed, however, that the qualitative findings about the features of alternative target setting principles are expected to prove robust against potential new findings in the above mentioned fields. Furthermore, in constructing the conceptual framework for target setting and in implementing the optimization problem, a number of precautionary methodological measures were taken in order to minimize the influence of model uncertainties and potential new findings on optimization results:

- For the AOT60, a cut-off level for optimization targets of 0.4 ppm.hours was introduced. This limit assures that model artifacts resulting from the inaccuracy of the ozone regression model for low values of the AOT60 do not influence optimization results;
- for the optimization of the AOT60 ceiling, the extreme situations (the worst of the five available meteorological years) were excluded as optimization targets;
- for the gap closure approach, the compensation mechanism minimizes the influence of possible inaccuracies in the description of ozone formation at individual grids.

Unfortunately, there is a potential source of uncertainty associated with the non-linear optimization problem for ground-level ozone. Given the functional form of the non-linear function of the ozone regression, there is no guarantee that the resulting mathematical optimization problem is convex and that no 'local minima' (i.e., solutions with similar overall costs, but with significantly different allocations of emission reductions) exist. In practice, this situation imposes two problems:

- The optimization software must be able to find the solution with minimum total costs and should not stop at a local optimum (which is sometimes a tricky technical task), and
- in case local minima exist, they could offer alternative solutions which might be politically attractive.

In order to increase the probability for finding the global minimum, the optimization tasks presented in this paper were performed with two independent non-linear optimization packages (CONOPT and MINOS). The solutions were confirmed by both solvers.

There are indications, however, that under certain conditions local minima may exist. The most important case is the situation in the Benelux region, where for achieving the AOT60 targets Belgium may either embark on stringent $NO_x$ control (in order to overcome the 'non-linear hill' of ozone formation in this region), or not touch $NO_x$ emissions at all and keep them at the REF level. The optimization indicates that the first solution (stringent $NO_x$ reductions in Belgium) is the global optimum. Keeping Belgium's $NO_x$ fixed at the Reference case is a local optimum and would require many other neighboring countries to compensate by additional $NO_x$ and VOC reductions. In practice, however, this particular problem is expected to disappear as soon as acidification concerns with strict demands for $NO_x$ reductions will be introduced into the analysis.

## 9.3 Further Work

Although the authors consider the overall aggregated optimization results presented in this study to be 'reasonably' robust, they anticipate possible major variations in individual country results in response to modified scenario assumptions and input data. Most prominently, potentially significant impacts are expected from

- the interaction of ozone-related strategies with the needs to control acidification in Europe. It has been shown before that introducing acidification targets will put higher priority on $NO_x$ controls, possibly relieving some of the most expensive VOC measures;

- assuming a different energy- and transport scenario. Analysis carried out for the Second Interim Report to the Commission suggested for an acidification-related scenario a 40 percent decline of abatement costs, if a low $CO_2$ energy pathway (comparable to the target agreed for the EU in the Kyoto protocol) was considered instead of the 'Conventional Wisdom' projection;
- considering the role of present non-EU countries for achieving the environmental targets within the EU as well as the impacts of measures taken in the EU Member states on ecosystems in the non-EU countries;
- revising the present information on possible emission controls and costs in the transport sector with updated information to be produced by the Auto/Oil 2 programme.

It is firmly planned to address these issues in the forthcoming Interim Report to the Commission, which will put its prime focus on the robustness of emission reductions attributed to individual countries.

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