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Simultaneous Optimization of Abatement Strategies for Ground-Level Ozone and Acidification

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Abstract

An updated Protocol on emissions of nitrogen oxides, under the UN/ECE Convention on Long-range Transboundary Air Pollution, is now at a preparatory stage. An effect-based approach is to be applied to the environmental problems to which nitrogen oxides contribute, either singly or in combination with other pollutants. One such multi-pollutant problem is ground-level ozone. In order to assist the negotiations on the forthcoming NO_x Protocol, IIASA has developed an integrated assessment tool that can be used to support the development of cost-effective European emission control strategies targeted at ground-level ozone.

This report presents a number of scenarios to illustrate the main features of ozone-related emission control strategies. One crucial element is the selection of appropriate environmental targets. Some alternative approaches are described to illustrate the problems involved and the implications of particular solutions. The target-setting process is, however, a genuinely political task, requiring judgments about political priorities.

The AOT60 measure has been used here as a health-related indicator of ozone exposure. Special attention is devoted to the considerable inter-annual variability in ozone due to differences in meteorological conditions. A possible approach for dealing with the problems caused by this variability is presented.

An illustrative control strategy for the reduction of vegetation damage by ozone is described, using the AOT40 exposure measure. For some areas of high NO_x emission density in NW Europe, the currently planned emission reductions would lead to an increase in the AOT40, owing to the non-linear character of ozone formation. However, it is possible to reduce ozone-related vegetation damage throughout Europe by reducing NO_x emissions beyond the current plans.

Recent progress has been made in considering different environmental targets together. This is illustrated by an optimization scenario which deals simultaneously with health- and vegetation-related ozone strategies. Such an approach offers a certain potential for cost savings.

Finally, the report illustrates the interaction of ozone control strategies with acidification, using an optimized emission control scenario aimed at the simultaneous achievement of environmental targets for AOT60, AOT40 and acidification.

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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 environmental threat posed by acidification and other air pollution problems. However, the measures will not be sufficient to eliminate the problem everywhere in Europe. To meet critical loads for acidification everywhere, further measures will be necessary. Furthermore, analysis also shows that critical levels for tropospheric ozone aiming at the protection of health and vegetation are currently widely exceeded in Europe, and that current policies in Europe will not be sufficient to eliminate the problem entirely. 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.

This report explores possibilities for cost-effective emission reductions in Europe, with the main emphasis on ground-level ozone. The cost-effectiveness of alternative strategies is presented, together with the anticipated environmental improvement brought about by the measures.

Section 2 of the report provides a brief summary of the basic methodology applied for the analysis and introduces the new approach for the integrated assessment of ozone-related emission control strategies. Section 3 reviews the possible range of emission development between 1990 and 2010. The possible development 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 following three sections focus on emission control strategies targeted at ground-level ozone. Keeping the possible range of emissions in mind, Section 4 assesses strategies for improving health-related criteria of ozone exposure, using the excess ozone over a threshold of 60 ppb accumulated over a time period of six months (AOT60) as a practical indicator. Special attention is devoted to the inter-annual meteorological variability of ozone formation. Section 5 addresses the improvement of a vegetation-related ozone criterion. The calculations use the 'AOT40', integrating the hourly daylight ozone in excess of a 40 ppb threshold over a three-month period. Section 6 combines the health- and vegetation-related targets and explores emission control strategies satisfying both environmental targets simultaneously.

The involvement of some of the ozone precursor emissions in other environmental problems makes it necessary to consider these problems simultaneously when developing optimal emission reduction strategies. Section 7 examines the interaction of ozone controls with acidification, paying particular attention to the role of nitrogen oxides emissions. In particular, an optimized emission control scenario is developed aiming at the simultaneous achievement of environmental targets for acidification, AOT40 and AOT60. Section 8 summarizes the main points of the report, reviews the major limitations which prohibit a final interpretation of the results, and draws preliminary conclusions.

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 to 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*., 1993). 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).

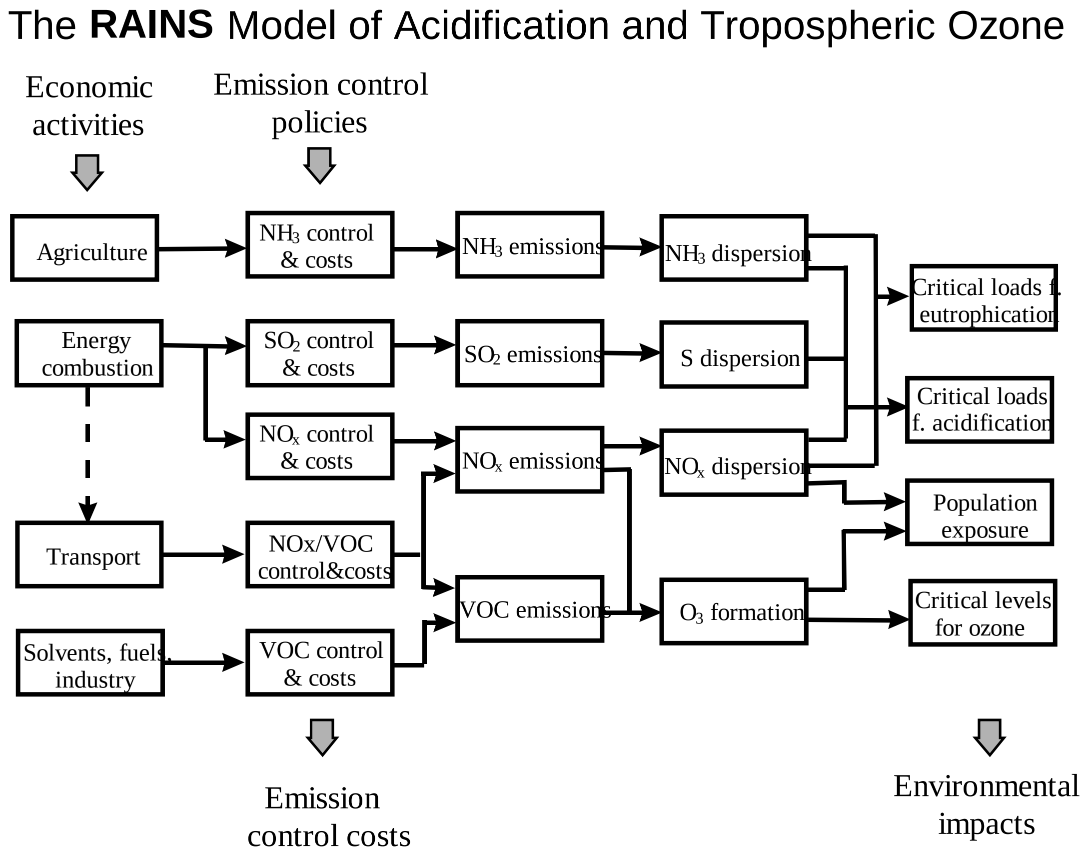

Figure 2.1: Schematic flowchart of the RAINS model framework

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 developed recently 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.

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 available energy and agricultural projection and the CORINAIR emission inventory.

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 and 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. Whereas 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) and Klaassen (1991).

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). In autumn 1996, the list of control options 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.

Specific details of the emission control options considered in the RAINS model are provided in Amann *et al.* (1997).

2.5 Atmospheric Transport

2.5.1 The Dispersion of Sulfur and Nitrogen Compounds in the Atmosphere

The RAINS model estimates deposition of sulfur and nitrogen compounds due to the emissions in each country, and then sums the contributions from each country with a background contribution to compute total deposition at any grid location. These calculations are based on source-receptor matrices derived from a Lagrangian model of long-range transport of air pollutants in Europe, developed by EMEP.

The EMEP model is a receptor-oriented single-layer air parcel trajectory model, in which air parcels follow two-dimensional trajectories calculated from the wind field at an altitude which represents transport within the atmospheric boundary layer. Budgets of chemical development within the air parcels are described by ordinary first-order differential equations integrated in time along the trajectories as they follow atmospheric motion. During transport, the equations take into account emissions from the underlying grid of a 150 km resolution, chemical processes in the air, and wet and dry deposition to the ground surface. Model calculations are based on six-hourly input data of the actual meteorological conditions for specific years.

In order to capture the inter-annual meteorological variability, model runs have been performed for 11 years (1985-1995, Barret and Sandnes, 1996). For each of these years, budgets of sources (aggregated to entire countries) and sinks (in a regular grid mesh with a size of 150 x 150 km) of pollutants have been calculated. These annual source-receptor budgets have been averaged over 11 years and re-scaled to provide the spatial distribution of one unit of emissions. The resulting atmospheric transfer matrices are then used as input in the RAINS model.

The use of such ‘country-to-grid’ transfer matrices implicitly assumes that the spatial relative distribution of emissions within a country will not dramatically change in the future. It has been shown that the error introduced by this simplification is within the range of other model uncertainties, when considering the long-range transport of pollutants (Alcamo, 1987).

2.5.2 Modelling Ozone Formation

The formation of ozone involves chemical reactions between NO_x and VOCs driven by solar radiation and occurs on a regional scale in many parts of the world. An integrated assessment model for ozone needs to relate ozone exposure to changes in the emissions of ozone precursors.

In order to provide RAINS with appropriate source-receptor relationships for ozone, a 'reduced-form' model has been constructed (Heyes *et al.*, 1997), using statistical methods to summarize the response of a more complex 'reference' model to emission changes. This 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 was 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.

The long-term ozone concentration at receptor j, $[O_3]_j$, 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, en_j, experienced at the receptor over the period in question. The reduced-form model is formulated as follows:

$$\overline{[O_3]}_j = k_j + \sum_{i=1}^{M}(a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^2) + \alpha_j \overline{en}_j^{\,2} + \overline{en}_j \sum_{i=1}^{M} d_{ij}v_i$$

where M is the number of emitter countries considered. The effective NO_x emissions variable allows for exchange processes between the boundary layer and the free troposphere above, and depends both on the relevant emissions and on the meteorology.

The terms of this reduced-form ozone model may be interpreted in relation to the physical and chemical processes that determine ozone formation in the atmosphere:

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 α_j are estimated by 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.

The formulation given above has been used in the construction of models of the AOT40 and AOT60 ozone exposure measures at some 600 European receptor grids for the summer periods of five different years.

2.6 Critical loads for Acidification and Eutrophication

A critical load for an ecosystem is defined as the deposition "below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge". Over the past years methodologies for computing critical loads have been elaborated for acidification and eutrophication and compiled by the Mapping Programme under the Working Group on Effects which operates under the UN/ECE Convention of Long-range Transboundary Air Pollution (LRTAP) (UBA, 1996). On a national level, critical loads data are compiled and submitted to the Coordination Center for Effects (CCE), located at the Dutch National Institute for Public Health and the Environment (RIVM), which collates and merges these national data into European maps and data bases, which are then approved by the Mapping Programme and the Working Group on Effects, before being used in emission reduction negotiations under the LRTAP Convention.

To be able to compare critical loads with European deposition fields, the numerous critical load values and functions (currently more than half a million; mostly for forest soils, but also lakes and semi-natural vegetation) have to be aggregated in the 150km x 150km EMEP-grid. For single values this is done by computing a percentile of the cumulative distribution function of all critical load values within an EMEP-grid cell.

To consider both sulfur and nitrogen deposition simultaneously, a surrogate for the multitude of critical load functions within an EMEP-grid cell has been defined: the so-called ecosystem protection isoline (for details see Posch *et al.*, 1995). These isolines are a generalization of the percentile concept in the case of single critical load values and can be used in integrated assessment models, such as RAINS, to evaluate emission reduction strategies for both sulfur and nitrogen. Owing to the different behavior of sulfur and nitrogen in the environment, it is not possible to compute a unique exceedance of a critical load. However, the protection isolines derived from the critical load functions allow the computation of the fraction of ecosystems protected in each grid cell, and, therefore, the evaluation of the effectiveness of any given emission scenario.

2.7 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. At the same time, these aspects also increase the complexity of the problem and, therefore, the demand for optimization techniques.

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

$$\sum_{i=1}^{N} c_i \longrightarrow \min$$

Cost curves providing emission control costs for varying levels of reductions can be converted into constraints for the optimization problem:

$$c_i = f(n_i, v_i)$$

A second set of constraints relates for each grid cell *j* emissions of NO_x and VOC to ozone exposure:

$$AOT40_j = f'(n_i, v_i, ...) \leq f''(AOT40_{\lim}, ...)$$

with *i* denoting emission sources (countries), *j* the receptor sites, n_i the emissions of NO_x, v_i the emissions of VOC, c_i the combined costs of reducing NO_x and VOC emissions in country *i*, $AOT40_j$ the ozone exposure (AOT40) at a receptor *j* and $AOT40_{lim}$ the critical level for ozone.

In addition, if required, a third set of (linear) constraints can be specified to limit the deposition of nitrogen and sulfur compounds in order to protect ecosystems from acidification and eutrophication.

The inputs to the optimization package include cost curves 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.

A smoothed approximation of the cost curves has been developed for use in the non-linear optimization problem. Analysis demonstrated that the given piece-wise linear cost curves could be best approximated with a second-order rational function

$$y_i = \frac{a_i + b_i x_i}{1 + c_i x + d_i x_i^2} + e_i ,$$

with y_i as the total costs and x_i as the emission level. e_i is used to calibrate the no-control level at zero costs. a_i, b_i, c_i and d_i are determined through non-linear regression. For NO_x, the maximum deviation from the piece-wise linear curve is typically within a range of ± five percent.

3 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. The ‘Current Reduction Plans’ (CRP) scenario incorporates officially adopted or internationally announced ceilings on national emissions.

3.1 The Current Reduction Plans (CRP) Scenario for 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 UN/ECE (1995). 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: (i) If a future projection is available, the latest number has been used for the year 2010; (ii) 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; (iii) if neither applies, the results from the RAINS estimate of a current legislation scenario has been used.

3.2 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 full achievement of critical loads.

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 are excluded.

The analysis presented in this report excludes the possible emission reductions discussed within the Auto/Oil 2 programme. The reasons for this are twofold: (a) there is no consensus yet about the costs for these measures, and (b) many emission control options for mobile sources reduce NO_x and VOC emissions simultaneously. In order to avoid a double-counting of the costs of these measures (which would inevitably occur if independent NO_x and VOC cost curves were used), the costs for these measures must be described by three-dimensional ‘cost surfaces’ instead of two-dimensional cost-curves, taking into account the simultaneous effects on two pollutants. Although a methodology has been developed to handle this approach in a proper way, practical difficulties made it impossible to complete this approach in time for this report. As a consequence of the exclusion of the Auto/Oil 2 measures and the assumption of the full implementation of current legislation (including the Auto/Oil 1 package), the scenarios carried out in this report consider in practice only the emission reduction potential for stationary sources.

Table 3.1 and Table 3.2 list the resulting emissions for the CRP and MFR scenarios. The measures assumed in MFR scenario enable a reduction of SO_2 emissions in Europe by 90%, of NO_x by 60%, of ammonia by 43% and of VOC by 62% compared to 1990.

Table 3.1: Emissions of SO_2 and NH_3 for 1990, the CRP scenario and the maximum feasible reductions (MFR) in 2010 (assuming the implementation of Auto/Oil-1)

Country	SO_2					NH_3				
	1990	CRP	*Change*	MFR	*Change*	1990	CRP	*Change*	MFR	*Change*
Albania	72	120	*67%*	6	*-92%*	31	34	*10%*	26	*-15%*
Austria	93	78	*-16%*	40	*-57%*	92	93	*1%*	54	*-41%*
Belarus	845	490	*-42%*	44	*-95%*	219	163	*-26%*	105	*-52%*
Belgium	317	215	*-32%*	49	*-85%*	86	96	*12%*	69	*-19%*
Bosnia-H	482	480	*0%*	33	*-93%*	31	23	*-25%*	15	*-51%*
Bulgaria	1842	1127	*-39%*	107	*-94%*	141	126	*-11%*	98	*-30%*
Croatia	178	117	*-34%*	18	*-90%*	40	38	*-6%*	28	*-31%*
Czech R.	1872	632	*-66%*	97	*-95%*	115	125	*9%*	78	*-32%*
Denmark	190	90	*-53%*	17	*-91%*	126	103	*-18%*	47	*-63%*
Estonia	273	275	*1%*	25	*-91%*	29	29	*-1%*	18	*-38%*
Finland	237	116	*-51%*	58	*-76%*	42	23	*-45%*	20	*-52%*
France	1300	737	*-43%*	221	*-83%*	692	668	*-4%*	409	*-41%*
Germany	5271	740	*-86%*	333	*-94%*	741	539	*-27%*	292	*-61%*
Greece	509	570	*12%*	56	*-89%*	78	76	*-2%*	53	*-32%*
Hungary	913	653	*-28%*	285	*-69%*	110	150	*36%*	94	*-15%*
Ireland	180	155	*-14%*	31	*-83%*	124	126	*2%*	118	*-5%*
Italy	1699	1042	*-39%*	173	*-90%*	384	394	*3%*	261	*-32%*
Latvia	122	115	*-6%*	16	*-87%*	39	29	*-26%*	17	*-57%*
Lithuania	213	145	*-32%*	24	*-89%*	79	84	*6%*	50	*-37%*
Luxembourg	14	4	*-71%*	2	*-86%*	7	6	*-12%*	6	*-12%*
Netherlands	197	56	*-72%*	34	*-83%*	229	82	*-64%*	81	*-65%*
Norway	54	34	*-37%*	18	*-67%*	23	25	*9%*	18	*-21%*
Poland	3001	1397	*-53%*	421	*-86%*	505	546	*8%*	415	*-18%*
Portugal	286	294	*3%*	31	*-89%*	91	92	*1%*	62	*-32%*
R. of Moldova	197	130	*-34%*	20	*-90%*	47	48	*2%*	31	*-34%*
Romania	1335	1311	*-2%*	92	*-93%*	290	301	*4%*	210	*-27%*
Russia	5046	4297	*-15%*	557	*-89%*	1283	895	*-30%*	522	*-59%*
Slovakia	549	240	*-56%*	65	*-88%*	61	53	*-12%*	39	*-36%*
Slovenia	199	37	*-81%*	14	*-93%*	23	27	*17%*	14	*-39%*
Spain	2234	2143	*-4%*	201	*-91%*	353	345	*-2%*	225	*-36%*
Sweden	115	87	*-24%*	59	*-49%*	62	53	*-14%*	37	*-40%*
Switzerland	45	30	*-33%*	15	*-67%*	62	58	*-6%*	46	*-26%*
FYRMacedonia	106	106	*0%*	7	*-93%*	17	16	*-7%*	9	*-46%*
Ukraine	3708	2310	*-38%*	383	*-90%*	729	649	*-11%*	374	*-49%*
United Kingdom	3754	980	*-74%*	173	*-95%*	325	320	*-2%*	209	*-36%*
F.Yugoslavia	581	1135	*95%*	45	*-92%*	90	83	*-8%*	54	*-40%*
Atlantic Ocean	641	641	*0%*	152	*-76%*	0				
Baltic Sea	73	73	*0%*	18	*-75%*	0				
North Sea	439	439	*0%*	104	*-76%*	0				
Total	39182	23641	*-40%*	4044	*-90%*	7394	6516	*-12%*	4204	*-43%*

Table 3.2: Emissions of NO_x and VOC for 1990, the CRP scenario and the maximum feasible reductions in the year 2010, assuming measures in the transport sectors limited to those laid down by Auto/Oil 1 (in kilotons)

Country	NO_x					VOC[1)]				
	1990	CRP	*Change*	MFR	*Change*	1990	CRP	*Change*	MFR	*Change*
Albania	24	30	*25%*	30	*25%*	29	44	*50%*	24	*-18%*
Austria	242	155	*-36%*	97	*-60%*	420	305	*-27%*	245	*-42%*
Belarus	402	315	*-22%*	193	*-52%*	337	321	*-5%*	204	*-39%*
Belgium	363	309	*-15%*	109	*-70%*	339	233	*-31%*	90	*-73%*
Bosnia-H	80	80	*0%*	37	*-54%*	45	63	*40%*	35	*-22%*
Bulgaria	354	290	*-18%*	192	*-46%*	194	152	*-21%*	104	*-46%*
Croatia	83	83	*0%*	71	*-14%*	88	80	*-8%*	53	*-40%*
Czech R.	522	398	*-24%*	131	*-75%*	281	220	*-22%*	109	*-61%*
Denmark	271	192	*-29%*	84	*-69%*	175	136	*-22%*	57	*-67%*
Estonia	84	72	*-14%*	47	*-44%*	48	58	*21%*	37	*-23%*
Finland	279	224	*-20%*	96	*-66%*	193	108	*-44%*	65	*-66%*
France	1619	1276	*-21%*	555	*-66%*	2395	1681	*-30%*	616	*-74%*
Germany	2985	2130	*-29%*	974	*-67%*	3106	1750	*-44%*	772	*-75%*
Greece	392	544	*39%*	222	*-43%*	295	205	*-31%*	111	*-62%*
Hungary	214	196	*-8%*	138	*-36%*	172	145	*-16%*	87	*-50%*
Ireland	107	105	*-2%*	29	*-73%*	96	138	*45%*	10	*-90%*
Italy	2009	2060	*3%*	746	*-63%*	1852	1376	*-26%*	582	*-69%*
Latvia	114	115	*1%*	95	*-17%*	61	68	*12%*	46	*-24%*
Lithuania	151	158	*5%*	106	*-30%*	88	84	*-4%*	52	*-41%*
Luxembourg	21	19	*-10%*	7	*-67%*	18	13	*-29%*	3	*-84%*
Netherlands	539	270	*-50%*	190	*-65%*	465	258	*-44%*	123	*-74%*
Norway	231	161	*-30%*	154	*-33%*	266	196	*-26%*	92	*-65%*
Poland	1209	1345	*11%*	494	*-59%*	687	1300	*89%*	350	*-49%*
Portugal	208	215	*3%*	120	*-42%*	197	144	*-27%*	95	*-52%*
R. of Moldova	87	87	*0%*	39	*-55%*	70	80	*15%*	43	*-38%*
Romania	513	546	*6%*	269	*-48%*	580	599	*3%*	277	*-52%*
Russia	3485	2653	*-24%*	1823	*-48%*	3335	3049	*-9%*	1703	*-49%*
Slovakia	207	197	*-5%*	82	*-60%*	144	122	*-15%*	61	*-58%*
Slovenia	60	31	*-48%*	26	*-57%*	47	25	*-47%*	19	*-60%*
Spain	1176	892	*-24%*	495	*-58%*	1036	794	*-23%*	294	*-72%*
Sweden	345	254	*-26%*	159	*-54%*	448	287	*-36%*	267	*-40%*
Switzerland	161	113	*-30%*	75	*-53%*	293	173	*-41%*	68	*-77%*
FYRMacedonia	39	39	*0%*	19	*-51%*	14	17	*24%*	12	*-14%*
Ukraine	1888	1094	*-42%*	822	*-56%*	1065	671	*-37%*	651	*-39%*
United Kingdom	2664	1186	*-55%*	740	*-72%*	2690	1276	*-53%*	744	*-72%*
F.Yugoslavia	211	147	*-30%*	96	*-55%*	97	106	*10%*	74	*-23%*
Atlantic Ocean	911	911	*0%*	181	*-80%*	0				
Baltic Sea	80	80	*0%*	16	*-80%*	0				
North Sea	639	639	*0%*	127	*-80%*	0				
Total	24969	19611	*-21%*	9886	*-60%*	21664	16278	*-25%*	8175	*-62%*

Note: [1]) Excluding agricultural emissions

4 Ground-level Ozone: Human Health

As mentioned in the Introduction of this report, the main focus of this analysis is on strategies for reducing ground-level ozone in Europe. It is important to realize that 'ozone concentrations' as such are not a useful environmental endpoint for the analysis. Depending on the type of environmental receptor to be protected (human health, natural vegetation, crops, forests, material, etc.), different temporal characteristics of ozone concentrations are relevant:

- For the protection of human health, the WHO has recently reviewed and updated the Air Quality Guidelines for Europe (WHO 1997). This update suggests an eight-hour maximum value of 60 ppb as a level at which acute adverse effects in the population are present. Although chronic exposure to ozone can cause adverse effects, quantitative information from humans is considered inadequate to estimate the degree of protection from chronic effects afforded by this guideline. To assess quantitatively the health impact of ozone and photochemical air pollution, however, population exposure and specific exposure-effects models have to be used to predict the risk for acute, episodic and long-term exposure.
- Recent research findings on ozone-related vegetation damage make it possible to determine biologically meaningful, but simple, indices to characterize ozone exposure and to identify the critical levels of exposure above which - by definition - adverse direct effects on receptors, such as certain plant species, may occur. Based on the scientific work on critical levels carried out under the UN/ECE Convention on Long-range Transboundary Air Pollution Working Group on Effects, a number of guideline values are recommended by WHO (1997). The cumulative exposure index using a threshold of 40 ppb (AOT40) has been accepted as the best available exposure index for damage to crops and natural vegetation (Kärenlampi and Skarby, 1996) using hourly concentrations during daylight hours over a three-month period (growing season). The critical level for agricultural crops (relating to a 5% crop loss) has been set at an AOT40 of three ppm.hours, averaged over a five-year period. For forest trees, the critical level is proposed at an AOT40 of 10 ppm.hours for daylight hours, accumulated over a six-month growing season (averaged over five years). It should be mentioned that work is proceeding to develop a Level-II approach for defining critical levels, taking into account modifying factors such as humidity, etc., but at present this work is not yet sufficiently advanced to derive quantitative conclusions.
- Research on damage to materials concludes that deterioration of materials is a cumulative and irreversible process. Threshold values are based on the concept of acceptable pollution levels and deterioration rates. Although many of the assumptions are still being discussed, the UN/ECE Mapping Manual proposed a preliminary level of ozone of 20 ppb as the annual mean concentration for sensitive organic materials.

This brief summary indicates that different exposure indices are relevant for different receptors. Acute risk to human health is related to higher ozone concentrations (above 60 ppb), although no conclusions are drawn about the importance of the frequency of such occurrences. The critical level for vegetation damage is currently expressed in terms of the cumulative excess exposure over 40 ppb over a several months period, while material damage is considered to be proportional to the long-term mean exposure. The relationships between these exposure indices vary greatly with space, time and the concentrations of precursor emissions over Europe. Consequently, optimized strategies will depend crucially on the target exposure index (whether giving preference to peak or long-term exposure), and will not necessarily be optimal for the improvement of the other indices.

This section analyzes the features of strategies aiming at health-related exposure criteria, while vegetation-oriented strategies are discussed in Section 5. Subsequently, Section 6 explores the potential for optimized strategies meeting both types of targets simultaneously.

4.1 The AOT60 as a Surrogate for a Health-Related Threshold

The modelling 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 modelling 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 the maximum eight-hour mean concentration) 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 to be equivalent to the full achievement of the WHO criterion. Any violation of this WHO guideline will, consequently, result in an AOT60 larger than zero.

It is important to stress that this AOT60 surrogate indicator has been introduced purely for practical modelling 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.

4.2 AOT60: The Situation in 1990 and the Scope for Improvement

This section examines the 1990 European AOT60 levels and the scope for future improvements based on the NO_x and VOC emissions expected as a result of current policies or following the (hypothetical) implementation of all technically feasible emission abatement measures. In practice, because for some countries the CRP emissions given in Table 3.2 exceed the RAINS estimates of the 2010 uncontrolled emissions, where necessary this analysis uses a modified version, designated CRP*, of the CRP emissions. The values used can be found in subsequent, relevant tables of this report.

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. As will be shown in Section 4.3.1, the inter-annual meteorological variability may change actual long-term ozone concentrations by more than a factor of two, for constant emissions. Consequently, it is difficult to draw far-reaching conclusions from short-term ozone observations.

Excluding for a moment the meteorological influence, the following figures attempt to portray the anticipated (from the CRP* scenario) and the possible (from the MFR scenario) changes in AOT60 between 1990 and 2010. This analysis is based on the mean AOT60 values 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 the latter depend on the specific meteorological conditions and emissions for the selected year.

Figure 4.1 illustrates that for the emissions of 1990, the highest (rural) AOT60 of more than 6 ppb.hours occurs in northern France, Belgium and Germany. In many other parts of France, Germany, Netherlands and Italy the AOT60 was modeled in a range of 5-6 ppm.hours. Typical rural values in the UK, Austria, Denmark, Poland, Czech Republic, Slovakia and Hungary were between 2 and 3 ppm.hours, while the highest AOT60 in Spain, Portugal and Greece was between 1 and 2 ppm.hours. Scandinavia did not experience significant excess of the AOT60.

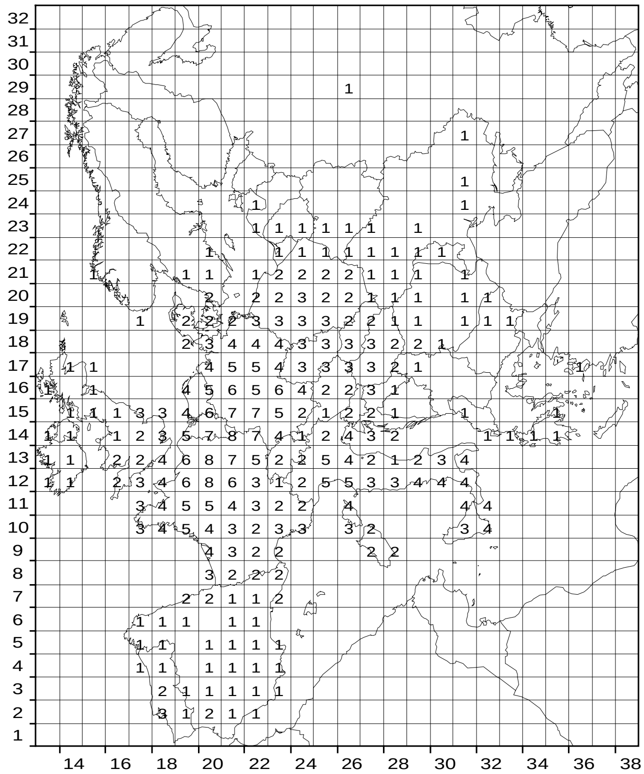

Figure 4.1: Five-year mean AOT60 (in ppm.hours) for the emissions of the year 1990

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 the number of days on which the WHO criterion is exceeded. Figure 4.2 displays the regional distribution of the "excess days". 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 occurs in the northern part of Europe (France/Belgium/Germany), the largest numbers of days exceeding the 60 ppb threshold are 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, an important factor when designing emission control strategies.

The emission controls assumed in the CRP* scenario (NO_x -32%, VOC -31% compared to 1990) for the year 2010 are expected to have quite considerable impacts on ozone exposure (Figure 4.3). The highest mean AOT60 in Europe would decline to about 5 ppm.hours, i.e., by about 40%. Across Europe the CRP* scenario would achieve an average drop of the AOT60 of a similar magnitude.

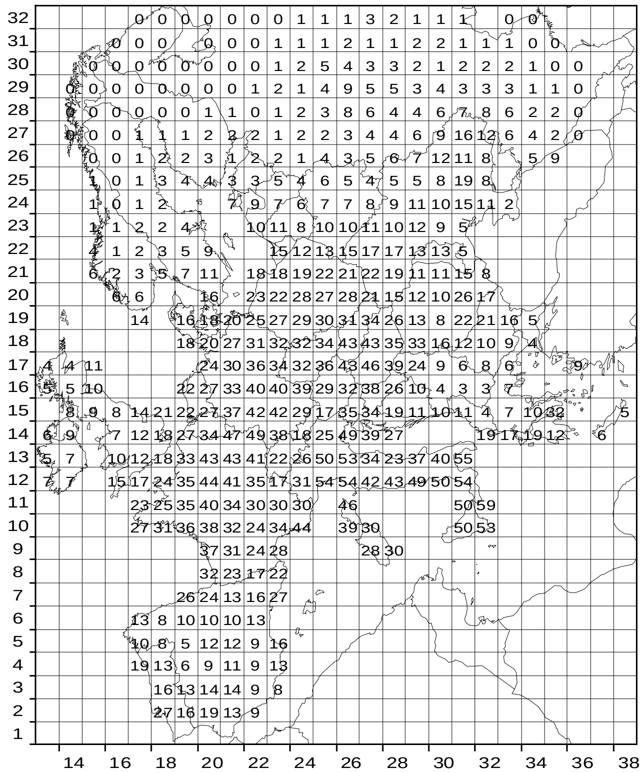

Figure 4.2: Five-year mean number of days with ozone above 60 ppb, using 1990 emissions

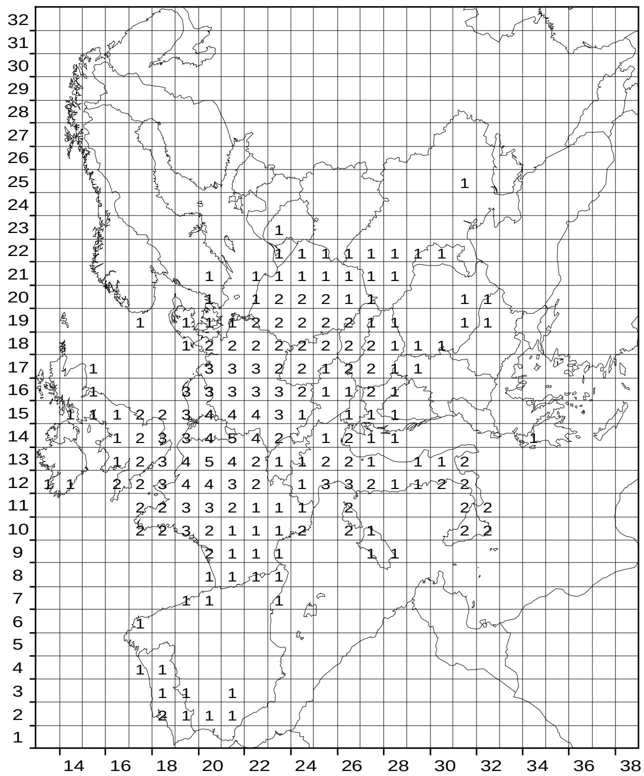

Figure 4.3: Five-year mean AOT60 (in ppm.hours) for the CRP* scenario in the year 2010

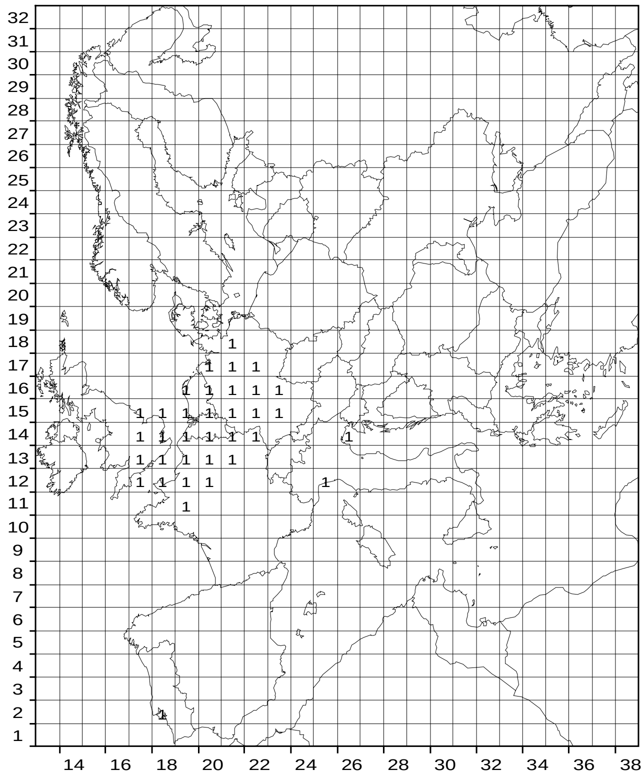

Figure 4.4: Five-year mean AOT60 (in ppm.hours) for the maximum feasible emission reductions (assuming the measures of Auto/Oil 1) in the year 2010

Even further cuts in the AOT60 could be achieved by the maximum feasible emission reductions (Figure 4.4). Excluding the emission control potential offered by Auto/Oil 2, a 60% decline of NO_x emissions accompanied by a 62% decrease of VOC emissions would bring the highest five-year mean AOT60 levels in Europe down to about 1.5 ppm.hours, which is 70-80 percent below the 1990 levels. The average AOT60 in Europe would be more than 80% lower than in 1990.

Table 4.1 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 by the total population. The indices presented in this report are based on the AOT60 values calculated for each grid, representing the rural ozone concentrations, and the total population per grid in 1990. 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.

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 populations) occurred in Germany, France, Italy and the UK. The cumulative exposure of the population in Europe is expected to decline by 40% as a result of the current policy. Larger improvements (more than 50%) occur in Austria, Finland, Greece, Italy, Slovenia and Switzerland, while for the UK and F. Yugoslavia a decrease in AOT60 of less than 20% could be expected. The maximum feasible emission reductions would reduce the exposure indices by about 90%.

Table 4.1: Population exposure indices (AOT60) for 1990, the CRP* scenario and the maximum feasible emission reductions (MFR), based on five-year mean AOT60 calculations. 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.

Country	Cumulative population exposure index (million person.ppm.hours)			Average population exposure index (ppm.hours)		
	1990	CRP*	MFR	1990	CRP*	MFR
Albania	2	1	0	0.5	0.2	0.0
Austria	17	8	0	2.2	1.1	0.0
Belarus	4	4	0	0.4	0.3	0.0
Belgium	67	44	14	6.2	4.0	1.3
Bosnia-H	3	2	0	0.8	0.4	0.0
Bulgaria	4	3	0	0.4	0.3	0.0
Croatia	9	5	0	1.9	1.1	0.0
Czech R.	35	19	0	3.3	1.8	0.0
Denmark	9	5	0	1.8	1.1	0.0
Estonia	0	0	0	0.3	0.2	0.0
Finland	1	0	0	0.2	0.1	0.0
France	280	156	25	5.0	2.7	0.4
Germany	391	226	52	5.0	2.9	0.7
Greece	7	3	0	0.7	0.3	0.0
Hungary	28	17	0	2.7	1.7	0.0
Ireland	3	2	0	0.7	0.5	0.0
Italy	183	86	2	3.2	1.5	0.0
Latvia	1	1	0	0.5	0.4	0.0
Lithuania	2	2	0	0.6	0.5	0.0
Luxembourg	3	2	1	8.1	4.7	1.3
Netherlands	68	48	17	4.5	3.2	1.1
Norway	1	1	0	0.2	0.1	0.0
Poland	90	58	0	2.3	1.5	0.0
Portugal	16	10	3	1.6	1.0	0.3
R. of Moldova	3	2	0	0.6	0.5	0.0
Romania	18	13	0	0.8	0.6	0.0
Russia	15	11	0	0.1	0.1	0.0
Slovakia	15	9	0	2.8	1.7	0.0
Slovenia	5	2	0	2.3	1.2	0.0
Spain	36	18	0	1.0	0.5	0.0
Sweden	4	2	0	0.5	0.3	0.0
Switzerland	14	6	0	2.1	0.8	0.0
FYRMacedonia	0	0	0	0.1	0.1	0.0
Ukraine	28	19	0	0.6	0.4	0.0
United Kingdom	113	99	18	2.0	1.7	0.3
F.Yugoslavia	6	5	0	0.6	0.4	0.0
Total	1481	889	132	2.2	1.3	0.2

4.3 Optimized Scenarios for the AOT60

The scenarios outlined in the preceding section illustrate the range of possible improvement of ozone exposure evaluated using the AOT60 criterion. It is obvious from the analysis that the currently planned emission reductions (the CRP* scenario) will not be sufficient to fully achieve the proposed environmental long-term target for the protection of human health (i.e., the WHO Air Quality Guidelines). Furthermore, even the maximum technically possible emission reductions (excluding the measures of Auto/Oil 2) would not meet these targets in the given time frame.

The above analysis was based on the five-year mean AOT60 values. In reality, ozone formation is highly dependent on the meteorological conditions, and in some years the situation will be worse than suggested using the mean approach. Unfortunately, this variability adds another dimension to the selection of appropriate environmental targets. While for vegetation the definition of the critical level (threshold) takes into account the meteorological variability, the health-related criteria are by their nature short-term related. Consequently, the choice of appropriate targets must actively address the meteorological variability.

The following section will explore the magnitude of changes in ozone exposure due to different meteorological conditions and thereby provide a basis for the selection of optimization targets in the subsequent section.

4.3.1 Dealing with the Inter-annual Meteorological Variability

Figure 4.5 to Figure 4.9 illustrate the differences in AOT60 for the meteorological conditions of the years 1989, 1990, 1992, 1993 and 1994, using constant anthropogenic emissions of the year 1990. Note that the natural VOC emissions are varied according to the actual climatic conditions of the years.

It is interesting to realize that the AOT60 differed in many respects over the five years:

- the maximum AOT60 varies between 5 ppm.hours for the 1992 and 1993 meteorology and 13 ppm.hours for the 1994 meteorology;
- the area with highest ozone in Europe varies from year to year;
- different regions experience maximum AOT60 in different years.

Table 4.2 lists the population exposure indices for the emissions of the year 1990 derived for the five meteorological conditions. The cumulative population exposure indices for Europe over the five years show a standard deviation of 36% of the mean value.

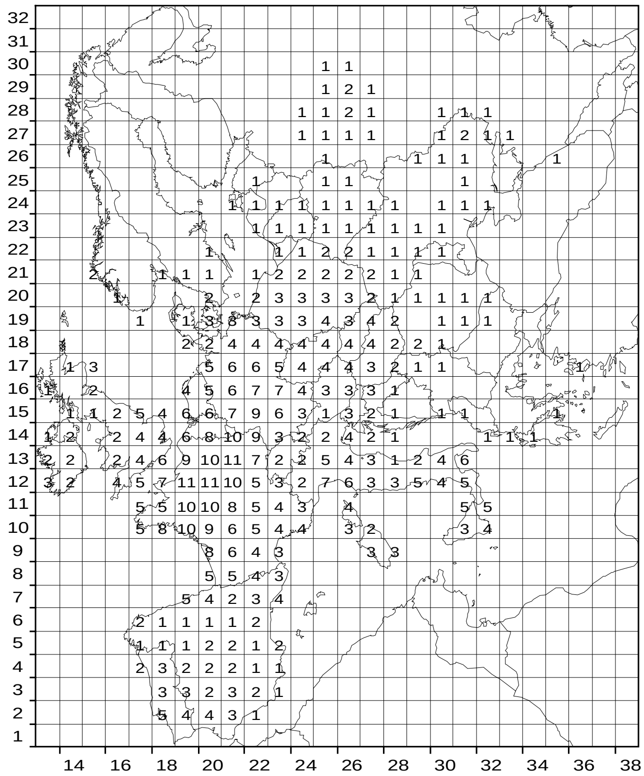

Figure 4.5: AOT60 (in ppm.hours) for the emissions of the year 1990, using the meteorology of 1989

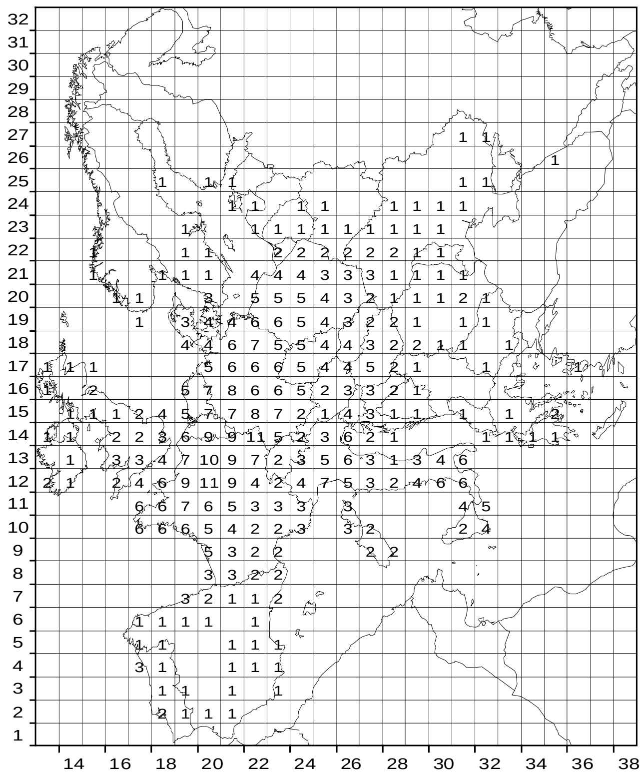

Figure 4.6: AOT60 (in ppm.hours) for the emissions of the year 1990, using the meteorology of 1990

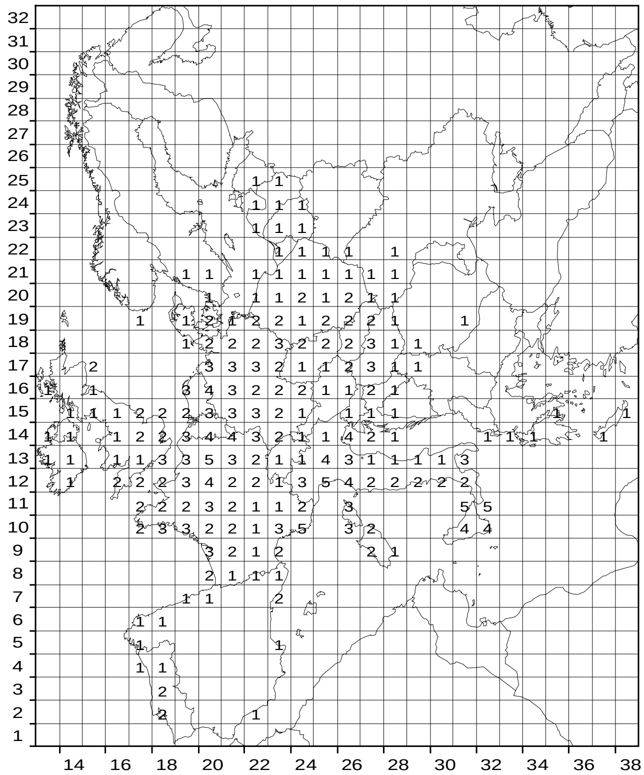

Figure 4.7: AOT60 (in ppm.hours) for the emissions of the year 1990, using the meteorology of 1992

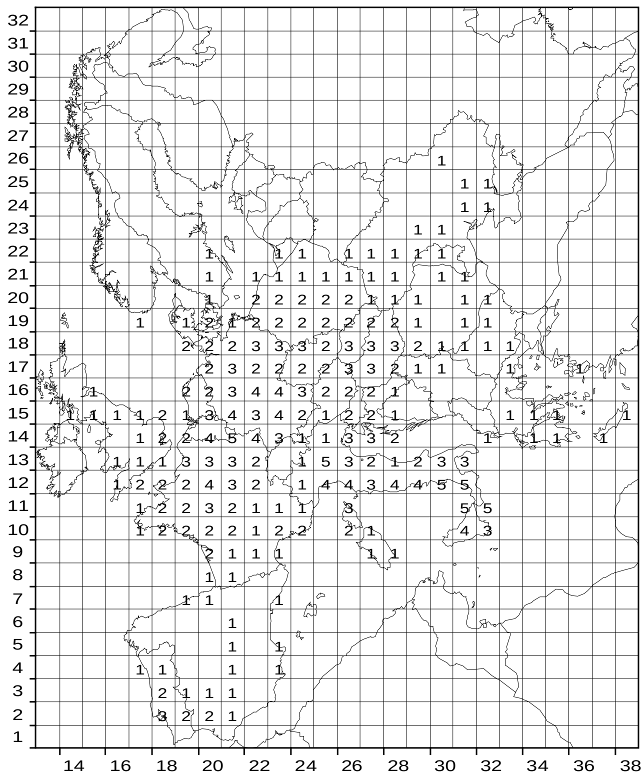

Figure 4.8 AOT60 (in ppm.hours) for the emissions of the year 1990, using the meteorology of 1993

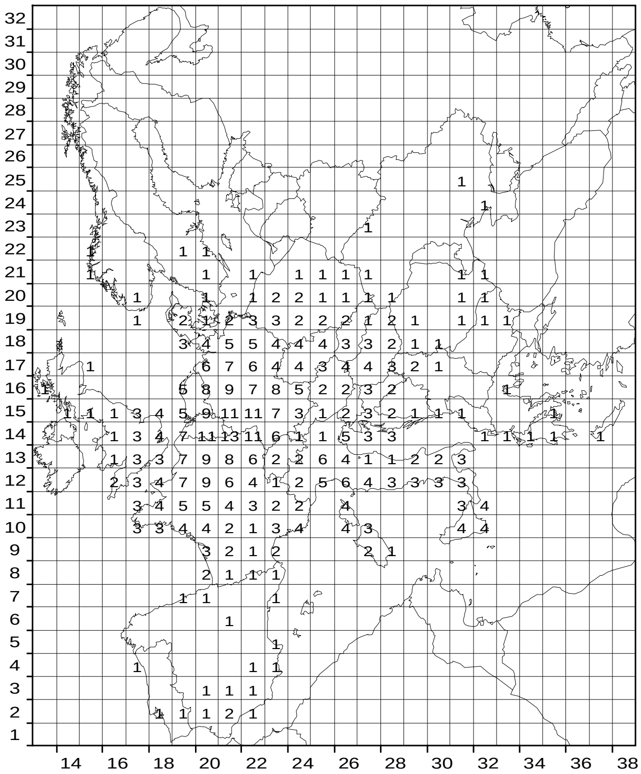

Figure 4.9: AOT60 (in ppm.hours) for the emissions of the year 1990, using the meteorology of 1994

Table 4.2: Population exposure indices for the emissions of the year 1990, for the five meteorological conditions

Country	Cumulative population exposure index (million person.ppm.hours)					Average population exposure index (ppm.hours)				
	1989	1990	1992	1993	1994	1989	1990	1992	1993	1994
Albania	2	2	1	1	2	0.5	0.7	0.2	0.5	0.6
Austria	23	22	8	12	19	3.0	2.9	1.0	1.6	2.5
Belarus	9	7	2	2	2	0.9	0.7	0.2	0.2	0.2
Belgium	79	83	38	34	103	7.2	7.6	3.5	3.1	9.5
Bosnia-H	3	5	2	3	5	0.7	1.1	0.5	0.6	1.0
Bulgaria	3	6	2	6	4	0.3	0.6	0.2	0.6	0.4
Croatia	8	10	6	9	11	1.7	2.2	1.2	1.9	2.4
Czech R.	44	49	17	23	41	4.2	4.8	1.6	2.2	3.9
Denmark	10	15	6	6	9	1.9	2.9	1.2	1.2	1.8
Estonia	1	0	1	0	0	0.5	0.3	0.5	0.1	0.1
Finland	1	1	1	0	1	0.2	0.2	0.2	0.1	0.1
France	434	366	160	128	315	7.7	6.5	2.8	2.3	5.6
Germany	449	507	198	231	568	5.7	6.4	2.5	2.9	7.2
Greece	6	10	6	8	8	0.6	1.0	0.6	0.8	0.8
Hungary	32	31	21	30	28	3.1	3.0	2.0	2.9	2.7
Ireland	6	3	2	1	0	1.8	0.9	0.7	0.2	0.1
Italy	209	218	145	165	180	3.6	3.8	2.5	2.9	3.1
Latvia	2	2	2	0	0	0.9	0.6	0.6	0.1	0.2
Lithuania	4	3	3	1	1	1.2	0.8	0.7	0.3	0.1
Luxembourg	4	4	1	2	5	9.6	9.3	3.7	4.7	13.1
Netherlands	82	88	40	29	100	5.5	5.9	2.7	1.9	6.7
Norway	1	2	1	1	1	0.2	0.4	0.2	0.2	0.3
Poland	106	157	55	65	64	2.8	4.1	1.4	1.7	1.7
Portugal	31	16	11	15	6	3.2	1.6	1.1	1.5	0.6
R. of Moldova	2	4	1	3	2	0.5	1.0	0.3	0.7	0.4
Romania	19	26	9	19	18	0.8	1.1	0.4	0.8	0.8
Russia	43	12	9	5	5	0.4	0.1	0.1	0.0	0.0
Slovakia	20	17	11	13	14	3.9	3.2	2.0	2.5	2.6
Slovenia	5	7	3	4	4	2.6	3.6	1.3	1.9	2.1
Spain	81	34	20	21	22	2.2	0.9	0.5	0.6	0.6
Sweden	5	7	3	3	4	0.6	0.8	0.3	0.3	0.4
Switzerland	17	20	7	6	19	2.6	3.0	1.1	0.9	2.8
FYRMacedonia	0	1	0	0	0	0.1	0.3	0.1	0.2	0.1
Ukraine	44	44	16	22	15	0.9	0.9	0.3	0.4	0.3
United Kingdom	179	128	78	54	124	3.1	2.2	1.4	0.9	2.2
F.Yugoslavia	6	7	4	6	7	0.5	0.7	0.3	0.6	0.7
Total	1970	1914	890	928	1707	2.9	2.8	1.3	1.4	2.5

4.3.2 Setting Environmental Targets for the Optimization

As explained in the Introduction, the goal of the report is to analyse alternative strategies for reducing ground-level ozone in Europe. Having explored the range for possible improvement as constrained by the current policy on the one side and the maximum technically feasible emission reductions on the other (see Section 4.2), the question of appropriate environmental targets becomes important.

A useful strategic environmental target should provide for a reasonable geographical spread of the environmental improvements. As with other environmental problems explored previously, the extent to which ground-level ozone exceeds the long-term environmental targets also shows great variations over the area of Europe. A strategy targeted solely at the improvement of the worst situation, e.g., the reduction of the highest excess exposure, will fail to reach a balanced set of measures and environmental improvements across Europe, since regions with less excess exposure would be excluded from the concern of the strategy. One way to attain a balanced distribution of environmental improvement, and of the implied emission control measures, across the region was to introduce the 'gap closure' concept. The gap was defined as the excess of the long-term environmental target in the base year, and the goal was to reduce this gap everywhere by an equal percentage. In principle, such a gap closure concept also appears useful for ground-level ozone.

A further prerequisite for an environmental target is the practical possibility to achieve it. This feasibility is influenced by the lowest achievable emission levels (the MFR scenario), but, particularly for ozone, also to a large extent by the actual meteorological conditions under which the target should be attained.

Determining a target and designing a strategy that considers only mean meteorology might result in the situation that in some years the environmental targets will not be met. As an illustration, Figure 4.10 displays the AOT60 (on the y-axis) for individual EMEP grids (along the x-axis) for the different meteorological regimes available for this analysis, always assuming constant emissions of 1990. The graph demonstrates that, compared to the mean meteorology, in certain years the actual AOT60 could reach levels twice as high, while in other years it could be 50 percent lower. It is interesting to note that the year with the maximum AOT60 is not always the same (for many grids it is 1989, indicated by the triangles; but for some grids the highest AOT60 occurs for 1994 - the diamonds). Also the relation between the AOT60 of a particular year and the mean is not constant over all of Europe. As a consequence, it will be necessary to address explicitly the question of the meteorological variations in the process of target setting.

Figure 4.11 displays for the various grid cells (along the x-axis, ordered according to EMEP x-coordinates) the maximum possible gap closure in terms of AOT60 resulting from the maximum technically feasible emission reductions for the different meteorological conditions. It is important to realize from this graph that there are a few grids, where for single years the maximum possible gap closure is exceptionally low. For example, two grids in the UK have a maximum gap closure of only 50% for the meteorology of 1990. A similarly low improvement is possible for two grids in the Netherlands and one in Portugal for the meteorological conditions of 1993. Applying the 'flat gap closure' principle to the full set of data would limit the ambition level to somewhat less than a 50% gap closure for all grids, although for most grids - and even for these 'difficult' grids for other meteorological conditions - a much higher improvement would be possible. The implied focus on high-NO_x regions would also lead to a preference for VOC reductions with a general tendency to minimize NO_x reductions. It will be shown later that for many countries NO_x reductions will play an important role in balanced ozone reduction strategies.

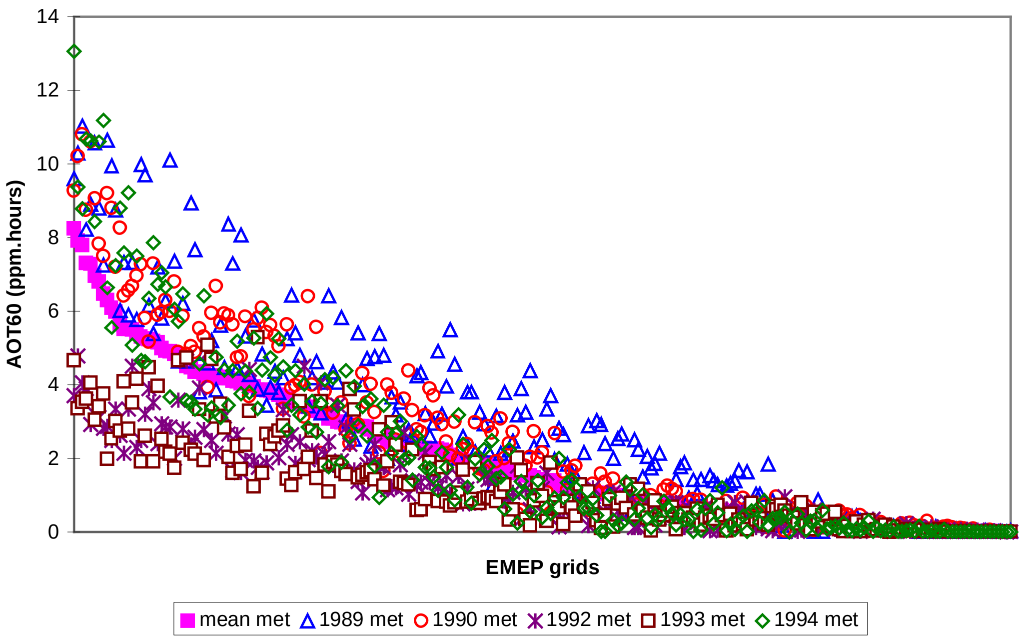

Figure 4.10: AOT60 for the emissions of 1990, using mean meteorological conditions and the meteorologies for the five individual years

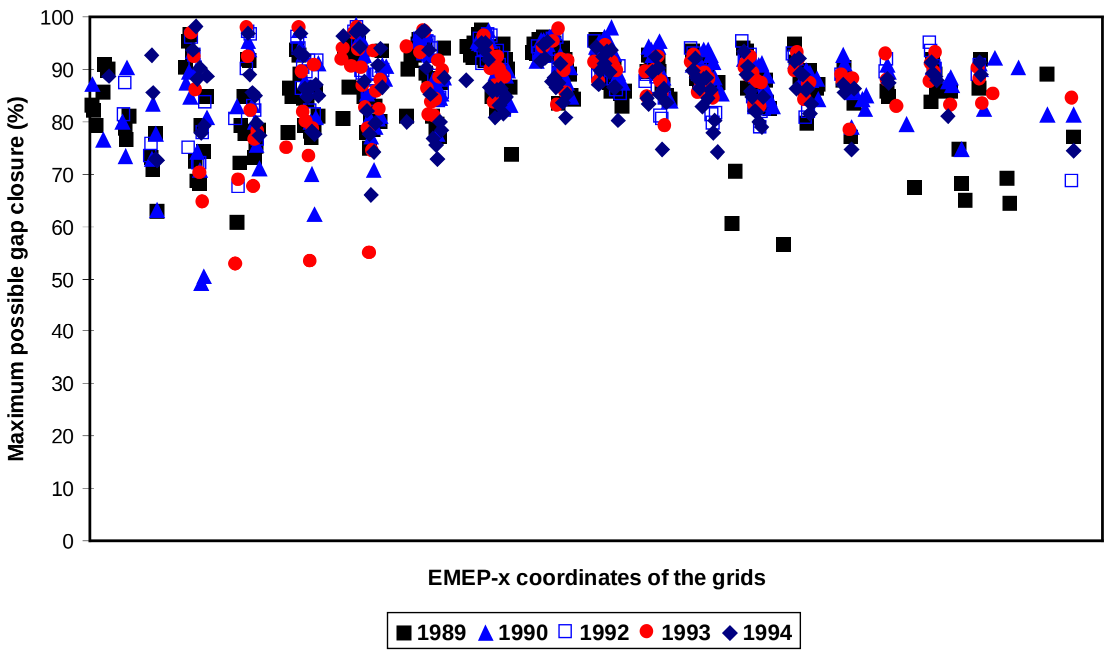

Figure 4.11: Maximum possible gap closure for the EMEP grids for the different meteorological conditions

The decision about the appropriate ambition level for the target setting must be left to the political process. However, there are some important methodological aspects to consider. From Figure 4.11 it is clear that, if a strategy is designed for the worst case, it will be driven by the available estimates for some extreme events. At the same time, it is unclear how representative the meteorological conditions of the five available years are in a longer time frame. There might be worse years, but it might also be that one of these years represents an extreme and rare event. Furthermore, it also seems questionable to rely on the performance of the available models for a few extreme events.

Without prejudging the outcome of a policy process, an attempt has been made to arrive at a broader base for the strategy analysis. For the reasons discussed above it does not appear advisable to drive a policy by a few extreme events. Arbitrarily, for each individual grid the meteorological conditions leading to the least possible gap closure have been excluded from the analysis. In other words, the objective of the strategy was set to achieve the ozone exposure targets (to be specified later) in four out of five years. Obviously, if more data become available, another ‘percentile’ could be selected.

It is important to mention that the year with the least possible gap closure does not necessarily coincide with the year producing the highest AOT60. In many cases it is more difficult to achieve a high gap closure in a ‘low ozone’ year (i.a., due to the influence of background ozone). Figure 4.12 displays the year for which the target has been excluded for each grid.

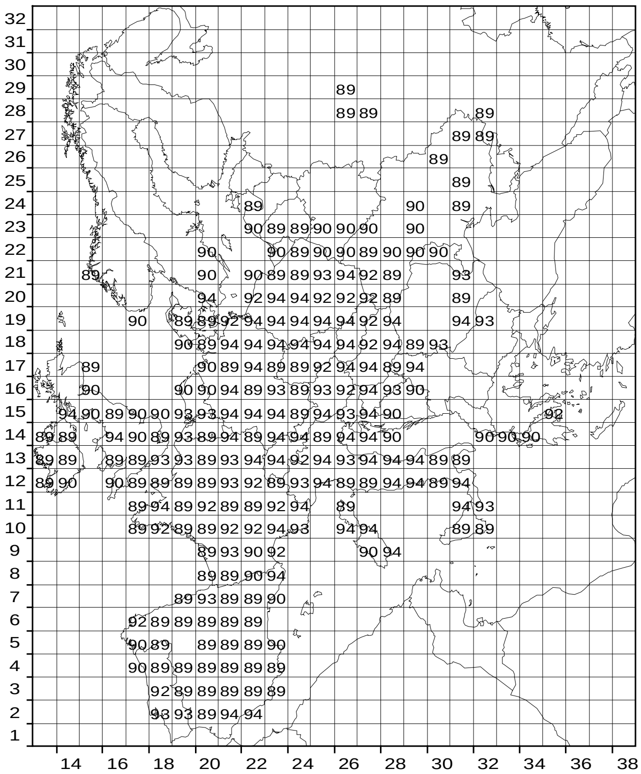

Figure 4.12: Year with the lowest gap closure of the maximum feasible emission reductions. These grid-year combinations have been excluded from the optimization

The exclusion of the worst meteorological conditions leads to the situation that at least a 60% gap closure is achievable for all grids by the maximum technically feasible emission reductions. Obviously, such a 60% gap closure is not a practical target; for many countries the maximum feasible measures are associated with very high costs.

It was explained in Section 2.5.2 how a ‘reduced form’ model for ozone formation has been constructed using statistical methods. In the case of the AOT60 a statistical problem occurs due to the fact that the AOT index is a non-continuous function: Every ppb in excess of 60 ppb counts, while every ppb of ozone concentrations below the 60 ppb threshold is disregarded. It is difficult accurately to approximate this feature with a linear regression. Inevitably, the quality of the fit is worst just around the 60 ppb level, or for low AOT60 values. (The problem is less severe for the AOT40, since the interest lies in ozone exposure above the critical level of three ppm.hours, which is sufficiently above the non-continuity).

In order not to transfer this inaccuracy to the strategy development, all grids where in 1990 the AOT60 was below 1 ppm.hour were excluded from the optimization analysis. In practice, this criterion excluded some grids in the northern UK, in Scandinavia and in remote Mediterranean areas. This means that for grids where in 1990 the AOT60 was relatively low (one ppm.hour relates to typically less than five days with a violation of the WHO Guideline in UK and Scandinavia and less than ten days in Mediterranean countries) no gap-closure targets were specified, so that these grids would not drive the optimization. Of course, measures targeted at the remaining receptors in these countries will also improve the situation at these sites.

4.3.3 Scenarios D1-D6 : 50 Percent Gap Closure for AOT60

Scenarios D1-D6 establish a 50 percent gap closure of the AOT60 (i.e., a 50 percent reduction of the AOT60 estimated for 1990) as an environmental target. The optimization analysis to identify the cost-optimal combination of measures for achieving this target was carried out in two steps:

- In a first step, five optimization runs for the five meteorological conditions were carried out (Scenarios D1 to D5). As discussed earlier, for each grid the target for the year with the lowest MFR gap closure was excluded.
- In a second step, an optimization was carried out, in which the targets for all five meteorological conditions (excluding the individually worst year) were considered simultaneously (Scenario D6). This means that this ‘composite’ optimization identified the least-cost set of measures that will achieve all specified environmental targets (i.e., the 50 percent gap closure of AOT60 in four out of five years).

Table 4.3 to Table 4.5 compare emission reductions of NO_x, VOC and the emission control costs for the 50 percent gap closure scenarios. The results show that reducing the AOT60 puts main pressure on VOC emissions. Compared to the level of the CRP* scenario (15022 kt VOC), the optimization suggests for the individual years a range between 12917 kt for 1992 and 13756 kt in 1993. Compared with the minimum emissions over all countries (12219 kt), the composite optimization for all years results in 12649 kt, while achieving the same environmental targets. The reductions in NO_x emissions are smaller: compared to the level of 16859 kt of the CRP* scenario, the 1993 optimization results in 16419 kt, while the 1990 meteorology yields 16753 kt. The cumulative minimum emissions are 16046 kt, while the composite optimization suggests 16502 kt. Emission control costs (on top of CRP*) range between 1318 in 1994 and 2458 million ECU/year for the 1990 meteorology. As a result of the composite optimization, costs are 17% lower (3160 million ECU/year) than the cumulative maximum over all countries (3802 million ECU/year).

Table 4.3: NO_x emissions for a 50 percent gap closure scenario for AOT60 (Scenarios D1-D6)

Country	NO_x emissions (kilotons)								Change compared to 1990							
		1989	1990	1992	1993	1994	*minimum*	composite		1989	1990	1992	1993	1994	*maximum*	composite
	CRP*	D1	D2	D3	D4	D5	*1989-94*	D6	CRP*	D1	D2	D3	D4	D5	*1989-94*	D6
Albania	30	30	30	30	30	30	*30*	30	25%	25%	25%	25%	25%	25%	*25%*	25%
Austria	155	155	155	155	151	155	*151*	155	-36%	-36%	-36%	-36%	-38%	-36%	*-38%*	-36%
Belarus	315	315	278	315	315	294	*278*	277	-22%	-22%	-31%	-22%	-22%	-27%	*-31%*	-31%
Belgium	222	222	222	222	160	166	*160*	222	-39%	-39%	-39%	-39%	-56%	-54%	*-56%*	-39%
Bosnia-H	61	61	61	61	59	61	*59*	61	-24%	-24%	-24%	-24%	-26%	-24%	*-26%*	-24%
Bulgaria	290	286	290	290	290	290	*286*	290	-18%	-19%	-18%	-18%	-18%	-18%	*-19%*	-18%
Croatia	83	83	83	83	83	83	*83*	83	0%	0%	0%	0%	0%	0%	*0%*	0%
Czech R.	305	305	305	305	293	305	*293*	305	-42%	-42%	-42%	-42%	-44%	-42%	*-44%*	-42%
Denmark	134	134	134	134	134	134	*134*	134	-51%	-51%	-51%	-51%	-51%	-51%	*-51%*	-51%
Estonia	72	72	72	72	72	72	*72*	72	-14%	-14%	-14%	-14%	-14%	-14%	*-14%*	-14%
Finland	203	203	203	203	203	203	*203*	203	-27%	-27%	-27%	-27%	-27%	-27%	*-27%*	-27%
France	791	771	791	689	726	689	*689*	775	-51%	-52%	-51%	-57%	-55%	-57%	*-57%*	-52%
Germany	1819	1819	1819	1819	1819	1771	*1771*	1819	-39%	-39%	-39%	-39%	-39%	-41%	*-41%*	-39%
Greece	365	365	365	365	365	365	*365*	365	-7%	-7%	-7%	-7%	-7%	-7%	*-7%*	-7%
Hungary	196	186	196	196	181	196	*181*	195	-8%	-13%	-8%	-8%	-15%	-8%	*-15%*	-9%
Ireland	69	69	69	69	69	69	*69*	69	-36%	-36%	-36%	-36%	-36%	-36%	*-36%*	-36%
Italy	1260	1247	1260	1260	1260	1260	*1247*	1260	-37%	-38%	-37%	-37%	-37%	-37%	*-38%*	-37%
Latvia	115	115	115	115	115	115	*115*	115	1%	1%	1%	1%	1%	1%	*1%*	1%
Lithuania	137	137	137	137	137	137	*137*	137	-9%	-9%	-9%	-9%	-9%	-9%	*-9%*	-9%
Luxembourg	12	12	12	12	12	12	*12*	12	-43%	-43%	-43%	-43%	-43%	-43%	*-43%*	-43%
Netherlands	270	270	270	270	270	270	*270*	270	-50%	-50%	-50%	-50%	-50%	-50%	*-50%*	-50%
Norway	161	161	161	161	161	161	*161*	161	-30%	-30%	-30%	-30%	-30%	-30%	*-30%*	-30%
Poland	1004	1000	1004	1004	841	915	*841*	995	-17%	-17%	-17%	-17%	-30%	-24%	*-30%*	-18%
Portugal	190	120	190	173	127	190	*120*	120	-9%	-42%	-9%	-17%	-39%	-9%	*-42%*	-42%
R. of Moldova	63	63	63	63	63	63	*63*	63	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Romania	453	390	425	453	430	453	*390*	401	-12%	-24%	-17%	-12%	-16%	-12%	*-24%*	-22%
Russia	2642	2642	2642	2642	2642	2642	*2642*	2642	-24%	-24%	-24%	-24%	-24%	-24%	*-24%*	-24%
Slovakia	134	123	133	134	125	131	*123*	127	-35%	-41%	-36%	-35%	-40%	-37%	*-41%*	-39%
Slovenia	31	31	31	31	31	31	*31*	31	-48%	-48%	-48%	-48%	-48%	-48%	*-48%*	-48%
Spain	844	803	844	701	844	844	*701*	722	-28%	-32%	-28%	-40%	-28%	-28%	*-40%*	-39%
Sweden	247	247	247	247	247	247	*247*	247	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Switzerland	100	100	100	100	100	100	*100*	100	-38%	-38%	-38%	-38%	-38%	-38%	*-38%*	-38%
FYRMacedonia	29	29	29	29	29	29	*29*	29	-26%	-26%	-26%	-26%	-26%	-26%	*-26%*	-26%
Ukraine	1094	1094	1068	1094	1094	1094	*1068*	1081	-42%	-42%	-43%	-42%	-42%	-42%	*-43%*	-43%
United Kingdom	1186	1186	1186	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	-55%	-55%	-55%	*-55%*	-55%
F.Yugoslavia	147	109	133	147	125	147	*109*	118	-30%	-48%	-37%	-30%	-41%	-30%	*-48%*	-44%
Atlantic Ocean	911	911	911	911	911	911	*911*	911	0%	0%	0%	0%	0%	0%	*0%*	0%
Baltic Sea	80	80	80	80	80	80	*80*	80	0%	0%	0%	0%	0%	0%	*0%*	0%
North Sea	639	639	639	639	639	639	*639*	639	0%	0%	0%	0%	0%	0%	*0%*	0%
Total	16859	16585	16753	16597	16419	16540	*16046*	16502	-32%	-34%	-33%	-34%	-34%	-34%	*-36%*	-34%

Table 4.4: VOC emissions for a 50 percent gap closure scenario for AOT60 (Scenarios D1-D6)

Country	VOC emissions (kilotons) CRP*	1989 D1	1990 D2	1992 D3	1993 D4	1994 D5	*minimum 1989-94*	composite D6	Change compared to 1990 CRP*	1989 D1	1990 D2	1992 D3	19.93 D4	1994 D5	*maximum 1989-94*	composite D6
Albania	40	40	40	40	40	40	*40*	40	37%	37%	37%	37%	37%	37%	*37%*	37%
Austria	305	305	305	305	305	305	*305*	305	-27%	-27%	-27%	-27%	-27%	-27%	*-27%*	-27%
Belarus	321	321	321	321	321	321	*321*	320	-5%	-5%	-5%	-5%	-5%	-5%	*-5%*	-5%
Belgium	220	131	126	120	150	135	*120*	123	-35%	-61%	-63%	-65%	-56%	-60%	*-65%*	-64%
Bosnia-H	58	58	58	58	55	58	*55*	58	29%	29%	29%	29%	22%	29%	*22%*	29%
Bulgaria	152	152	152	152	152	152	*152*	152	-21%	-21%	-21%	-21%	-21%	-21%	*-21%*	-21%
Croatia	80	80	80	68	80	80	*68*	80	-9%	-9%	-9%	-22%	-9%	-9%	*-22%*	-9%
Czech R.	205	185	193	138	190	198	*138*	162	-27%	-34%	-31%	-51%	-32%	-30%	*-51%*	-42%
Denmark	108	108	108	108	108	108	*108*	108	-38%	-38%	-38%	-38%	-38%	-38%	*-38%*	-38%
Estonia	55	55	55	55	55	55	*55*	55	14%	14%	14%	14%	14%	14%	*14%*	14%
Finland	108	108	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1665	1048	1665	982	1608	980	*980*	1253	-30%	-56%	-30%	-59%	-33%	-59%	*-59%*	-48%
Germany	1616	1341	1105	1147	1229	1210	*1105*	1100	-48%	-57%	-64%	-63%	-60%	-61%	*-64%*	-65%
Greece	205	180	205	205	205	201	*180*	195	-31%	-39%	-31%	-31%	-31%	-32%	*-39%*	-34%
Hungary	143	127	137	132	134	130	*127*	124	-17%	-26%	-21%	-23%	-22%	-25%	*-26%*	-28%
Ireland	57	57	57	57	57	57	*57*	57	-40%	-40%	-40%	-40%	-40%	-40%	*-40%*	-40%
Italy	1365	1365	1365	1244	1187	1167	*1167*	1165	-26%	-26%	-26%	-33%	-36%	-37%	*-37%*	-37%
Latvia	68	68	68	68	68	68	*68*	68	12%	12%	12%	12%	12%	12%	*12%*	12%
Lithuania	76	76	76	76	76	76	*76*	76	-13%	-13%	-13%	-13%	-13%	-13%	*-13%*	-13%
Luxembourg	9	9	9	9	9	9	*9*	9	-51%	-51%	-51%	-51%	-51%	-51%	*-51%*	-51%
Netherlands	258	180	150	153	158	186	*150*	151	-45%	-61%	-68%	-67%	-66%	-60%	*-68%*	-68%
Norway	168	168	168	168	168	168	*168*	168	-37%	-37%	-37%	-37%	-37%	-37%	*-37%*	-37%
Poland	687	597	627	490	667	589	*490*	551	0%	-13%	-9%	-29%	-3%	-14%	*-29%*	-20%
Portugal	144	96	144	144	126	144	*96*	100	-27%	-51%	-27%	-27%	-36%	-27%	*-51%*	-49%
R. of Moldova	60	60	60	60	60	60	*60*	60	-14%	-14%	-14%	-14%	-14%	-14%	*-14%*	-14%
Romania	553	492	515	553	527	548	*492*	490	-5%	-15%	-11%	-5%	-9%	-6%	*-15%*	-16%
Russia	2839	2839	2799	2839	2839	2838	*2799*	2802	-15%	-15%	-16%	-15%	-15%	-15%	*-16%*	-16%
Slovakia	113	98	109	113	104	107	*98*	100	-22%	-32%	-24%	-22%	-28%	-26%	*-32%*	-31%
Slovenia	25	25	25	25	25	25	*25*	25	-47%	-47%	-47%	-47%	-47%	-47%	*-47%*	-47%
Spain	794	557	794	794	794	794	*557*	569	-23%	-46%	-23%	-23%	-23%	-23%	*-46%*	-45%
Sweden	287	287	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	-36%	-36%	*-36%*	-36%
Switzerland	170	170	170	170	170	170	*170*	170	-42%	-42%	-42%	-42%	-42%	-42%	*-42%*	-42%
FYRMacedonia	15	15	15	15	15	15	*15*	15	8%	8%	8%	8%	8%	8%	*8%*	8%
Ukraine	671	671	671	671	671	671	*671*	671	-37%	-37%	-37%	-37%	-37%	-37%	*-37%*	-37%
United Kingdom	1276	898	804	936	910	1157	*804*	826	-53%	-67%	-70%	-65%	-66%	-57%	*-70%*	-69%
F.Yugoslavia	106	101	106	106	98	106	*98*	106	10%	5%	10%	10%	2%	10%	*2%*	10%
Total	15022	13068	13677	12917	13756	13323	*12219*	12649	-31%	-40%	-37%	-40%	-37%	-39%	*-44%*	-42%

Table 4.5: Costs for a 50 percent gap closure scenario for AOT60 (D1-D6), in million ECU/year

Country	Total costs CRP*	Additional costs on top of CRP* 1989 D1	1990 D2	1992 D3	1993 D4	1994 D5	*maximum 1989-94*	composite D6
Albania	14	0	0	0	0	0	*0*	0
Austria	844	0	0	0	0	0	*0*	0
Belarus	30	0	6	0	0	2	*6*	7
Belgium	1094	68	83	103	80	95	*103*	90
Bosnia-H	3	0	0	0	0	0	*0*	0
Bulgaria	142	1	0	0	0	0	*1*	0
Croatia	52	0	0	5	0	0	*5*	0
Czech R.	623	1	0	48	2	0	*48*	11
Denmark	449	0	0	0	0	0	*0*	0
Estonia	1	0	0	0	0	0	*0*	0
Finland	685	0	0	0	0	0	*0*	0
France	5908	408	0	521	50	524	*524*	249
Germany	8841	184	484	404	373	336	*484*	489
Greece	832	10	0	0	0	1	*10*	3
Hungary	479	11	0	1	13	2	*13*	6
Ireland	471	0	0	0	0	0	*0*	0
Italy	6206	0	0	0	23	38	*38*	39
Latvia	0	0	0	0	0	0	*0*	0
Lithuania	0	0	0	0	0	0	*0*	0
Luxembourg	72	0	0	0	0	0	*0*	0
Netherlands	2137	83	163	150	132	71	*163*	157
Norway	471	0	0	0	0	0	*0*	0
Poland	1820	10	2	95	42	30	*95*	32
Portugal	949	347	0	6	115	0	*347*	315
R. of Moldova	12	0	0	0	0	0	*0*	0
Romania	140	18	3	0	1	0	*18*	14
Russia	923	0	0	0	0	0	*0*	0
Slovakia	348	4	0	0	1	0	*4*	2
Slovenia	132	0	0	0	0	0	*0*	0
Spain	3538	161	0	51	0	0	*161*	186
Sweden	1129	0	0	0	0	0	*0*	0
Switzerland	605	0	0	0	0	0	*0*	0
FYRMacedonia	0	0	0	0	0	0	*0*	0
Ukraine	1144	0	37	0	0	0	*37*	19
United Kingdom	5721	1060	1670	881	999	219	*1670*	1500
F.Yugoslavia	0	75	10	0	25	0	*75*	41
Atlantic Ocean	231	0	0	0	0	0	*0*	0
Baltic Sea	26	0	0	0	0	0	*0*	0
North Sea	159	0	0	0	0	0	*0*	0
Total	46232	2441	2458	2265	1856	1318	*3802*	3160

Figure 4.13 displays the ‘binding’ grids for the composite scenario D6, i.e., the grids where the optimized AOT60 level is at, or closely below, the specified targets. For all other grids the gap closure is higher than stipulated. It is in the nature of an optimized result that modifications of the target of such ‘binding’ grid cells will influence the optimized emission reductions. For the 50% gap closure scenario, binding grid cells occur in the UK, Portugal, Italy, Greece, F. Yugoslavia, Poland and Ukraine.

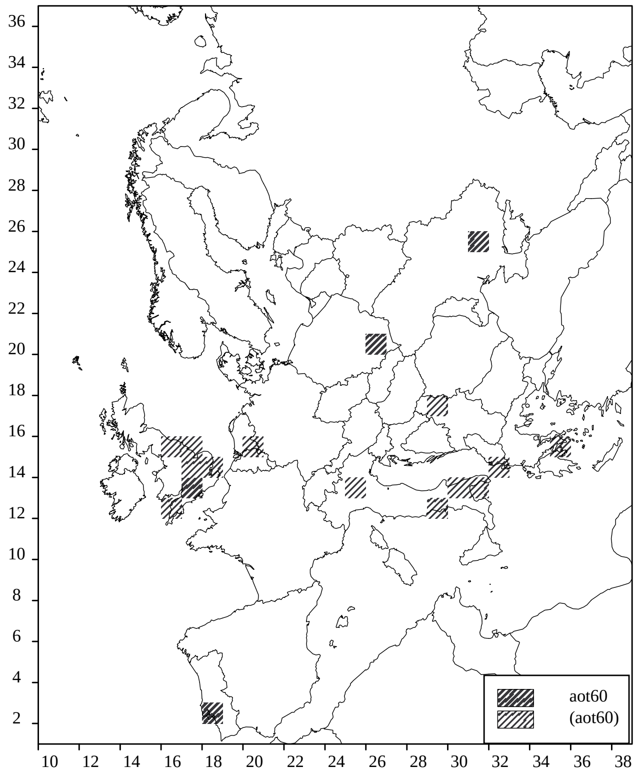

Figure 4.13: Binding grids for the D6 scenario. The map indicates where the AOT60 after the optimization is exactly at (grids indicated with ’aot60’) or is very close to [indicated with ’(aot60)’] the target level. At all other grids the optimized AOT60 is below the specified target.

Examining the measures of individual countries, the main action on NO_x emissions would be required in Belarus, Belgium, France, Hungary, Poland, Portugal, Romania, Slovakia and F. Yugoslavia (Figure 4.14), depending on the meteorological conditions. While for Belarus and Portugal the composite optimization results in the maximum NO_x reduction spanned by the solutions for the individual years, for Belgium the composite scenario ends at the lowest point, and for the other countries at intermediate points in the range. For VOC (Figure 4.15), a number of countries would take action in at least one year. The composite optimization ends typically close to the lowest emissions spanned by the individual years.

Figure 4.16 shows the emission reductions of the AOT60-related gap closure scenario beyond those of the CRP* scenario and illustrates the preference for further VOC reductions. Only Yugoslavia and Belarus would control only NO_x emissions, while Portugal, Spain, Romania and Slovakia embark on additional measures to control both pollutants. Many other countries show a strong priority for VOC control, which is sometimes caused by lower marginal costs for further VOC measures after the implementation of the CRP* scenario, but largely by the atmospheric chemistry responsible for the reduction of the higher ozone concentrations.

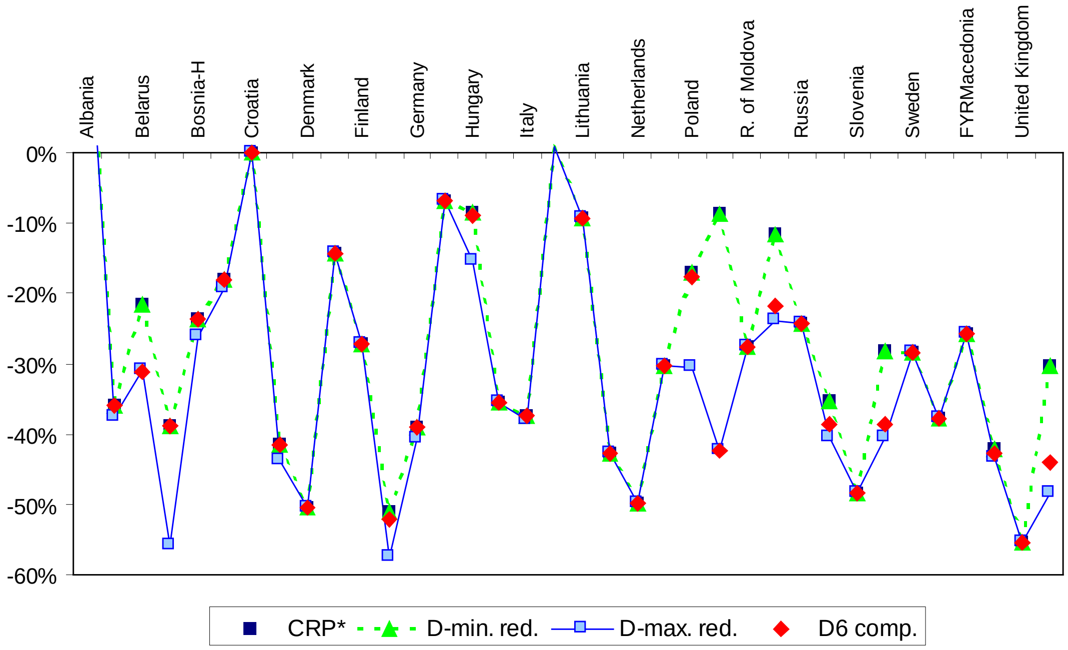

Figure 4.14: NO_x reductions for the 50 percent gap closure scenarios for the AOT60 (Scenarios D1-D6), compared to 1990

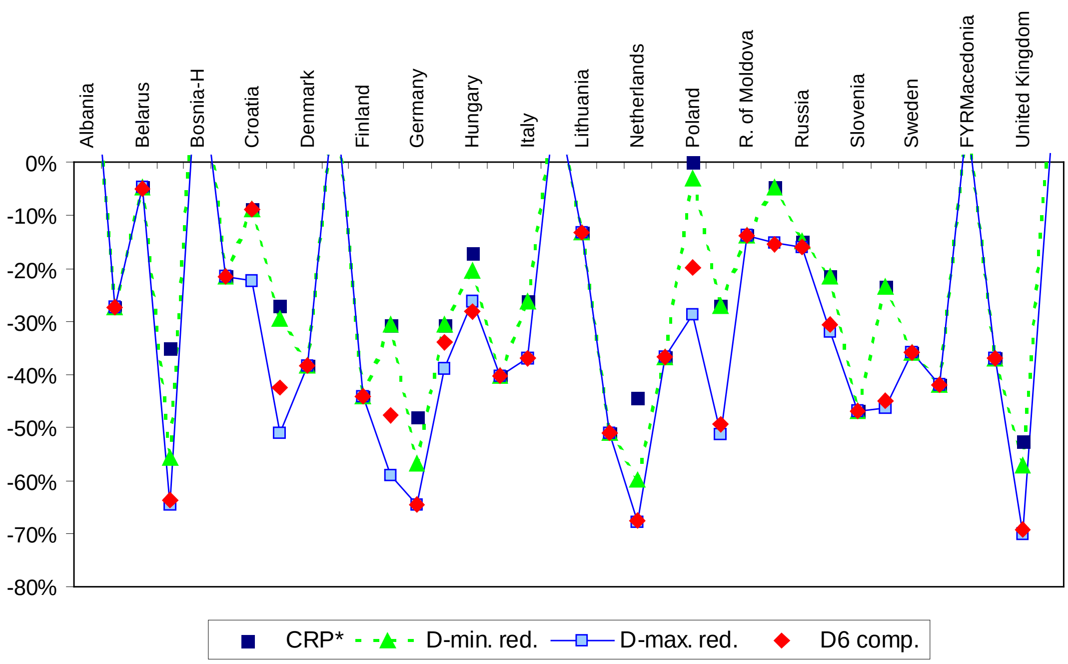

Figure 4.15: VOC reductions for the 50 percent gap closure scenarios for the AOT60 (Scenarios D1-D6), compared to 1990

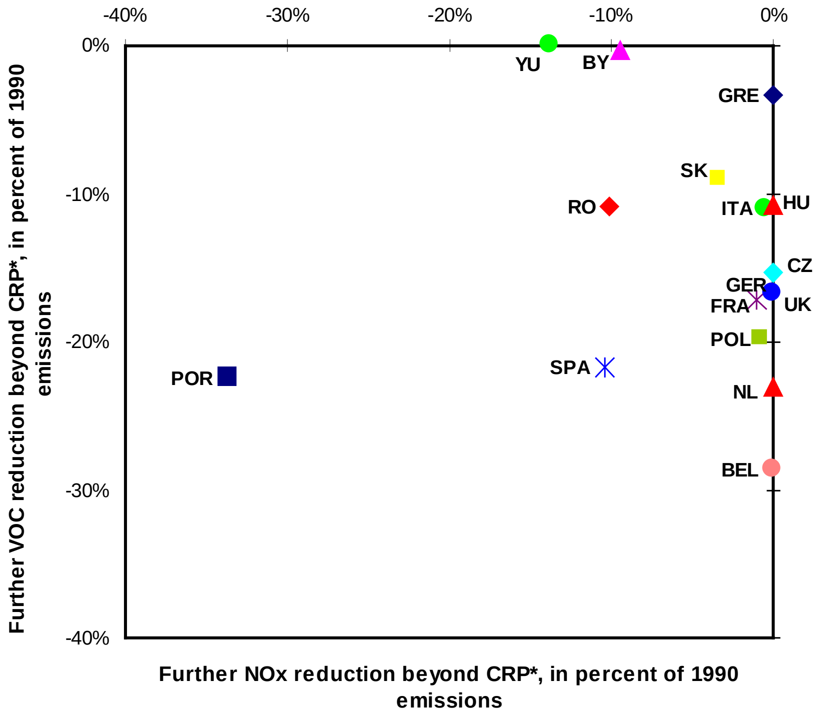

Figure 4.16: Further NO_x and VOC reductions (beyond CRP*) for the AOT60 gap closure scenario D6

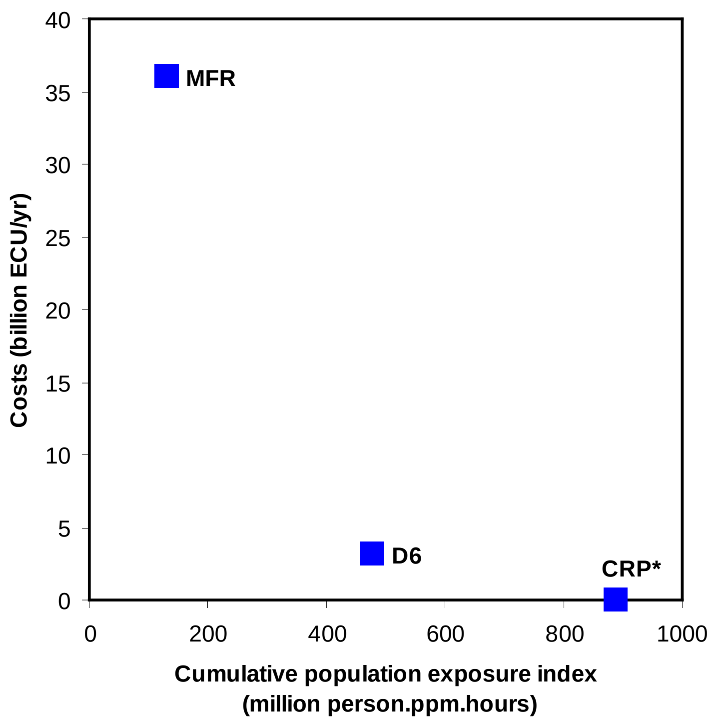

Figure 4.17: Cost-effectiveness of the 50% gap closure composite scenario for the AOT60

Table 4.6 lists the population exposure indices of the D6 composite AOT60 gap closure scenario based on the calculated five-year mean AOT60. Overall across Europe, this scenario achieves a reduction of 46% in the cumulative exposure index compared to the CRP* scenario. Figure 4.17 compares the costs of the D6 scenario against the improvements in the cumulative population exposure index.

Table 4.6: Population exposure indices for the AOT60 gap closure scenario

Country	Cumulative population exposure index (million person.ppm.hours)			Average population exposure index (ppm.hours)		
	CRP*	D6	MFR	CRP*	D6	MFR
Albania	1	1	0	0.2	0.2	0.0
Austria	8	4	0	1.1	0.6	0.0
Belarus	4	2	0	0.3	0.2	0.0
Belgium	44	23	14	4.0	2.1	1.3
Bosnia-H	2	1	0	0.4	0.2	0.0
Bulgaria	3	1	0	0.3	0.2	0.0
Croatia	5	3	0	1.1	0.7	0.0
Czech R.	19	10	0	1.8	1.0	0.0
Denmark	5	3	0	1.1	0.5	0.0
Estonia	0	0	0	0.2	0.1	0.0
Finland	0	0	0	0.1	0.1	0.0
France	156	68	25	2.7	1.2	0.4
Germany	226	122	52	2.9	1.5	0.7
Greece	3	3	0	0.3	0.3	0.0
Hungary	17	10	0	1.7	1.0	0.0
Ireland	2	1	0	0.5	0.2	0.0
Italy	86	65	2	1.5	1.1	0.0
Latvia	1	0	0	0.4	0.2	0.0
Lithuania	2	1	0	0.5	0.2	0.0
Luxembourg	2	1	1	4.7	2.6	1.3
Netherlands	48	26	17	3.2	1.7	1.1
Norway	1	0	0	0.1	0.1	0.0
Poland	58	31	0	1.5	0.8	0.0
Portugal	10	6	3	1.0	0.6	0.3
R. of Moldova	2	1	0	0.5	0.2	0.0
Romania	13	6	0	0.6	0.3	0.0
Russia	11	9	0	0.1	0.1	0.0
Slovakia	9	5	0	1.7	1.0	0.0
Slovenia	2	1	0	1.2	0.7	0.0
Spain	18	7	0	0.5	0.2	0.0
Sweden	2	1	0	0.3	0.1	0.0
Switzerland	6	3	0	0.8	0.4	0.0
FYRMacedonia	0	0	0	0.1	0.1	0.0
Ukraine	19	12	0	0.4	0.2	0.0
United Kingdom	99	48	18	1.7	0.8	0.3
F.Yugoslavia	5	2	0	0.4	0.2	0.0
Total	889	477	132	1.3	0.7	0.2

5 Ground-level Ozone: Vegetation Effects

While the preceding section focused on a health-related ozone exposure criterion, the following analysis explores important features of strategies aimed at reducing the risk of ozone-induced damage to 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 has 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.

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 level for forest trees is 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.

5.1 The Situation in 1990 and the Scope for Improvement

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 5.1 displays the excess AOT40 (over the critical level of 3 ppm.hours) calculated for the emissions of the year 1990 using the five-year mean meteorology. The map shows clearly the large area of Europe in which the AOT40 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 up to 16 ppm.hours, i.e., it exceeded the critical level by more than a factor of five. It is noteworthy that ozone levels in many areas which do not experience any substantial excess of the AOT60 do, however, exceed the AOT40 criterion significantly. This applies particularly to the Mediterranean countries and some Alpine regions.

The emission reductions of the CRP* scenario will generally lead to a decline of the excess AOT40, but will not significantly increase the protected area (Figure 5.2). The maximum feasible emission reductions are expected to achieve a 50 percent and higher cut of the excess AOT40 in most regions (Figure 5.3).

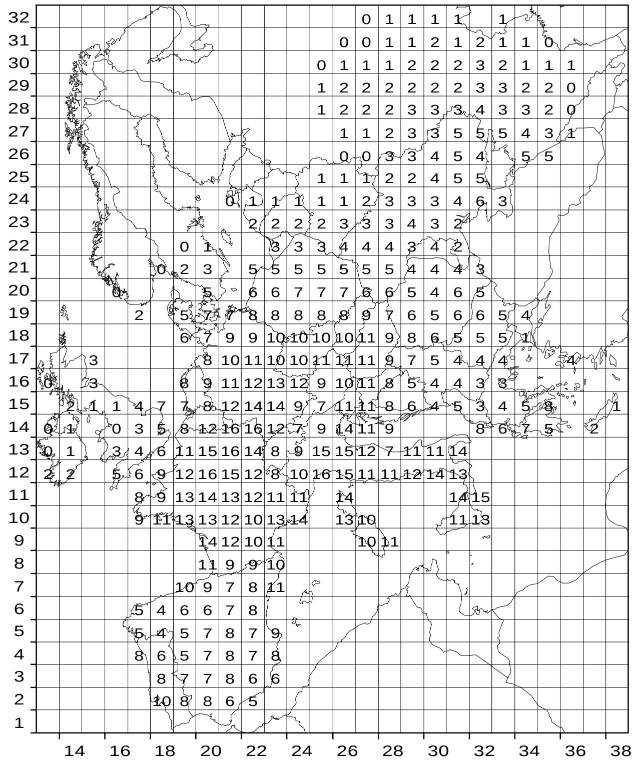

Figure 5.1: Excess AOT40 above the critical level of 3 ppm.hours for the year 1990 (using five years mean meteorology), in ppm.hours. Land area left blank had no excess in 1990.

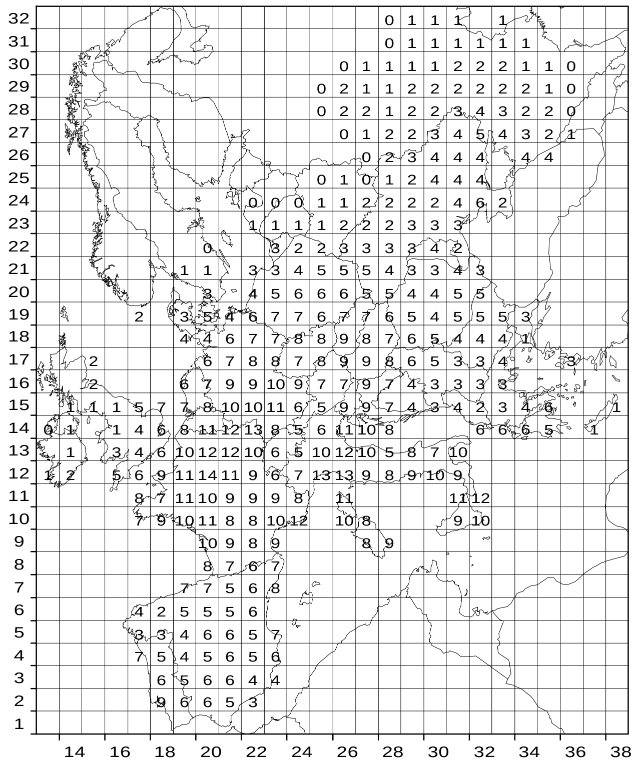

Figure 5.2: Excess AOT40 above the critical level of 3 ppm.hours for the CRP* scenario in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario.

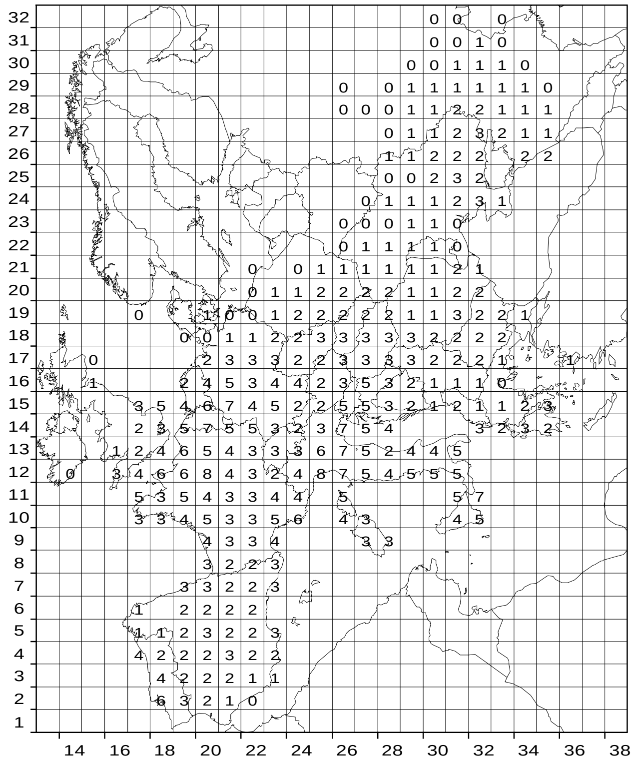

Figure 5.3: Excess AOT40 above the critical level of 3 ppm.hours for the maximum feasible emission reductions in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario.

Table 5.1 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.

In 1990, France, Germany, Spain and Italy experienced the highest cumulative indices. Per ecosystem, the highest exposure was experienced in Luxembourg, France, Italy, Belgium, Germany, Slovenia and the Czech Republic. The current reduction measures are expected to decrease the indices by about 20% across Europe as a whole, which is significantly lower than the expected decline in the health-related exposure indices (40%). While some areas (Ireland, Sweden, etc.) achieve a 50% reduction, the expected improvement in Belgium and the Netherlands is only about 10%, and in the UK the cumulative vegetation exposure index shows a 10% *increase* for the CRP* scenario. This low, or non-existent, improvement is caused by features of ozone chemistry in high-NO_x regions, as outlined below. The maximum feasible reductions would overcome these effects and lead to a 70% reduction in the vegetation exposure index for Europe as a whole.

Table 5.1: Vegetation exposure indices for 1990, the CRP* Scenario in 2010 and the maximum feasible emission reductions

Country	Cumulative vegetation exposure index (million hectares.excess ppm.hours)			Average vegetation exposure index (excess ppm.hours)		
	1990	CRP*	MFR	1990	CRP*	MFR
Albania	8	7	3	4.8	3.9	1.5
Austria	48	36	14	9.4	7.0	2.7
Belarus	15	11	1	1.6	1.3	0.1
Belgium	18	16	10	11.3	10.3	6.2
Bosnia-H	25	21	9	6.6	5.4	2.3
Bulgaria	37	31	14	4.9	4.1	1.9
Croatia	34	28	14	9.5	7.9	3.9
Czech R.	57	43	14	10.2	7.7	2.6
Denmark	14	9	1	4.7	3.1	0.3
Estonia	0	0	0	0.1	0.0	0.0
Finland	0	0	0	0.0	0.0	0.0
France	405	315	133	12.5	9.8	4.1
Germany	235	174	65	11.1	8.2	3.0
Greece	24	21	8	4.4	3.8	1.4
Hungary	64	51	20	9.9	7.9	3.1
Ireland	2	1	0	1.0	0.6	0.0
Italy	181	136	73	11.5	8.7	4.7
Latvia	4	2	0	0.9	0.4	0.0
Lithuania	7	5	0	1.8	1.2	0.0
Luxembourg	2	2	1	15.9	12.3	5.4
Netherlands	10	9	5	8.0	7.0	4.0
Norway	0	0	0	0.0	0.0	0.0
Poland	149	123	26	6.5	5.4	1.2
Portugal	37	30	16	6.4	5.2	2.8
R. of Moldova	6	6	2	3.7	3.8	1.3
Romania	84	73	28	5.3	4.7	1.8
Russia	110	87	30	0.6	0.5	0.2
Slovakia	34	28	10	9.4	7.7	2.7
Slovenia	14	11	6	10.6	8.5	4.4
Spain	203	151	56	6.6	4.9	1.8
Sweden	13	6	0	0.4	0.2	0.0
Switzerland	16	11	5	8.9	6.2	2.7
FYRMacedonia	5	5	2	3.5	3.0	1.2
Ukraine	145	125	48	3.7	3.2	1.2
United Kingdom	21	23	11	2.6	2.7	1.3
F.Yugoslavia	34	29	13	5.0	4.3	1.8
Total	2061	1626	638	3.9	3.1	1.2

The explanation for the expected increase, in some areas, in AOT40, and consequently in the vegetation exposure index, for the CRP* scenario 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 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 Figure 5.5, reducing NO_x will lead for some time to increased ozone. Beyond a certain NO_x reduction level, however, ozone will decline again.

Figure 5.4 supports this explanation by illustrating the NO_x emission densities in Europe in 1990. Emissions in the areas where the increase in AOT40 occurs (UK, and, to a lesser extent, Belgium and the Netherlands) are up to a factor of 10 higher than in other industrialized European regions (compare, e.g., southern Germany).

In general, Figure 5.4 also outlines the region in Europe where the non-linear ozone response is important and where lower NO_x emissions could cause increased ozone. In other regions this phenomenon does not occur (due to lower NO_x emission densities), and a reduction of NO_x will always result in lower ozone.

It is also worth emphasizing that this ozone increase disappears for the maximum feasible emission reductions (see Figure 5.5). This means that sufficiently high NO_x reductions (which are considered as technically feasible) can overcome the temporary ozone increase everywhere.

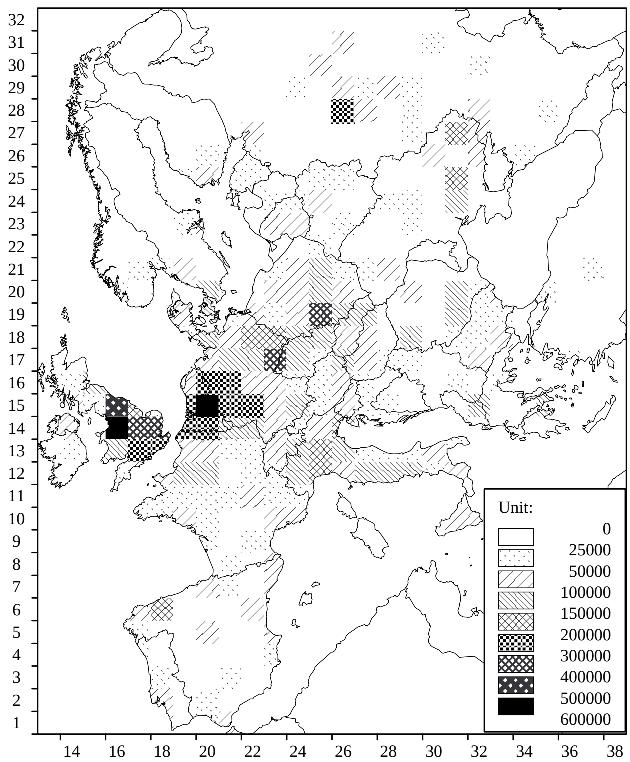

Figure 5.4: NO_x emissions per EMEP grid cell in 1990 (in tonnes)

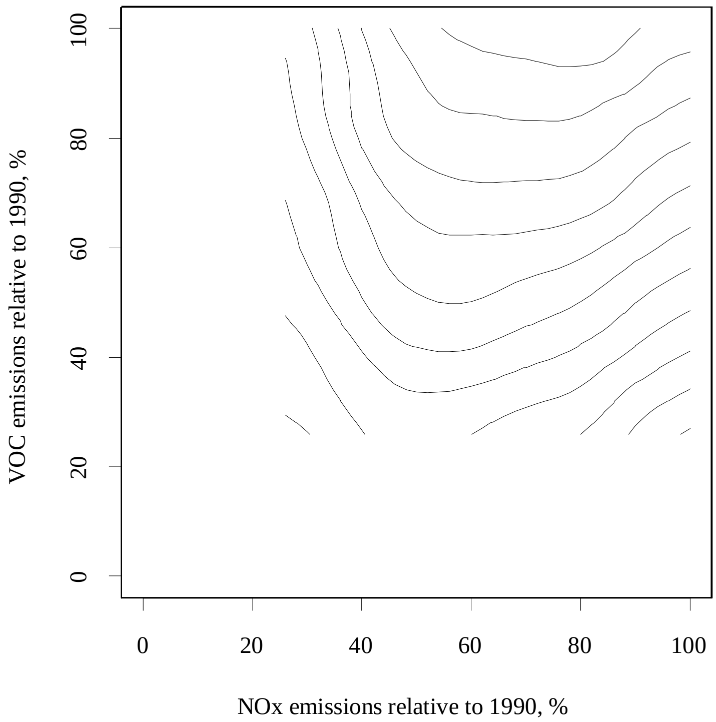

Figure 5.5: A typical ozone isopleth diagram for the non-linear region. The isopleths indicate the ozone concentrations (e.g., in terms of AOT40) as a function of NO_x and VOC emissions. Starting from the level in 1990 (the upper right corner), NO_x reductions (along the x-axis, to the left) will initially increase ozone and only after a certain reduction level lead to an ozone decrease.

5.2 An Optimized Scenario for the AOT40

Keeping in mind the possible scope for improvement, the selection of an appropriate environmental target for an ozone strategy becomes relevant. From the maps above it is clear that the AOT40 levels vary greatly over Europe, both for the CRP* scenario and for the maximum feasible emission reductions. Consequently, setting an absolute target in terms of AOT40 will affect necessarily only a small region, but will not force improvements for most other regions which already have lower excess ozone.

Similar situations have occurred for other environmental problems, such as acidification. In such cases the use of a gap-closure principle, i.e., establishing a relative measure for the excess exposure, offered useful solutions.

Figure 5.6 examines the situation for the AOT40. The graph compares for each EMEP grid cell on the x-axis (ordered according to the gap closure achieved by the CRP* scenario) the possible gap closure of the maximum feasible emission reductions (with the diamond symbols, along the y-axis). The figure clearly shows that there are some grids with a negative gap closure of the CRP* scenario, i.e., where the excess AOT40 of the CRP* scenario will be higher than it was in the year 1990. The reason for this is the non-linear ozone chemistry for high NO_x regions, discussed above. However, the graph clearly demonstrates that there is a certain scope for improvement in these regions (even compared to the 1990 situation), if the emissions are reduced further.

The most important conclusion from this graph is that there are several grids where the maximum achievable gap closure for the excess AOT40 is in the range of 30-40 percent. Unfortunately, some of these grids show quite high ozone and should not, therefore, be eliminated from the improvement strategy. This means that a conventional ‘uniform’ gap closure target, as applied for acidification, would be limited, realistically, to about 20%. On the other hand, the graph also shows that for about two-thirds of the grid cells the CRP* scenario will result in an improvement of more than 20%, so that such a target would not force substantial, widespread environmental improvement over Europe.

A further complication arises from the fact that the low possible gap closures of AOT40 occur in those regions where the non-linearity in ozone formation prevails. Optimized strategies focusing on these regions will inevitably propose exclusively further VOC reductions and will keep the NO_x as high as possible.

Theoretically, there are several possibilities to overcome these problems in target setting:

- One could specify a certain uniform gap closure target and exclude all grids from the optimization where this target is not achievable. In practice this would mean excluding entire countries (Belgium, Netherlands, large parts of the UK) from the analysis, where the ozone problem is serious and the ozone formation chemistry works in a different (non-linear) regime from that in other countries.
- Alternatively, the gap could be defined as the difference between, e.g., the 1990 situation (or the CRP* scenario) and the maximum technically feasible reduction. In such a case a uniform gap closure could be specified which would determine the step towards the long-term environmental target in relation to the actual technical possibilities. Such an approach has certain advantages, e.g., that the target will always be achievable (by definition), and that practically all areas will experience an environmental improvement. There are, however, also serious disadvantages of such an approach:
    1. The basic concept of effect-based strategies (‘the extent of measures is determined by environmental needs’) will be replaced by a source-oriented rationale (the extent of measures is mainly determined by what is technically possible).
    2. There is no inherent driving force to strive for measures not considered in the set of the ‘maximum technically feasible reductions’. Since in practice the current modelling approach excludes, e.g., non-technical measures and structural changes from the cost curves, the emission reduction potential of such measures would never be considered, even if there were an environmental need.
    3. For a number of reasons (non-existing large-scale practical experience with advanced future emission control technologies, exclusion of non-technical measures and structural changes, etc.) the maximum feasible reductions are one of the most uncertain areas of the entire current modelling framework. It seems dangerous to rely on one of the most uncertain model elements as a major driving force for strategy development.
- A third option is to define the gap closure target not in relation to 1990 (e.g., a minimum gap closure of 50% in relation to 1990), but in relation, e.g., to the CRP* scenario, which reflects much of the different characteristics of ozone formation. As shown in Figure 5.6, the CRP* scenario achieves gap closures between -20% and +100%. For most grids there is the possibility for an additional 20-30 percent improvement on top of the CRP* scenario. A practical target could, e.g., aim at increasing the gap closure by 10 percentage points compared to the CRP* scenario. An important advantage of such an approach is that it forces

improvements for all grids, and thereby will most likely achieve a balance of the measures for regions with different ozone regimes.

Again, the choice of the appropriate environmental target is a political decision. Without prejudging such a decision, the analysis carried out here adopted the last principle to provide some illustrative results for AOT40-related optimization scenarios. Arbitrarily, a 10% improvement has been selected for the illustrative scenario. Furthermore, for areas with very low (or even negative) gap closures of the CRP* scenario (where much more than a 10% improvement is achievable by the maximum feasible emission reductions), a minimum 15% gap closure (related to 1990) has been specified as an additional criterion. The selected target gap closure is indicated in Figure 5.6 by the black line.

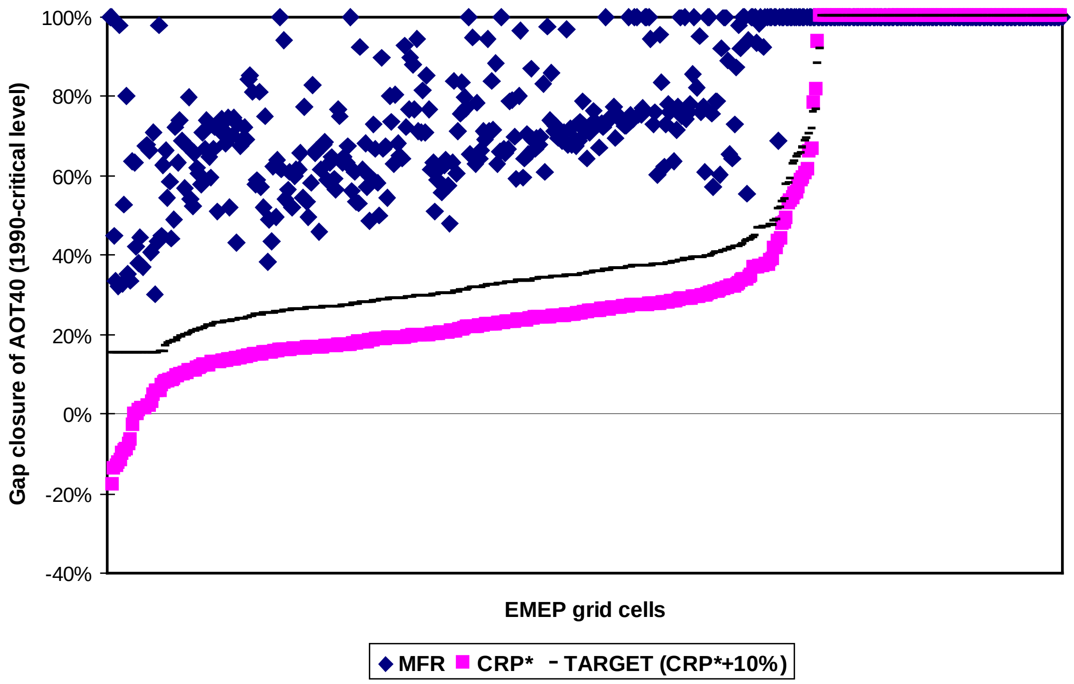

Figure 5.6: The possible gap closure of AOT40 (on the y-axis) for the EMEP grids (along the x-axis, ordered according to their gap closure of the CRP* scenario). The maximum possible gap closure is essentially determined by the maximum feasible emission reductions (MFR). Meaningful targets for the optimization should lie between the gap closure achieved by the CRP* scenario and the MFR. TARGET indicates the illustrative choice made for this analysis.

5.2.1 Scenario D7: AOT40 CRP* +10% Gap Closure Scenario

Table 5.2 to Table 5.4 present emission reductions and control costs for the AOT40-related gap closure scenario. In comparison with the AOT60-related scenario D6, scenario D7 requires further overall reductions of both NO_x and VOC emissions (an additional 2% reduction of the 1990 emissions for both pollutants) but the additional costs (above CRP*) are 14% lower than for D6. The causes of this apparent discrepancy are revealed by examination of the differences in costs between the scenarios for individual countries. Comparing scenarios D7 and D6, the AOT40 scenario suggests more expensive measures in Belarus, Czech Republic, France, Italy, Russia, Switzerland and Ukraine, while Belgium, Germany, the Netherlands, Portugal, Spain, the UK and Yugoslavia end up with less expensive measures. The largest cost difference occurs for the UK, where the costs of the AOT40 scenario are 88% lower than those of the AOT60, related entirely to the different VOC reductions required by the two scenarios. One important reason for these differences is the different nature of the gap closure target. The AOT40 scenario aimed at further improvement - beyond CRP* - everywhere in Europe, while the AOT60 gap closure target is already partly achieved by the CRP* scenario. Consequently, although the measures required for the AOT40 scenario result in greater overall emission reductions, they are distributed more evenly across Europe. The larger costs of the AOT60 scenario reflect the measures required to achieve the AOT60 targets in the most ‘difficult’ grids in NW Europe, which tend to dominate the AOT60 optimization result. Another reason is the different ozone regime contributing to the AOT40 index.

The binding grids for the D7 AOT40-related scenario are shown in Figure 5.7. For this scenario the binding grids occur in the UK, Portugal, Italy, Greece and Ukraine.

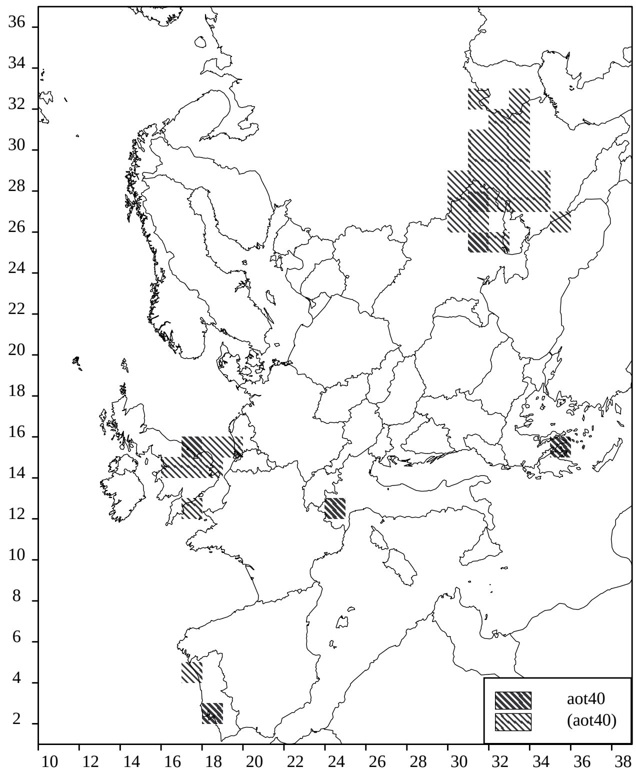

Figure 5.7: Binding grids for the D7 scenario. The map indicates where the AOT40 after the optimization is exactly at (grids indicated with 'aot40') or very close to [indicated with '(aot40)'] the target level. At all other grids the optimized AOT40 level is below the specified target.

Figure 5.8 demonstrates that NO_x reductions play a role in reducing the AOT40 in more countries than was the case for AOT60.

Table 5.5 presents the vegetation exposure indices for the D7 scenario. Compared to CRP*, D7 achieves a 31% decrease in the overall vegetation index. The largest relative improvements occur for Ireland, Sweden and Lithuania, where significant parts of their ecosystems will achieve the critical levels. Finally, Figure 5.9 assesses the cost-effectiveness of the AOT40 scenario, using the cumulative vegetation exposure index.

Table 5.2: NO_x emissions for the AOT40 gap closure scenario

Country	NO_x emissions (kilotons)		Change compared to 1990	
	CRP*	CRP + 10% D7	CRP*	CRP + 10% D7
Albania	30	30	25%	25%
Austria	155	145	-36%	-40%
Belarus	315	248	-22%	-38%
Belgium	222	222	-39%	-39%
Bosnia-H	61	61	-24%	-24%
Bulgaria	290	278	-18%	-21%
Croatia	83	83	0%	0%
Czech R.	305	239	-42%	-54%
Denmark	134	134	-51%	-51%
Estonia	72	72	-14%	-14%
Finland	203	177	-27%	-37%
France	791	652	-51%	-60%
Germany	1819	1819	-39%	-39%
Greece	365	365	-7%	-7%
Hungary	196	196	-8%	-8%
Ireland	69	69	-36%	-36%
Italy	1260	1260	-37%	-37%
Latvia	115	115	1%	1%
Lithuania	137	129	-9%	-15%
Luxembourg	12	12	-43%	-43%
Netherlands	270	270	-50%	-50%
Norway	161	161	-30%	-30%
Poland	1004	1004	-17%	-17%
Portugal	190	125	-9%	-40%
R. of Moldova	63	63	-28%	-28%
Romania	453	395	-12%	-23%
Russia	2642	2504	-24%	-28%
Slovakia	134	134	-35%	-35%
Slovenia	31	31	-48%	-48%
Spain	844	743	-28%	-37%
Sweden	247	247	-28%	-28%
Switzerland	100	84	-38%	-48%
FYRMacedonia	29	29	-26%	-26%
Ukraine	1094	1028	-42%	-46%
United Kingdom	1186	1186	-55%	-55%
F.Yugoslavia	147	147	-30%	-30%
Atlantic Ocean	911	911	0%	0%
Baltic Sea	80	80	0%	0%
North Sea	639	639	0%	0%
Total	16859	16087	-32%	-36%

Table 5.3: VOC emissions for the AOT40 gap closure scenario

Country	VOC emissions (kilotons)		Change compared to 1990	
	CRP*	CRP + 10% D7	CRP*	CRP + 10% D7
Albania	40	37	37%	26%
Austria	305	305	-27%	-27%
Belarus	321	303	-5%	-10%
Belgium	220	138	-35%	-59%
Bosnia-H	58	58	29%	29%
Bulgaria	152	152	-21%	-21%
Croatia	80	80	-9%	-9%
Czech R.	205	164	-27%	-42%
Denmark	108	108	-38%	-38%
Estonia	55	55	14%	14%
Finland	108	108	-44%	-44%
France	1665	902	-30%	-62%
Germany	1616	1192	-48%	-62%
Greece	205	180	-31%	-39%
Hungary	143	142	-17%	-18%
Ireland	57	57	-40%	-40%
Italy	1365	749	-26%	-60%
Latvia	68	68	12%	12%
Lithuania	76	72	-13%	-18%
Luxembourg	9	9	-51%	-51%
Netherlands	258	175	-45%	-62%
Norway	168	168	-37%	-37%
Poland	687	558	0%	-19%
Portugal	144	115	-27%	-42%
R. of Moldova	60	60	-14%	-14%
Romania	553	483	-5%	-17%
Russia	2839	2676	-15%	-20%
Slovakia	113	113	-22%	-22%
Slovenia	25	25	-47%	-47%
Spain	794	648	-23%	-37%
Sweden	287	287	-36%	-36%
Switzerland	170	86	-42%	-71%
FYRMacedonia	15	15	8%	8%
Ukraine	671	671	-37%	-37%
United Kingdom	1276	1175	-53%	-56%
F.Yugoslavia	106	106	10%	10%
Total	15022	12240	-31%	-44%

Table 5.4: Emission control costs for the AOT40 scenario (million ECU/year)

Country	Total costs CRP*	Additional costs on top of CRP* CRP + 10% D7
Albania	14	0
Austria	844	3
Belarus	30	33
Belgium	1094	53
Bosnia-H	3	0
Bulgaria	142	4
Croatia	52	0
Czech R.	623	29
Denmark	449	0
Estonia	1	0
Finland	685	7
France	5908	674
Germany	8841	334
Greece	832	10
Hungary	479	0
Ireland	471	0
Italy	6206	683
Latvia	0	0
Lithuania	0	3
Luxembourg	72	0
Netherlands	2137	91
Norway	471	0
Poland	1820	26
Portugal	949	173
R. of Moldova	12	0
Romania	140	18
Russia	923	56
Slovakia	348	0
Slovenia	132	0
Spain	3538	113
Sweden	1129	0
Switzerland	605	118
FYRMacedonia	0	0
Ukraine	1144	107
United Kingdom	5721	182
F.Yugoslavia	0	0
Atlantic Ocean	231	0
Baltic Sea	26	0
North Sea	159	0
Total	46232	2717

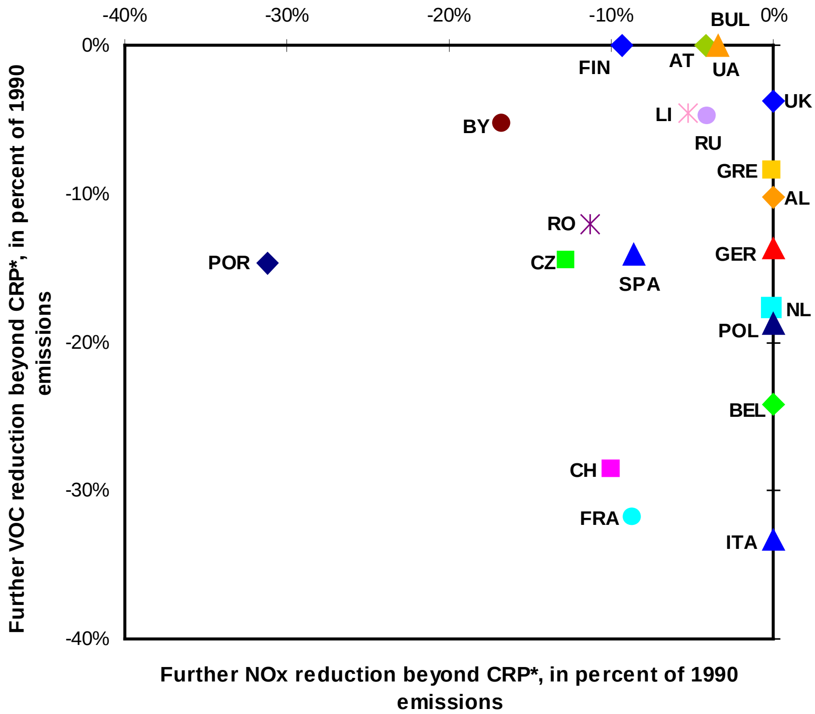

Figure 5.8: Change in NOx and VOC emissions beyond the CRP* scenario for the D7 AOT40-related gap closure scenario

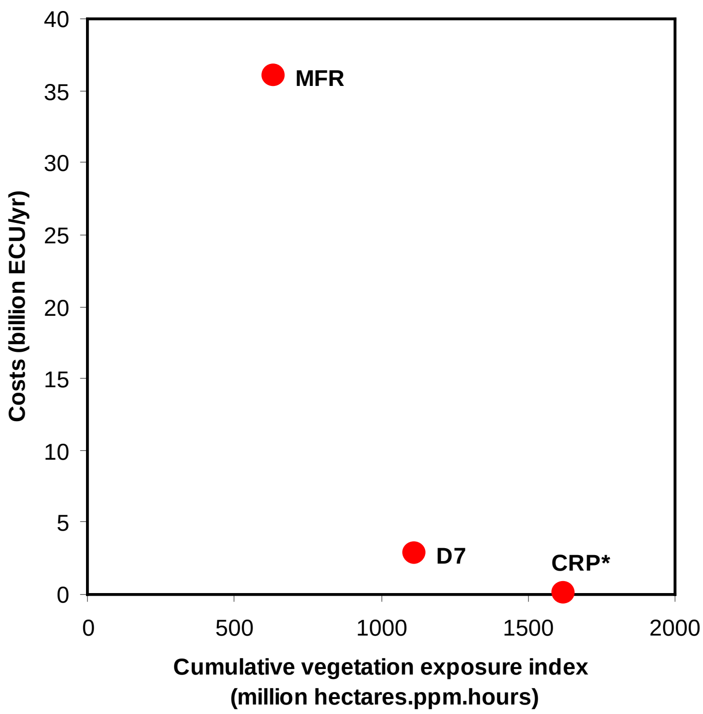

Figure 5.9: Cost-effectiveness of the AOT40-related gap closure scenario

Table 5.5: Vegetation exposure indices for the optimized AOT40 scenario

Country	Cumulative vegetation exposure index (million hectares.excess ppm.hours)			Average vegetation exposure index (excess ppm.hours)		
	CRP*	D7	MFR	CRP*	D7	MFR
Albania	7	5	3	3.9	2.8	1.5
Austria	36	26	14	7.0	5.0	2.7
Belarus	11	5	1	1.3	0.6	0.1
Belgium	16	12	10	10.3	7.5	6.2
Bosnia-H	21	15	9	5.4	3.9	2.3
Bulgaria	31	24	14	4.1	3.3	1.9
Croatia	28	22	14	7.9	6.1	3.9
Czech R.	43	29	14	7.7	5.2	2.6
Denmark	9	5	1	3.1	1.8	0.3
Estonia	0	0	0	0.0	0.0	0.0
Finland	0	0	0	0.0	0.0	0.0
France	315	191	133	9.8	5.9	4.1
Germany	174	114	65	8.2	5.4	3.0
Greece	21	15	8	3.8	2.8	1.4
Hungary	51	37	20	7.9	5.8	3.1
Ireland	1	0	0	0.6	0.2	0.0
Italy	136	105	73	8.7	6.6	4.7
Latvia	2	1	0	0.4	0.1	0.0
Lithuania	5	2	0	1.2	0.5	0.0
Luxembourg	2	1	1	12.3	8.0	5.4
Netherlands	9	6	5	7.0	4.9	4.0
Norway	0	0	0	0.0	0.0	0.0
Poland	123	75	26	5.4	3.3	1.2
Portugal	30	23	16	5.2	3.9	2.8
R. of Moldova	6	5	2	3.8	2.7	1.3
Romania	73	53	28	4.7	3.4	1.8
Russia	87	68	30	0.5	0.4	0.2
Slovakia	28	19	10	7.7	5.4	2.7
Slovenia	11	9	6	8.5	6.6	4.4
Spain	151	106	56	4.9	3.4	1.8
Sweden	6	2	0	0.2	0.1	0.0
Switzerland	11	7	5	6.2	4.0	2.7
FYRMacedonia	5	4	2	3.0	2.3	1.2
Ukraine	125	93	48	3.2	2.4	1.2
United Kingdom	23	16	11	2.7	1.9	1.3
F.Yugoslavia	29	22	13	4.3	3.2	1.8
Total	1626	1117	638	3.1	2.1	1.2

6 Considering AOT40 and AOT60 Simultaneously

The preceding two sections explored strategies for reducing the risk for human health and vegetation separately. In the real world, however, the task is to find one single emission control strategy complying with both types of environmental targets.

Recent progress in ozone optimization modelling at IIASA makes it now possible to consider human health- and vegetation-related targets simultaneously. In practice, the optimization problem looks for the least-cost combination of measures to satisfy simultaneously constraints on the composite AOT60 (ignoring the most unfavorable year) and on the AOT40.

This section presents the results from an optimization scenario, D8, which combines the composite 50% gap closure optimization for the AOT60 (Scenario D6) with the 10 percent (minimum) increase of the gap closure for the AOT40 (Scenario D7).

Table 6.1 to Table 6.3 present the results in terms of NO_x and VOC emissions and emission control costs. When combining the targets of two different environmental problems without having an optimization facility available, one would need to combine the lowest emissions of the two individual problems, or in other words, the lower envelope of the emissions for the two problems. As can be seen from the tables, however, the optimization identifies the potential for synergistic emission reductions serving both environmental problems optimally, and thereby relaxes the most stringent and expensive reduction requirements in many situations. For Europe as a whole, the combined optimization leads to 12% less NO_x reductions and 3% less VOC reduction, with a cost saving of about 8%.Figure 6.1 shows the binding grids for the joint optimization of Scenario D8. It is interesting to note that the AOT60 targets serve as the driving force in the UK, Portugal, and F. Yugoslavia, while in Italy, Greece and Ukraine the AOT40 targets are more stringent.

The NO_x and VOC emission reductions required in individual countries are displayed in Figure 6.2 and Figure 6.3, which indicate that for most countries the combined optimization ends with slightly less ambitious emission reductions than the individually most stringent optimization result.

Table 6.1: NO_x emissions for the ozone-related optimization scenarios

Country	NO_x emissions (kt)					Change compared to 1990				
		AOT60	AOT40	*minimum*	joint		AOT60	AOT40	*maximum*	joint
	CRP*	D6	D7	*D6 and D7*	D8	CRP*	D6	D7	*D6 and D7*	D8
Albania	30	30	30	*30*	30	25%	25%	25%	*25%*	25%
Austria	155	155	145	*145*	146	-36%	-36%	-40%	*-40%*	-40%
Belarus	315	277	248	*248*	252	-22%	-31%	-38%	*-38%*	-37%
Belgium	222	222	222	*222*	222	-39%	-39%	-39%	*-39%*	-39%
Bosnia-H	61	61	61	*61*	61	-24%	-24%	-24%	*-24%*	-24%
Bulgaria	290	290	278	*278*	284	-18%	-18%	-21%	*-21%*	-20%
Croatia	83	83	83	*83*	83	0%	0%	0%	*0%*	0%
Czech R.	305	305	239	*239*	249	-42%	-42%	-54%	*-54%*	-52%
Denmark	134	134	134	*134*	134	-51%	-51%	-51%	*-51%*	-51%
Estonia	72	72	72	*72*	72	-14%	-14%	-14%	*-14%*	-14%
Finland	203	203	177	*177*	183	-27%	-27%	-37%	*-37%*	-34%
France	791	775	652	*652*	673	-51%	-52%	-60%	*-60%*	-58%
Germany	1819	1819	1819	*1819*	1819	-39%	-39%	-39%	*-39%*	-39%
Greece	365	365	365	*365*	365	-7%	-7%	-7%	*-7%*	-7%
Hungary	196	195	196	*195*	196	-8%	-9%	-8%	*-9%*	-8%
Ireland	69	69	69	*69*	69	-36%	-36%	-36%	*-36%*	-36%
Italy	1260	1260	1260	*1260*	1260	-37%	-37%	-37%	*-37%*	-37%
Latvia	115	115	115	*115*	115	1%	1%	1%	*1%*	1%
Lithuania	137	137	129	*129*	126	-9%	-9%	-15%	*-15%*	-17%
Luxembourg	12	12	12	*12*	12	-43%	-43%	-43%	*-43%*	-43%
Netherlands	270	270	270	*270*	270	-50%	-50%	-50%	*-50%*	-50%
Norway	161	161	161	*161*	161	-30%	-30%	-30%	*-30%*	-30%
Poland	1004	995	1004	*995*	1004	-17%	-18%	-17%	*-18%*	-17%
Portugal	190	120	125	*120*	120	-9%	-42%	-40%	*-42%*	-42%
R. of Moldova	63	63	63	*63*	63	-28%	-28%	-28%	*-28%*	-28%
Romania	453	401	395	*395*	392	-12%	-22%	-23%	*-23%*	-24%
Russia	2642	2642	2504	*2504*	2503	-24%	-24%	-28%	*-28%*	-28%
Slovakia	134	127	134	*127*	132	-35%	-39%	-35%	*-39%*	-36%
Slovenia	31	31	31	*31*	31	-48%	-48%	-48%	*-48%*	-48%
Spain	844	722	743	*722*	748	-28%	-39%	-37%	*-39%*	-36%
Sweden	247	247	247	*247*	247	-28%	-28%	-28%	*-28%*	-28%
Switzerland	100	100	84	*84*	85	-38%	-38%	-48%	*-48%*	-47%
FYRMacedonia	29	29	29	*29*	29	-26%	-26%	-26%	*-26%*	-26%
Ukraine	1094	1081	1028	*1028*	1038	-42%	-43%	-46%	*-46%*	-45%
United Kingdom	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	*-55%*	-55%
F.Yugoslavia	147	118	147	*118*	128	-30%	-44%	-30%	*-44%*	-39%
Atlantic Ocean	911	911	911	*911*	911	0%	0%	0%	*0%*	0%
Baltic Sea	80	80	80	*80*	80	0%	0%	0%	*0%*	0%
North Sea	639	639	639	*639*	639	0%	0%	0%	*0%*	0%
Total	16859	16502	16087	*16015*	16118	-32%	-34%	-36%	*-36%*	-35%

Table 6.2: VOC emissions for the ozone-related optimization scenarios

Country	VOC emissions (kt)					Change compared to 1990				
	CRP*	AOT60 D6	AOT40 D7	*minimum D6 and D7*	joint D8	CRP*	AOT60 D6	AOT40 D7	*maximum D6 and D7*	joint D8
Albania	40	40	37	*37*	37	37%	37%	26%	26%	26%
Austria	305	305	305	*305*	305	-27%	-27%	-27%	-27%	-27%
Belarus	321	320	303	*303*	307	-5%	-5%	-10%	-10%	-9%
Belgium	220	123	138	*123*	125	-35%	-64%	-59%	-64%	-63%
Bosnia-H	58	58	58	*58*	58	29%	29%	29%	29%	29%
Bulgaria	152	152	152	*152*	152	-21%	-21%	-21%	-21%	-21%
Croatia	80	80	80	*80*	80	-9%	-9%	-9%	-9%	-9%
Czech R.	205	162	164	*162*	165	-27%	-42%	-42%	-42%	-41%
Denmark	108	108	108	*108*	108	-38%	-38%	-38%	-38%	-38%
Estonia	55	55	55	*55*	55	14%	14%	14%	14%	14%
Finland	108	108	108	*108*	108	-44%	-44%	-44%	-44%	-44%
France	1665	1253	902	*902*	926	-30%	-48%	-62%	-62%	-61%
Germany	1616	1100	1192	*1100*	1086	-48%	-65%	-62%	-65%	-65%
Greece	205	195	180	*180*	179	-31%	-34%	-39%	-39%	-39%
Hungary	143	124	142	*124*	135	-17%	-28%	-18%	-28%	-22%
Ireland	57	57	57	*57*	57	-40%	-40%	-40%	-40%	-40%
Italy	1365	1165	749	*749*	773	-26%	-37%	-60%	-60%	-58%
Latvia	68	68	68	*68*	68	12%	12%	12%	12%	12%
Lithuania	76	76	72	*72*	68	-13%	-13%	-18%	-18%	-22%
Luxembourg	9	9	9	*9*	9	-51%	-51%	-51%	-51%	-51%
Netherlands	258	151	175	*151*	154	-45%	-68%	-62%	-68%	-67%
Norway	168	168	168	*168*	168	-37%	-37%	-37%	-37%	-37%
Poland	687	551	558	*551*	561	0%	-20%	-19%	-20%	-18%
Portugal	144	100	115	*100*	104	-27%	-49%	-42%	-49%	-47%
R. of Moldova	60	60	60	*60*	60	-14%	-14%	-14%	-14%	-14%
Romania	553	490	483	*483*	479	-5%	-16%	-17%	-17%	-17%
Russia	2839	2802	2676	*2676*	2691	-15%	-16%	-20%	-20%	-19%
Slovakia	113	100	113	*100*	106	-22%	-31%	-22%	-31%	-26%
Slovenia	25	25	25	*25*	25	-47%	-47%	-47%	-47%	-47%
Spain	794	569	648	*569*	560	-23%	-45%	-37%	-45%	-46%
Sweden	287	287	287	*287*	287	-36%	-36%	-36%	-36%	-36%
Switzerland	170	170	86	*86*	90	-42%	-42%	-71%	-71%	-69%
FYRMacedonia	15	15	15	*15*	15	8%	8%	8%	8%	8%
Ukraine	671	671	671	*671*	671	-37%	-37%	-37%	-37%	-37%
United Kingdom	1276	826	1175	*826*	844	-53%	-69%	-56%	-69%	-69%
F.Yugoslavia	106	106	106	*106*	106	10%	10%	10%	10%	10%
Total	15022	12649	12240	*11626*	11722	-31%	-42%	-44%	-46%	-46%

Table 6.3: Emission control costs for the ozone-related optimization scenarios, in million ECU/year

Country	Total costs CRP*	Additional costs on top of CRP*			
		AOT60 D6	AOT40 D7	*maximum D6 and D7*	joint D8
Albania	14	0	0	*0*	0
Austria	844	0	3	*3*	2
Belarus	30	7	33	*33*	27
Belgium	1094	90	53	*90*	83
Bosnia-H	3	0	0	*0*	0
Bulgaria	142	0	4	*4*	2
Croatia	52	0	0	*0*	0
Czech R.	623	11	29	*29*	23
Denmark	449	0	0	*0*	0
Estonia	1	0	0	*0*	0
Finland	685	0	7	*7*	5
France	5908	249	674	*674*	607
Germany	8841	489	334	*489*	520
Greece	832	3	10	*10*	11
Hungary	479	6	0	*6*	1
Ireland	471	0	0	*0*	0
Italy	6206	39	683	*683*	608
Latvia	0	0	0	*0*	0
Lithuania	0	0	3	*3*	5
Luxembourg	72	0	0	*0*	0
Netherlands	2137	157	91	*157*	147
Norway	471	0	0	*0*	0
Poland	1820	32	26	*32*	24
Portugal	949	315	173	*315*	279
R. of Moldova	12	0	0	*0*	0
Romania	140	14	18	*18*	21
Russia	923	0	56	*56*	54
Slovakia	348	2	0	*2*	0
Slovenia	132	0	0	*0*	0
Spain	3538	186	113	*186*	179
Sweden	1129	0	0	*0*	0
Switzerland	605	0	118	*118*	104
FYRMacedonia	0	0	0	*0*	0
Ukraine	1144	19	107	*107*	88
United Kingdom	5721	1500	182	*1500*	1374
F.Yugoslavia	0	41	0	*41*	17
Atlantic Ocean	231	0	0	*0*	0
Baltic Sea	26	0	0	*0*	0
North Sea	159	0	0	*0*	0
Total	46232	3160	2717	*4563*	4181

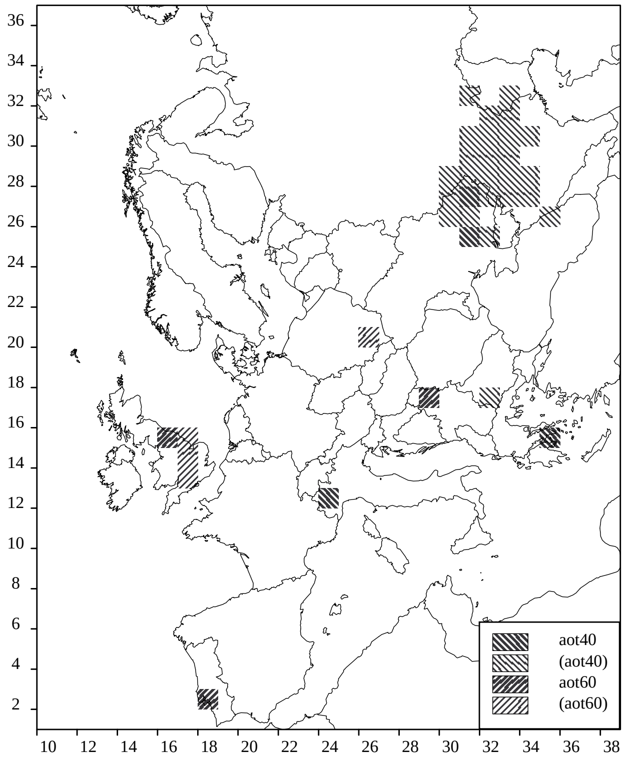

Figure 6.1: Binding grids for the Scenario D8. The map indicates where after optimization the ozone levels are at or are very close to the specified targets. The map distinguishes grids where the AOT40 is binding (indicated by 'aot40') or almost binding ['(aot40)'], and where the AOT60 is binding ['aot60'] or almost binding ['(aot60)'].

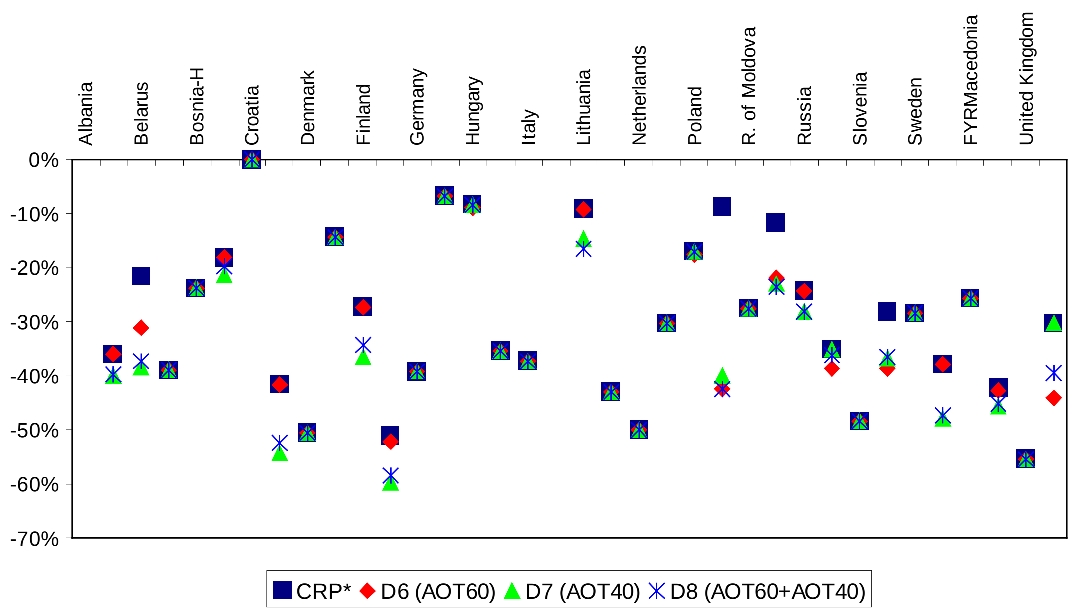

Figure 6.2: Change in NO_x emissions for the ozone-related optimization scenarios

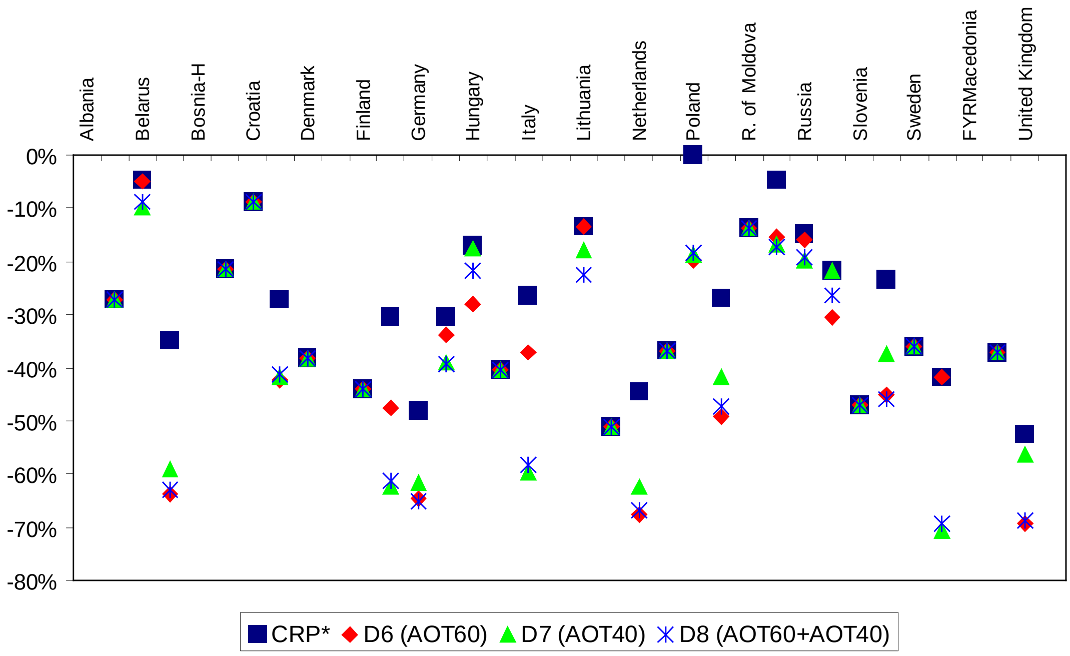

Figure 6.3: Change in VOC emissions for the ozone-optimized scenarios

7 Acidification

NO_x emissions are not only an important precursor substance for ground-level ozone, but they also make a major contribution to the acidification and eutrophication of ecosystems. It has been found in earlier work that the targeted control of NO_x emissions is an important element for the cost-effective reduction of acidification. The question arises how NO_x abatement schedules developed for acidification strategies interact with the interests of controlling ground-level ozone. A potential conflict has been identified in the earlier sections of this report for regions with high NO_x concentrations, where the ozone formation clearly shows non-linear behavior and the ozone-focused optimization tends to keep NO_x emissions as high as possible.

As a further advancement, a new feature of the RAINS ozone optimization is capable of simultaneously considering (linear) constraints on acid deposition in order to take the environmental targets of an acidification-oriented strategy into account. This new feature will be used in this section to attempt an analysis of the possible interaction of acidification and ozone-related strategies.

It is not the subject of this report to explore acidification-related scenarios in great detail. Consequently, the analysis presented here is restricted to one, illustrative 50% gap closure scenario for acidification (Scenario D9)

7.1 A 50% Gap Closure Scenario for Acidification (Scenario D9)

In order to examine the interaction of acidification and ozone strategies, a practical, basic acidification scenario has been constructed, in which the target is to reduce the area of unprotected ecosystems within each receptor grid by 50%. A brief outline of the scenario details follows:

- A 50% (area-related) gap closure for acidification to be achieved for each grid;
- Ships on the North Sea, the Baltic Sea and parts of the Atlantic Ocean use fuel oil with a maximum sulfur content of 1.5 percent;
- Shipping emissions are kept fixed at their CRP* values;
- Grid 14/13 in Ireland, where the 50% gap closure is impossible to achieve with the latest critical loads data, is excluded from the optimization. It has been agreed with Ireland to make further checks on the assumptions underlying the critical loads and emission estimates and to return to the problem at a later date;
- Grid 17/27 in northern Sweden has been excluded from the optimization since an error in the critical loads database was discovered;
- Grid 17/19 in southern Norway, where the 50% gap closure target is impossible to achieve, is excluded from the optimization.

It must be stressed that the assumptions made above still need careful review and further analysis. Consequently, the resulting Scenario D9 should be considered as illustrative only, mainly useful for exploring the interaction of ozone and acidification strategies.

The resulting emissions and costs for Scenario D9 are listed in Table 7.1 to Table 7.6.

The binding grid cells for Scenario D9, shown in Figure 7.1, include grid 20/17 in Germany/Netherlands. In previous studies this grid proved to be difficult and expensive to protect, i.e., this grid was the most ‘binding’. It should be noted that the critical loads data for this area are well-checked and robust, and that the optimization is not driven by a marginal ecosystem. The target ecosystem for the 50% gap closure approach in this grid is the 44th percentile; which means that even after successful gap closure, 43% of the ecosystems in this grid would face deposition above their critical loads. Neighboring grids show similar sensitivities and become immediately binding if grid 20/17 is excluded from the optimization.

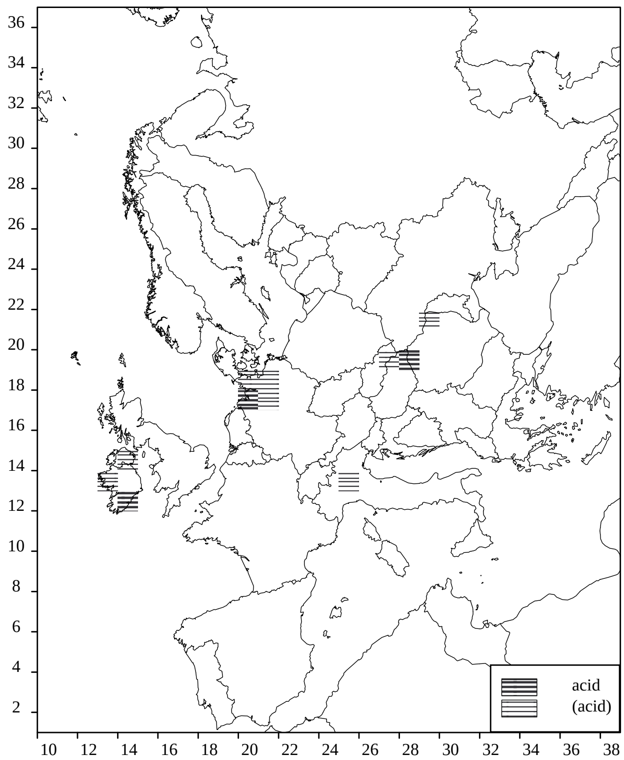

Figure 7.1: Binding grid cells for Scenario D9. The map indicates where after optimization acid deposition is at (indicated by 'acid') or closely below (indicated by '(acid)') the specified target. Note, however, that three grids where the 50% gap closure target is not achievable have been excluded from the optimization.

7.2 Joint Optimization for Acidification, AOT40 and AOT60 (Scenario D10)

At the end of this report, Scenario D10 explores the interaction of ozone- and acidification-related strategies. The joint analysis looks for a single solution for the combination of the following environmental targets:

- A 50% gap closure of AOT60, using the composite method to incorporate the meteorological variations of five years. For each grid cell the year with the lowest possible gap closure is excluded from the optimization, i.e., the 50% gap closure target must be achieved in four out of five years (Scenario D6);
- A minimum 10% improvement of the gap closure achieved by the CRP* scenario for the AOT40, with a minimum 15% gap closure compared to 1990 (Scenario D7);
- A 50% gap closure for acidification; however, the targets for three grids have been excluded for the reasons given above (Scenario D9).

The binding grids for the joint ozone-acidification scenario are shown in Figure 7.2. To a large extent, the grids that have most influence on the joint optimization solution are found in the same areas as for the individual problems. Binding grids for AOT60 are located in the UK, Portugal and Yugoslavia, with AOT40 binding grids being found in the Netherlands/Belgium/Germany, Italy, Greece and Ukraine. Acidification-related targets are seen to be most demanding in Northern Germany, Ireland and eastern Hungary.

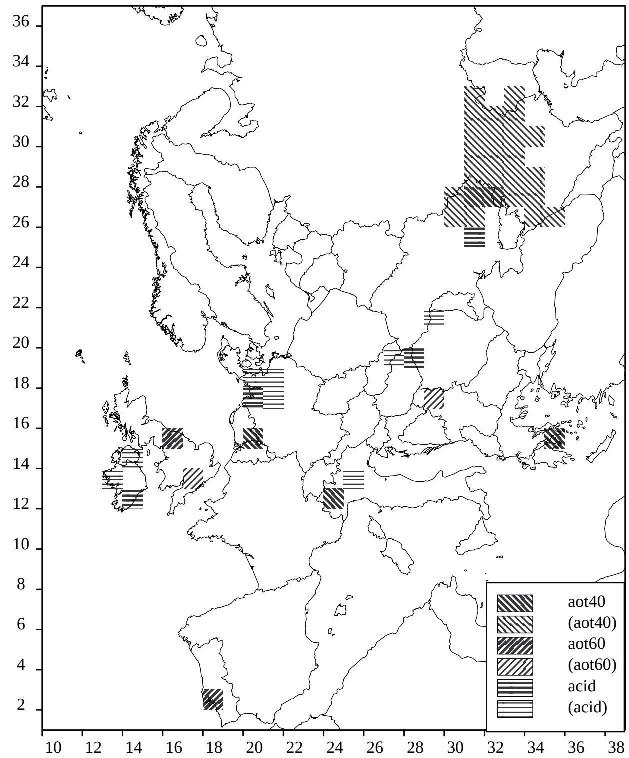

Figure 7.2: Binding grid cells for the combined ozone/acidification scenario D10. The map indicates where after optimization the exposures of AOT40, AOT60 and acidification, respectively, are at or slightly below (indicated with brackets) the targets.

The following tables (Table 7.1 to Table 7.6) provide the detailed results for the joint optimization and compare them with the optimization outcomes for the three environmental problems treated separately. As to be expected from theory, the joint optimization is cheaper than the upper envelope of the individual problems. In this example it is found, however, that the cost saving is not dramatic (3%) and that relaxation of the most stringent reduction requirements is limited, although for individual countries the differences might be significant (Figure 7.3 and Figure 7.4). Further analysis will be necessary to study this effect in more detail (and particularly to identify the relation between the potential cost savings and the stringency of the environmental targets). Some preliminary explanations can be put forward:

- By their nature, acidification and ozone are not strongly interrelated problems.
- In terms of emission reductions, acidification could trade additional NO_x reductions against less SO_2 and/or NH_3 measures (or vice versa), and ozone (in the 'linear' region) could trade additional NO_x reductions against lower demand on VOC measures. This means that one unit of NO_x reduction must be balanced against SO_2, and NH_3 and VOC reductions. Major rearrangements would prove cost-efficient only if there were significant differences in marginal costs. After the optimizations for the individual problems (with sufficiently stringent environmental targets) such big differences are, however, already eliminated to a large extent.

In the 'non-linear' ozone region (particularly in the UK) there is the interesting effect that for the ozone objective the NO_x emissions are kept high. Ecosystems sensitive towards acidification, however, require large NO_x reductions, in clear contrast to the ozone objective. The joint optimization could (a) keep NO_x high and compensate the excess acidity by additional measures for SO_2 and NH_3 emissions; or (b) reduce NO_x emissions as far as necessary to achieve the acidification targets, and compensate the additional ozone formation from these lower NO_x emissions by further VOC reductions. At least for this example the optimization tends more towards the second option. This can be explained by the facts that (a) the strong NO_x reductions required for acidification move the ozone system closer to the 'linear' behavior, where only modest additional VOC reductions are required to compensate for the ozone increase, (b) the high NO_x reductions are expensive (if not impossible) to compensate for by further SO_2 and NH_3 reductions, particularly since the binding grid for the acidification problem is located in Ireland, where the UK NH_3 emissions make only little contribution, and (c) the NO_x reductions also have a positive effect for downwind sites on the continent and relax the most expensive measures required there. For this particular example, the benefits to be gained downwind for the ozone abatement lead to slightly greater NO_x and VOC reductions than would result from the acidification interest alone.

Table 7.7 compares the areas of unprotected ecosystems in each country resulting from the acidification-related scenarios D9 and D10 with the situation in 1990 and with the CRP* and MFR scenarios. Considering all of Europe, the current emission reduction plans would be expected to reduce the total unprotected ecosystem area by 54%, with substantially better improvements in Latvia, Lithuania, Belarus, France and Denmark. On the basis of the current data sets, the maximum feasible reductions would protect 96% of the total European ecosystem area unprotected in 1990.

In terms of the improvements in unprotected ecosystem area, there is very little difference between the acidification scenario D9 and the joint scenario D10. Both scenarios would expect to achieve an 81% reduction in the total European unprotected area compared to the CRP* scenario. Norway (52% improvement over CRP*) and Ireland (53% improvement) would fare worse than the average in this regard.

Table 7.1: NO_x emissions for the scenarios targeted at acidification and ground-level ozone

Country	NO_x emissions (kilotons)						Change compared to 1990					
		AOT60	AOT40	Acidification	*minimum*	joint		AOT60	AOT40	Acidification	*maximum*	joint
	CRP*	D6	D7	D9	*D6, D7, D9*	D10	CRP*	D6	D7	D9	*D6, D7, D9*	D10
Albania	30	30	30	30	*30*	30	25%	25%	25%	25%	*25%*	25%
Austria	155	155	145	122	*122*	118	-36%	-36%	-40%	-50%	*-50%*	-51%
Belarus	315	277	248	297	*248*	261	-22%	-31%	-38%	-26%	*-38%*	-35%
Belgium	222	222	222	109	*109*	109	-39%	-39%	-39%	-70%	*-70%*	-70%
Bosnia-H	61	61	61	57	*57*	57	-24%	-24%	-24%	-29%	*-29%*	-29%
Bulgaria	290	290	278	290	*278*	284	-18%	-18%	-21%	-18%	*-21%*	-20%
Croatia	83	83	83	83	*83*	83	0%	0%	0%	0%	*0%*	0%
Czech R.	305	305	239	150	*150*	149	-42%	-42%	-54%	-71%	*-71%*	-71%
Denmark	134	134	134	88	*88*	88	-51%	-51%	-51%	-68%	*-68%*	-68%
Estonia	72	72	72	72	*72*	72	-14%	-14%	-14%	-14%	*-14%*	-14%
Finland	203	203	177	203	*177*	190	-27%	-27%	-37%	-27%	*-37%*	-32%
France	791	775	652	580	*580*	571	-51%	-52%	-60%	-64%	*-64%*	-65%
Germany	1819	1819	1819	979	*979*	979	-39%	-39%	-39%	-67%	*-67%*	-67%
Greece	365	365	365	365	*365*	365	-7%	-7%	-7%	-7%	*-7%*	-7%
Hungary	196	195	196	161	*161*	161	-8%	-9%	-8%	-25%	*-25%*	-25%
Ireland	69	69	69	30	*30*	30	-36%	-36%	-36%	-72%	*-72%*	-72%
Italy	1260	1260	1260	1084	*1084*	1260	-37%	-37%	-37%	-46%	*-46%*	-37%
Latvia	115	115	115	115	*115*	115	1%	1%	1%	1%	*1%*	1%
Lithuania	137	137	129	126	*126*	123	-9%	-9%	-15%	-17%	*-17%*	-19%
Luxembourg	12	12	12	8	*8*	8	-43%	-43%	-43%	-62%	*-62%*	-62%
Netherlands	270	270	270	190	*190*	190	-50%	-50%	-50%	-65%	*-65%*	-65%
Norway	161	161	161	161	*161*	161	-30%	-30%	-30%	-30%	*-30%*	-30%
Poland	1004	995	1004	582	*582*	576	-17%	-18%	-17%	-52%	*-52%*	-52%
Portugal	190	120	125	190	*120*	121	-9%	-42%	-40%	-9%	*-42%*	-42%
R. of Moldova	63	63	63	63	*63*	63	-28%	-28%	-28%	-28%	*-28%*	-28%
Romania	453	401	395	373	*373*	365	-12%	-22%	-23%	-27%	*-27%*	-29%
Russia	2642	2642	2504	2642	*2504*	2530	-24%	-24%	-28%	-24%	*-28%*	-27%
Slovakia	134	127	134	102	*102*	101	-35%	-39%	-35%	-51%	*-51%*	-51%
Slovenia	31	31	31	31	*31*	31	-48%	-48%	-48%	-48%	*-48%*	-48%
Spain	844	722	743	673	*673*	629	-28%	-39%	-37%	-43%	*-43%*	-47%
Sweden	247	247	247	192	*192*	191	-28%	-28%	-28%	-44%	*-44%*	-45%
Switzerland	100	100	84	89	*84*	83	-38%	-38%	-48%	-45%	*-48%*	-48%
FYRMacedonia	29	29	29	29	*29*	29	-26%	-26%	-26%	-26%	*-26%*	-26%
Ukraine	1094	1081	1028	1094	*1028*	1076	-42%	-43%	-46%	-42%	*-46%*	-43%
United Kingdom	1186	1186	1186	740	*740*	740	-55%	-55%	-55%	-72%	*-72%*	-72%
F.Yugoslavia	147	118	147	141	*118*	141	-30%	-44%	-30%	-33%	*-44%*	-33%
Atlantic Ocean	911	911	911	911	*911*	911	0%	0%	0%	0%	*0%*	0%
Baltic Sea	80	80	80	80	*80*	80	0%	0%	0%	0%	*0%*	0%
North Sea	639	639	639	639	*639*	639	0%	0%	0%	0%	*0%*	0%
Total	16859	16502	16087	13871	*13482*	13710	-32%	-34%	-36%	-44%	*-46%*	-45%

Table 7.2: VOC emissions for the scenarios targeted at acidification and ground-level ozone

Country	VOC emissions (kilotons)						Change compared to 1990					
		AOT60	AOT40	Acidification	*minimum*	joint		AOT60	AOT40	Acidification	*maximum*	joint
	CRP*	D6	D7	D9	*D6, D7, D9*	D10	CRP*	D6	D7	D9	*D6, D7, D9*	D10
Albania	40	40	37	40	*37*	38	37%	37%	26%	37%	*26%*	30%
Austria	305	305	305	305	*305*	305	-27%	-27%	-27%	-27%	*-27%*	-27%
Belarus	321	320	303	321	*303*	318	-5%	-5%	-10%	-5%	*-10%*	-5%
Belgium	220	123	138	220	*123*	129	-35%	-64%	-59%	-35%	*-64%*	-62%
Bosnia-H	58	58	58	58	*58*	58	29%	29%	29%	29%	*29%*	29%
Bulgaria	152	152	152	152	*152*	152	-21%	-21%	-21%	-21%	*-21%*	-21%
Croatia	80	80	80	80	*80*	80	-9%	-9%	-9%	-9%	*-9%*	-9%
Czech R.	205	162	164	205	*162*	172	-27%	-42%	-42%	-27%	*-42%*	-39%
Denmark	108	108	108	108	*108*	108	-38%	-38%	-38%	-38%	*-38%*	-38%
Estonia	55	55	55	55	*55*	55	14%	14%	14%	14%	*14%*	14%
Finland	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1665	1253	902	1665	*902*	978	-30%	-48%	-62%	-30%	*-62%*	-59%
Germany	1616	1100	1192	1616	*1100*	1099	-48%	-65%	-62%	-48%	*-65%*	-65%
Greece	205	195	180	205	*180*	190	-31%	-34%	-39%	-31%	*-39%*	-36%
Hungary	143	124	142	143	*124*	142	-17%	-28%	-18%	-17%	*-28%*	-18%
Ireland	57	57	57	57	*57*	57	-40%	-40%	-40%	-40%	*-40%*	-40%
Italy	1365	1165	749	1365	*749*	814	-26%	-37%	-60%	-26%	*-60%*	-56%
Latvia	68	68	68	68	*68*	68	12%	12%	12%	12%	*12%*	12%
Lithuania	76	76	72	76	*72*	71	-13%	-13%	-18%	-13%	*-18%*	-19%
Luxembourg	9	9	9	9	*9*	9	-51%	-51%	-51%	-51%	*-51%*	-51%
Netherlands	258	151	175	258	*151*	162	-45%	-68%	-62%	-45%	*-68%*	-65%
Norway	168	168	168	168	*168*	168	-37%	-37%	-37%	-37%	*-37%*	-37%
Poland	687	551	558	687	*551*	579	0%	-20%	-19%	0%	*-20%*	-16%
Portugal	144	100	115	144	*100*	109	-27%	-49%	-42%	-27%	*-49%*	-45%
R. of Moldova	60	60	60	60	*60*	60	-14%	-14%	-14%	-14%	*-14%*	-14%
Romania	553	490	483	553	*483*	511	-5%	-16%	-17%	-5%	*-17%*	-12%
Russia	2839	2802	2676	2839	*2676*	2739	-15%	-16%	-20%	-15%	*-20%*	-18%
Slovakia	113	100	113	113	*100*	113	-22%	-31%	-22%	-22%	*-31%*	-22%
Slovenia	25	25	25	25	*25*	25	-47%	-47%	-47%	-47%	*-47%*	-47%
Spain	794	569	648	794	*569*	600	-23%	-45%	-37%	-23%	*-45%*	-42%
Sweden	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	*-36%*	-36%
Switzerland	170	170	86	170	*86*	95	-42%	-42%	-71%	-42%	*-71%*	-68%
FYRMacedonia	15	15	15	15	*15*	15	8%	8%	8%	8%	*8%*	8%
Ukraine	671	671	671	671	*671*	671	-37%	-37%	-37%	-37%	*-37%*	-37%
United Kingdom	1276	826	1175	1276	*826*	809	-53%	-69%	-56%	-53%	*-69%*	-70%
F.Yugoslavia	106	106	106	106	*106*	106	10%	10%	10%	10%	*10%*	10%
Total	15022	12649	12240	15022	*11626*	12000	-31%	-42%	-44%	-31%	*-46%*	-45%

Table 7.3: SO_2 emissions for the scenarios targeted at acidification and ground-level ozone

Country	SO_2 emissions (kilotons)						Change compared to 1990					
		AOT60	AOT40	Acidification	*minimum*	joint		AOT60	AOT40	Acidification	*maximum*	joint
	CRP*	D6	D7	D9	*D6, D7, D9*	D10	CRP*	D6	D7	D9	*D6, D7, D9*	D10
Albania	52	52	52	52	*52*	52	-28%	-28%	-28%	-28%	*-28%*	-28%
Austria	78	78	78	50	*50*	50	-16%	-16%	-16%	-46%	*-46%*	-46%
Belarus	399	399	399	139	*139*	141	-53%	-53%	-53%	-84%	*-84%*	-83%
Belgium	215	215	215	49	*49*	49	-32%	-32%	-32%	-85%	*-85%*	-85%
Bosnia-H	395	395	395	33	*33*	33	-18%	-18%	-18%	-93%	*-93%*	-93%
Bulgaria	1127	1127	1127	276	*276*	271	-39%	-39%	-39%	-85%	*-85%*	-85%
Croatia	117	117	117	18	*18*	18	-34%	-34%	-34%	-90%	*-90%*	-90%
Czech R.	632	632	632	97	*97*	97	-66%	-66%	-66%	-95%	*-95%*	-95%
Denmark	90	90	90	19	*19*	19	-53%	-53%	-53%	-90%	*-90%*	-90%
Estonia	175	175	175	175	*175*	175	-36%	-36%	-36%	-36%	*-36%*	-36%
Finland	116	116	116	116	*116*	116	-51%	-51%	-51%	-51%	*-51%*	-51%
France	737	737	737	221	*221*	221	-43%	-43%	-43%	-83%	*-83%*	-83%
Germany	740	740	740	336	*336*	337	-86%	-86%	-86%	-94%	*-94%*	-94%
Greece	570	570	570	570	*570*	570	12%	12%	12%	12%	*12%*	12%
Hungary	653	653	653	285	*285*	285	-28%	-28%	-28%	-69%	*-69%*	-69%
Ireland	155	155	155	31	*31*	31	-14%	-14%	-14%	-83%	*-83%*	-83%
Italy	1042	1042	1042	280	*280*	281	-39%	-39%	-39%	-84%	*-84%*	-83%
Latvia	105	105	105	105	*105*	105	-14%	-14%	-14%	-14%	*-14%*	-14%
Lithuania	107	107	107	40	*40*	41	-50%	-50%	-50%	-81%	*-81%*	-81%
Luxembourg	4	4	4	3	*3*	3	-71%	-71%	-71%	-79%	*-79%*	-79%
Netherlands	56	56	56	34	*34*	34	-72%	-72%	-72%	-83%	*-83%*	-83%
Norway	34	34	34	34	*34*	34	-37%	-37%	-37%	-37%	*-37%*	-37%
Poland	1397	1397	1397	421	*421*	421	-53%	-53%	-53%	-86%	*-86%*	-86%
Portugal	294	294	294	294	*294*	294	3%	3%	3%	3%	*3%*	3%
R. of Moldova	91	91	91	91	*91*	91	-54%	-54%	-54%	-54%	*-54%*	-54%
Romania	976	976	976	92	*92*	92	-27%	-27%	-27%	-93%	*-93%*	-93%
Russia	2635	2635	2635	2382	*2382*	2382	-48%	-48%	-48%	-53%	*-53%*	-53%
Slovakia	240	240	240	65	*65*	65	-56%	-56%	-56%	-88%	*-88%*	-88%
Slovenia	37	37	37	14	*14*	14	-81%	-81%	-81%	-93%	*-93%*	-93%
Spain	2119	2119	2119	201	*201*	201	-5%	-5%	-5%	-91%	*-91%*	-91%
Sweden	87	87	87	77	*77*	77	-24%	-24%	-24%	-33%	*-33%*	-33%
Switzerland	30	30	30	30	*30*	30	-33%	-33%	-33%	-33%	*-33%*	-33%
FYRMacedonia	81	81	81	81	*81*	81	-24%	-24%	-24%	-24%	*-24%*	-24%
Ukraine	1807	1807	1807	681	*681*	686	-51%	-51%	-51%	-82%	*-82%*	-81%
United Kingdom	980	980	980	173	*173*	173	-74%	-74%	-74%	-95%	*-95%*	-95%
F.Yugoslavia	459	459	459	45	*45*	45	-21%	-21%	-21%	-92%	*-92%*	-92%
Atlantic Ocean	385	385	385	385	*385*	385	-40%	-40%	-40%	-40%	*-40%*	-40%
Baltic Sea	43	43	43	43	*43*	43	-41%	-41%	-41%	-41%	*-41%*	-41%
North Sea	264	264	264	264	*264*	264	-40%	-40%	-40%	-40%	*-40%*	-40%
Total	19524	19524	19524	8302	*8302*	8307	-50%	-50%	-50%	-79%	*-79%*	-79%

Table 7.4: NH_3 emissions for the scenarios targeted at acidification and ground-level ozone

Country	NH_3 emissions (kilotons)						Change compared to 1990					
		AOT60	AOT40	Acidification	*minimum*	joint		AOT60	AOT40	Acidification	*maximum*	joint
	CRP*	D6	D7	D9	*D6, D7, D9*	D10	CRP*	D6	D7	D9	*D6, D7, D9*	D10
Albania	33	33	33	33	*33*	33	7%	7%	7%	7%	*7%*	7%
Austria	93	93	93	87	*87*	88	1%	1%	1%	-6%	*-6%*	-4%
Belarus	163	163	163	163	*163*	163	-26%	-26%	-26%	-26%	*-26%*	-26%
Belgium	96	96	96	70	*70*	70	12%	12%	12%	-18%	*-18%*	-18%
Bosnia-H	23	23	23	23	*23*	23	-25%	-25%	-25%	-25%	*-25%*	-25%
Bulgaria	126	126	126	126	*126*	126	-10%	-10%	-10%	-10%	*-10%*	-10%
Croatia	38	38	38	37	*37*	37	-6%	-6%	-6%	-8%	*-8%*	-8%
Czech R.	124	124	124	94	*94*	94	8%	8%	8%	-18%	*-18%*	-18%
Denmark	103	103	103	55	*55*	55	-18%	-18%	-18%	-56%	*-56%*	-56%
Estonia	29	29	29	29	*29*	29	0%	0%	0%	0%	*0%*	0%
Finland	23	23	23	23	*23*	23	-45%	-45%	-45%	-45%	*-45%*	-45%
France	668	668	668	439	*439*	441	-4%	-4%	-4%	-37%	*-37%*	-36%
Germany	539	539	539	299	*299*	299	-27%	-27%	-27%	-60%	*-60%*	-60%
Greece	76	76	76	76	*76*	76	-2%	-2%	-2%	-2%	*-2%*	-2%
Hungary	137	137	137	98	*98*	97	24%	24%	24%	-11%	*-11%*	-12%
Ireland	126	126	126	122	*122*	122	2%	2%	2%	-1%	*-1%*	-1%
Italy	386	386	386	380	*380*	380	1%	1%	1%	-1%	*-1%*	-1%
Latvia	29	29	29	29	*29*	29	-26%	-26%	-26%	-26%	*-26%*	-26%
Lithuania	81	81	81	81	*81*	81	2%	2%	2%	2%	*2%*	2%
Luxembourg	6	6	6	6	*6*	6	-12%	-12%	-12%	-12%	*-12%*	-12%
Netherlands	82	82	82	82	*82*	82	-64%	-64%	-64%	-64%	*-64%*	-64%
Norway	23	23	23	23	*23*	23	0%	0%	0%	0%	*0%*	0%
Poland	546	546	546	479	*479*	480	8%	8%	8%	-5%	*-5%*	-5%
Portugal	84	84	84	84	*84*	84	-8%	-8%	-8%	-8%	*-8%*	-8%
R. of Moldova	47	47	47	47	*47*	47	1%	1%	1%	1%	*1%*	1%
Romania	301	301	301	235	*235*	235	4%	4%	4%	-19%	*-19%*	-19%
Russia	894	894	894	894	*894*	894	-30%	-30%	-30%	-30%	*-30%*	-30%
Slovakia	53	53	53	53	*53*	53	-13%	-13%	-13%	-13%	*-13%*	-13%
Slovenia	20	20	20	20	*20*	20	-13%	-13%	-13%	-13%	*-13%*	-13%
Spain	345	345	345	345	*345*	345	-2%	-2%	-2%	-2%	*-2%*	-2%
Sweden	53	53	53	53	*53*	53	-14%	-14%	-14%	-14%	*-14%*	-14%
Switzerland	58	58	58	58	*58*	58	-6%	-6%	-6%	-6%	*-6%*	-6%
FYRMacedonia	15	15	15	15	*15*	15	-11%	-11%	-11%	-11%	*-11%*	-11%
Ukraine	649	649	649	649	*649*	649	-11%	-11%	-11%	-11%	*-11%*	-11%
United Kingdom	270	270	270	214	*214*	214	-17%	-17%	-17%	-34%	*-34%*	-34%
F.Yugoslavia	83	83	83	83	*83*	83	-8%	-8%	-8%	-8%	*-8%*	-8%
Total	6422	6422	6422	5604	*5604*	5607	-13%	-13%	-13%	-24%	*-24%*	-24%

Table 7.5: Emission control costs for SO_2 and NH_3 (in million ECU/year)

Country	Costs SO_2 CRP*	Additional costs on top of CRP* SO_2 AOT60 D6	AOT40 D7	Acidification D9	*maximum D6, D7, D9*	joint D10	Costs NH_3 CRP*	Additional costs on top of CRP* NH_3 AOT60 D6	AOT40 D7	Acidification D9	*maximum D6, D7, D9*	joint D10
Albania	1	0	0	0	*0*	0	1	0	0	0	*0*	0
Austria	214	0	0	42	*42*	42	4	0	0	17	*17*	15
Belarus	29	0	0	97	*97*	96	0	0	0	0	*0*	0
Belgium	240	0	0	315	*315*	315	22	0	0	327	*327*	321
Bosnia-H	3	0	0	99	*99*	99	0	0	0	0	*0*	0
Bulgaria	129	0	0	142	*142*	144	0	0	0	0	*0*	0
Croatia	47	0	0	50	*50*	50	0	0	0	0	*0*	0
Czech R.	244	0	0	213	*213*	213	1	0	0	95	*95*	92
Denmark	91	0	0	166	*166*	165	41	0	0	379	*379*	370
Estonia	0	0	0	0	*0*	0	0	0	0	0	*0*	0
Finland	202	0	0	0	*0*	0	34	0	0	0	*0*	0
France	1105	0	0	215	*215*	215	1	0	0	1279	*1279*	1250
Germany	2535	0	0	2113	*2113*	2086	0	0	0	1771	*1771*	1763
Greece	327	0	0	0	*0*	0	0	0	0	0	*0*	0
Hungary	153	0	0	147	*147*	147	0	0	0	264	*264*	271
Ireland	76	0	0	92	*92*	92	206	0	0	93	*93*	90
Italy	1582	0	0	284	*284*	283	0	0	0	1	*1*	1
Latvia	0	0	0	0	*0*	0	0	0	0	0	*0*	0
Lithuania	0	0	0	30	*30*	30	0	0	0	0	*0*	0
Luxembourg	10	0	0	4	*4*	4	12	0	0	0	*0*	0
Netherlands	199	0	0	82	*82*	82	763	0	0	0	*0*	0
Norway	49	0	0	0	*0*	0	0	0	0	0	*0*	0
Poland	892	0	0	451	*451*	451	0	0	0	182	*182*	177
Portugal	121	0	0	0	*0*	0	0	0	0	0	*0*	0
R. of Moldova	7	0	0	0	*0*	0	1	0	0	0	*0*	0
Romania	140	0	0	284	*284*	284	0	0	0	235	*235*	241
Russia	922	0	0	72	*72*	71	1	0	0	0	*0*	0
Slovakia	76	0	0	72	*72*	72	2	0	0	0	*0*	0
Slovenia	56	0	0	11	*11*	11	0	0	0	0	*0*	0
Spain	454	0	0	576	*576*	576	92	0	0	0	*0*	0
Sweden	227	0	0	17	*17*	16	16	0	0	0	*0*	0
Switzerland	74	0	0	0	*0*	0	5	0	0	0	*0*	0
FYRMacedonia	0	0	0	0	*0*	0	0	0	0	0	*0*	0
Ukraine	383	0	0	395	*395*	392	0	0	0	0	*0*	0
United Kingdom	843	0	0	1133	*1133*	1133	0	0	0	328	*328*	322
F.Yugoslavia	0	0	0	262	*262*	262	0	0	0	0	*0*	0
Atlantic Ocean	231	0	0	0	*0*	0						
Baltic Sea	26	0	0	0	*0*	0						
North Sea	159	0	0	0	*0*	0						
Total	11848	0	0	7364	*7364*	7331	1202	0	0	4971	*4971*	4913

Table 7.6: Emission control costs for NO_x and VOC and the sum for all pollutants (in million ECU/year)

Country	Costs NO_x and VOC CRP*	Additional costs on top of CRP* NO_x and VOC: AOT60 D6	AOT40 D7	Acidification D9	*Maximum*[(1)] *D6, D7, D9*	joint D10	Total costs CRP*	Additional costs on top of CRP* All pollutants: AOT60 D6	AOT40 D7	Acidification D9	*maximum D6, D7, D9*	joint D10
Albania	12	0	0	0	*1*	0	14	0	0	0	*1*	0
Austria	626	0	3	27	*27*	36	844	0	3	86	*86*	93
Belarus	1	7	33	1	*33*	15	30	7	33	98	*130*	111
Belgium	831	90	53	356	*448*	431	1094	90	53	998	*1090*	1067
Bosnia-H	0	0	0	0	*1*	0	3	0	0	99	*100*	99
Bulgaria	13	0	4	0	*4*	2	142	0	4	142	*146*	146
Croatia	5	0	0	0	*0*	0	52	0	0	50	*50*	50
Czech R.	377	11	29	196	*209*	210	623	11	29	504	*517*	515
Denmark	317	0	0	90	*90*	88	449	0	0	635	*635*	623
Estonia	1	0	0	0	*0*	0	1	0	0	0	*0*	0
Finland	449	0	7	0	*8*	3	685	0	7	0	*8*	3
France	4802	249	674	452	*1029*	1016	5908	249	674	1946	*2523*	2481
Germany	6306	489	334	1941	*2435*	2441	8841	489	334	5825	*6319*	6290
Greece	505	3	10	0	*10*	5	832	3	10	0	*10*	5
Hungary	326	6	0	41	*47*	42	479	6	0	452	*458*	460
Ireland	189	0	0	71	*72*	70	471	0	0	256	*257*	252
Italy	4624	39	683	0	*814*	500	6206	39	683	285	*1099*	784
Latvia	0	0	0	0	*0*	0	0	0	0	0	*0*	0
Lithuania	0	0	3	2	*3*	6	0	0	3	32	*33*	36
Luxembourg	51	0	0	7	*7*	7	72	0	0	11	*11*	11
Netherlands	1174	157	91	550	*706*	672	2137	157	91	632	*788*	754
Norway	422	0	0	0	*0*	0	471	0	0	0	*0*	0
Poland	928	32	26	368	*402*	402	1820	32	26	1001	*1035*	1030
Portugal	828	315	173	0	*315*	240	949	315	173	0	*315*	240
R. of Moldova	4	0	0	0	*0*	0	12	0	0	0	*0*	0
Romania	0	14	18	24	*34*	34	140	14	18	543	*553*	559
Russia	0	0	56	0	*58*	35	923	0	56	72	*130*	106
Slovakia	270	2	0	21	*23*	21	348	2	0	93	*95*	93
Slovenia	77	0	0	0	*0*	0	132	0	0	11	*11*	11
Spain	2992	186	113	76	*234*	253	3538	186	113	652	*810*	829
Sweden	886	0	0	47	*47*	48	1129	0	0	64	*64*	64
Switzerland	526	0	118	8	*117*	100	605	0	118	8	*117*	100
FYRMacedonia	0	0	0	0	*0*	0	0	0	0	0	*0*	0
Ukraine	761	19	107	0	*107*	26	1144	19	107	395	*502*	418
United Kingdom	4878	1500	182	1355	*2857*	2984	5721	1500	182	2816	*4318*	4439
F.Yugoslavia	0	41	0	3	*41*	3	0	41	0	265	*303*	265
Atlantic Ocean	0	0	0	0	*0*	0	231	0	0	0	*0*	0
Baltic Sea	0	0	0	0	*0*	0	26	0	0	0	*0*	0
North Sea	0	0	0	0	*0*	0	159	0	0	0	*0*	0
Total	33182	3160	2717	5636	*10177*	9690	46232	3160	2717	17971	*22512*	21934

Note 1): This column lists the costs for NO_x and VOC measures. Therefore this column is not always identical with the maximum costs for the individual scenarios, which relate, depending on the scenario, sometimes to NO_x or VOC measures only.

Table 7.7: Area of ecosystems with deposition above their critical loads for acidification (in 1000 hectares)

Country	1990	CRP*	(acid.) D9	(Ozone+acid) D10	MFR
Albania	0	0	0	0	0
Austria	2902	1452	496	504	263
Belarus	160	17	0	0	0
Belgium	475	292	15	15	5
Bosnia-H	132	131	0	0	0
Bulgaria	0	0	0	0	0
Croatia	487	451	0	0	0
Czech R.	2449	1605	115	115	68
Denmark	229	39	9	9	4
Estonia	292	108	10	10	0
Finland	5619	2175	791	786	176
France	3164	395	27	27	9
Germany	7344	3767	401	404	211
Greece	0	0	0	0	0
Hungary	1085	901	192	192	183
Ireland	249	196	92	92	76
Italy	1218	720	151	155	35
Latvia	40	0	0	0	0
Lithuania	11	0	0	0	0
Luxembourg	68	45	7	7	2
Netherlands	285	150	20	20	15
Norway	7811	4221	2021	2020	1337
Poland	4889	1050	54	54	39
Portugal	1	1	0	0	0
R. of Moldova	0	0	0	0	0
Romania	641	467	33	33	6
Russia	18234	9739	870	869	34
Slovakia	1537	732	15	15	10
Slovenia	454	138	12	13	3
Spain	81	64	0	0	0
Sweden	6136	1576	630	630	427
Switzerland	392	206	53	54	27
FYRMacedonia	0	0	0	0	0
Ukraine	955	209	25	24	5
United Kingdom	4001	1650	251	251	142
F.Yugoslavia	2	2	0	0	0
Total	71343	32499	6290	6299	3077

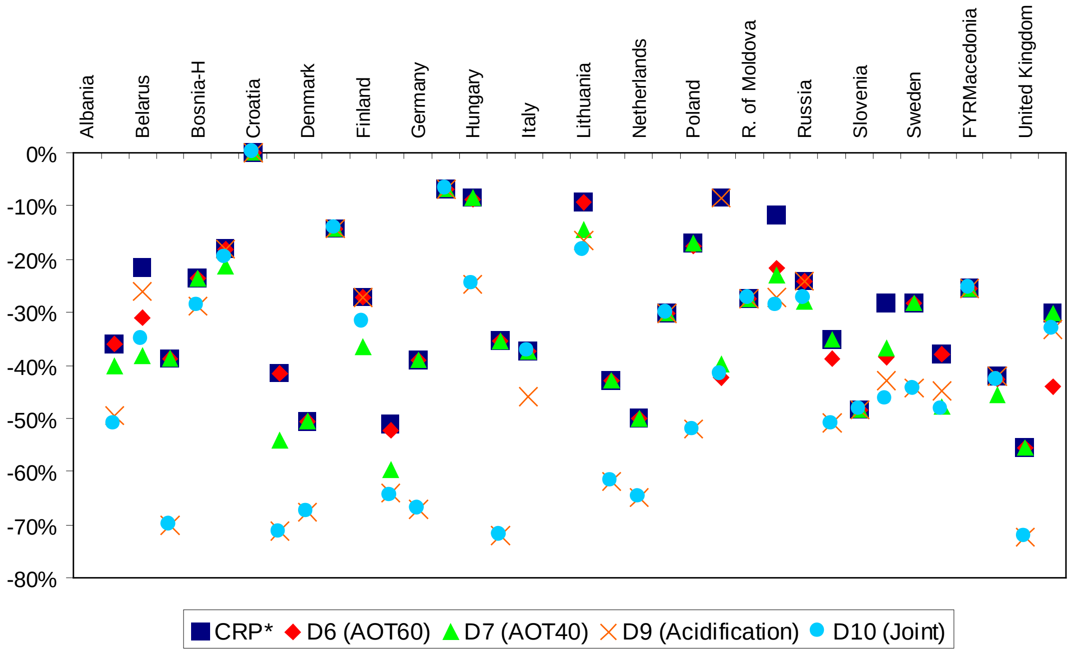

Figure 7.3: Change in NO_x emissions for the combined scenarios

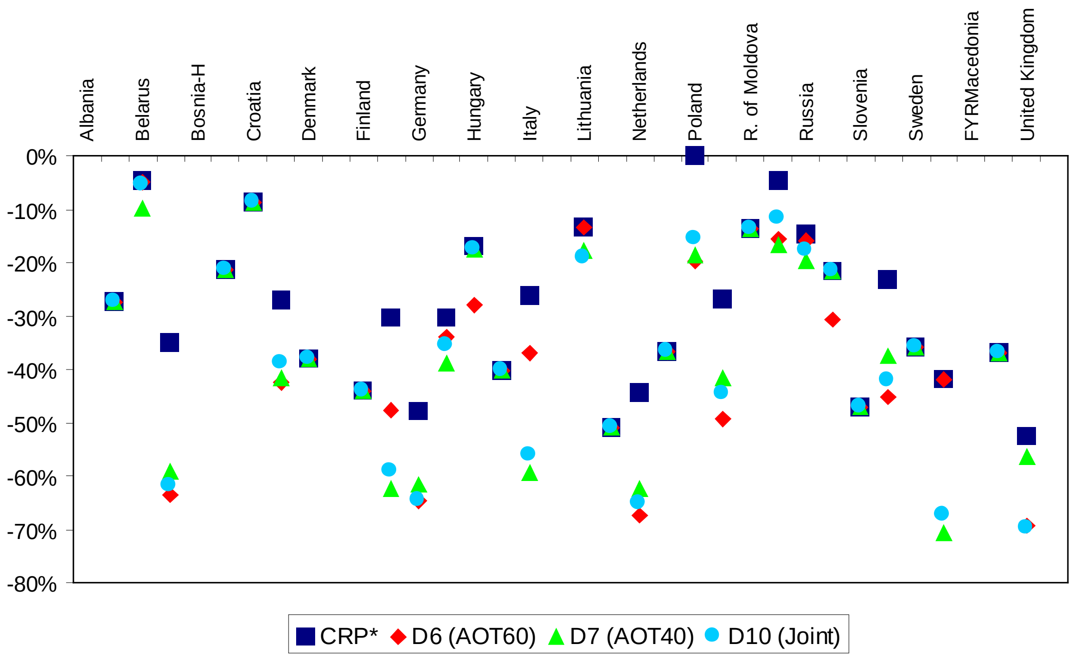

Figure 7.4: Change in VOC emissions for the combined scenarios

7.3 Comparison of the Exposure Indices

Table 7.8 to Table 7.10 compare the cumulative exposure indices for vegetation, human health and acid deposition. It is interesting that the optimization does not always yield the minimum cumulative exposure index for the target environmental problem. For instance, in the case of the cumulative population exposure index, the AOT40-optimization achieves (at somewhat lower costs) a lower cumulative exposure index for Europe as a whole than the AOT60-related optimization. The reason for this is that the optimization does not directly aim at the minimization of these exposure indices, but at the achievement of grid-specific gap closure targets in terms of AOT40 or AOT60. The observed differences are a strong indication that, i.a., the spatial aspect of the target selection plays an important role in the cost-effectiveness of scenarios. For instance, the wider scope of the ‘ten percent improvement over the CRP* gap closure’ target as used for the AOT40-optimization yields a higher overall protection for Europe than the ‘peak-shaving’ implied with the uniform minimum gap closure target of the illustrative AOT60 optimization. Further work will be necessary to explore this aspect in more detail and to maximize the possible benefits.

Figure 7.5 to Figure 7.7 display graphically the cost-effectiveness of the scenarios in relation to the different environmental problems. Although in these graphs the combined solutions always show higher total abatement costs than the optimizations focused on individual problems alone, they still provide a more cost-effective way of achieving the various targets simultaneously.

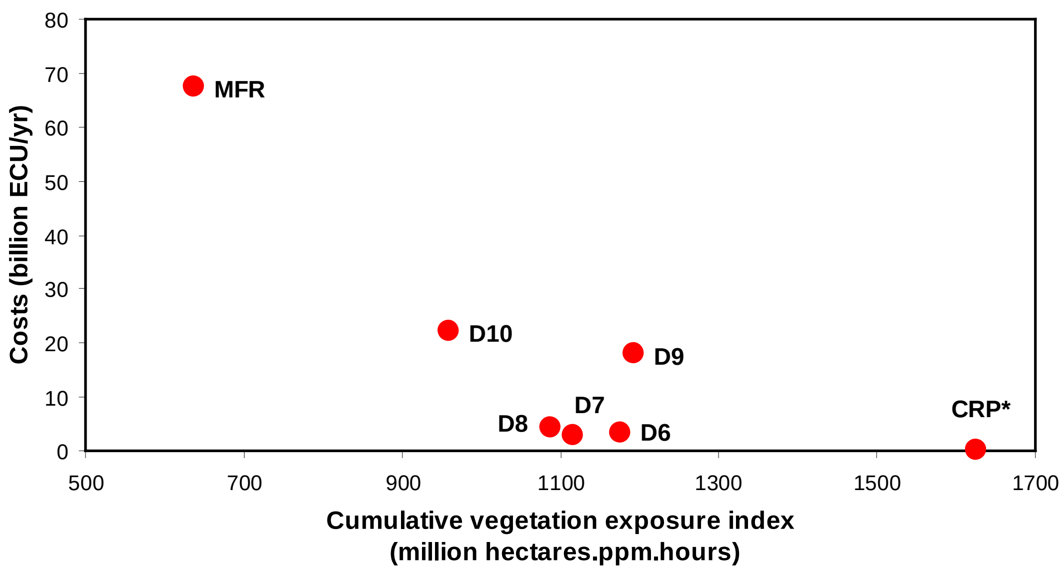

Figure 7.5: Cost-effectiveness of the scenarios for the AOT40 cumulative vegetation exposure index

Table 7.8: Comparison of the AOT40 cumulative vegetation exposure indices

Country	Cumulative vegetation exposure index (million hectares.ppm.hours)					
		(AOT60)	(AOT40)	(AOT40+ AOT60)	(acid.)	(Ozone +acid)
	CRP*	D6	D7	D8	D9	D10
Albania	7	5	5	5	5	5
Austria	36	28	26	26	25	21
Belarus	11	6	5	5	6	4
Belgium	16	12	12	11	15	12
Bosnia-H	21	16	15	15	15	13
Bulgaria	31	26	24	25	24	23
Croatia	28	23	22	22	22	20
Czech R.	43	30	29	28	28	22
Denmark	9	5	5	5	4	2
Estonia	0	0	0	0	0	0
Finland	0	0	0	0	0	0
France	315	211	191	185	220	167
Germany	174	116	114	108	124	90
Greece	21	16	15	15	16	15
Hungary	51	38	37	37	35	30
Ireland	1	0	0	0	1	0
Italy	136	121	105	105	124	102
Latvia	2	1	1	0	0	0
Lithuania	5	2	2	2	1	0
Luxembourg	2	1	1	1	1	1
Netherlands	9	6	6	6	9	7
Norway	0	0	0	0	0	0
Poland	123	76	75	72	64	49
Portugal	30	21	23	21	28	21
R. of Moldova	6	5	5	5	5	4
Romania	73	55	53	53	51	46
Russia	87	76	68	68	76	68
Slovakia	28	20	19	19	18	15
Slovenia	11	9	9	9	9	8
Spain	151	103	106	101	115	88
Sweden	6	2	2	2	1	1
Switzerland	11	9	7	7	9	6
FYRMacedonia	5	4	4	4	4	3
Ukraine	125	98	93	93	96	86
United Kingdom	23	13	16	12	23	13
F.Yugoslavia	29	23	22	22	21	19
Total	1626	1177	1117	1089	1195	961

Table 7.9: Comparison of the AOT60 cumulative population exposure indices

Country	Cumulative population exposure index (million person.ppm.hours)					
		(AOT60)	(AOT40)	(AOT40+ AOT60)	(acid.)	(Ozone +acid)
	CRP*	D6	D7	D8	D9	D10
Albania	1	1	0	0	1	0
Austria	8	4	4	4	4	3
Belarus	4	2	2	2	2	1
Belgium	44	23	23	21	33	21
Bosnia-H	2	1	1	1	1	1
Bulgaria	3	1	1	1	2	1
Croatia	5	3	2	2	3	2
Czech R.	19	10	9	9	8	6
Denmark	5	3	3	2	3	2
Estonia	0	0	0	0	0	0
Finland	0	0	0	0	0	0
France	156	68	59	53	82	49
Germany	226	122	115	105	136	90
Greece	3	3	2	2	4	3
Hungary	17	10	9	9	9	7
Ireland	2	1	1	1	1	0
Italy	86	65	40	41	72	42
Latvia	1	0	0	0	0	0
Lithuania	2	1	1	1	1	1
Luxembourg	2	1	1	1	1	1
Netherlands	48	26	26	23	40	25
Norway	1	0	0	0	0	0
Poland	58	31	30	28	28	20
Portugal	10	6	6	6	9	6
R. of Moldova	2	1	1	1	1	1
Romania	13	6	6	6	6	5
Russia	11	9	8	8	10	8
Slovakia	9	5	5	5	5	4
Slovenia	2	1	1	1	1	1
Spain	18	7	7	6	10	5
Sweden	2	1	1	1	1	1
Switzerland	6	3	2	2	3	1
FYRMacedonia	0	0	0	0	0	0
Ukraine	19	12	11	11	13	10
United Kingdom	99	48	60	45	82	41
F.Yugoslavia	5	2	3	2	3	2
Total	889	477	440	400	575	360

Table 7.10: Ecosystems with acid deposition above their critical loads for acidification (1000 hectares)

Country	CRP*	(AOT60) D6	(AOT40) D7	(AOT40+ AOT60) D8	(acid.) D9	(Ozone +acid) D10
Albania	0	0	0	0	0	0
Austria	1452	1257	1234	1237	496	504
Belarus	17	6	6	6	0	0
Belgium	292	72	72	72	15	15
Bosnia-H	131	131	131	131	0	0
Bulgaria	0	0	0	0	0	0
Croatia	451	0	0	0	0	0
Czech R.	1605	1445	1431	1433	115	115
Denmark	39	16	16	16	9	9
Estonia	108	17	13	17	10	10
Finland	2175	1458	1445	1448	791	786
France	395	163	162	162	27	27
Germany	3767	3338	3287	3297	401	404
Greece	0	0	0	0	0	0
Hungary	901	108	108	108	192	192
Ireland	196	239	238	238	92	92
Italy	720	1648	1522	1526	151	155
Latvia	0	0	0	0	0	0
Lithuania	0	0	0	0	0	0
Luxembourg	45	35	34	34	7	7
Netherlands	150	138	137	137	20	20
Norway	4221	2600	2590	2591	2021	2020
Poland	1050	2242	2216	2220	54	54
Portugal	1	1	1	1	0	0
R. of Moldova	0	0	0	0	0	0
Romania	467	180	180	180	33	33
Russia	9739	5815	5767	5768	870	869
Slovakia	732	681	678	679	15	15
Slovenia	138	106	105	105	12	13
Spain	64	63	63	63	0	0
Sweden	1576	1193	1190	1191	630	630
Switzerland	206	160	152	153	53	54
FYRMacedonia	0	0	0	0	0	0
Ukraine	209	118	116	116	25	24
United Kingdom	1650	1524	1515	1516	251	251
F.Yugoslavia	2	2	2	2	0	0
Total	32499	24756	24411	24447	6290	6299

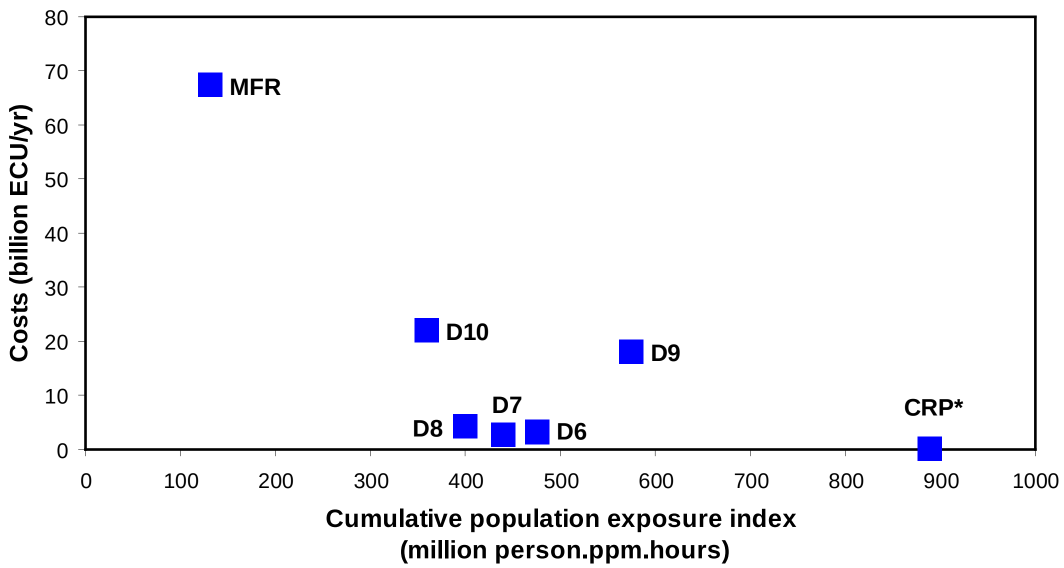

Figure 7.6: Cost-effectiveness of the scenarios for the AOT60 cumulative population exposure index

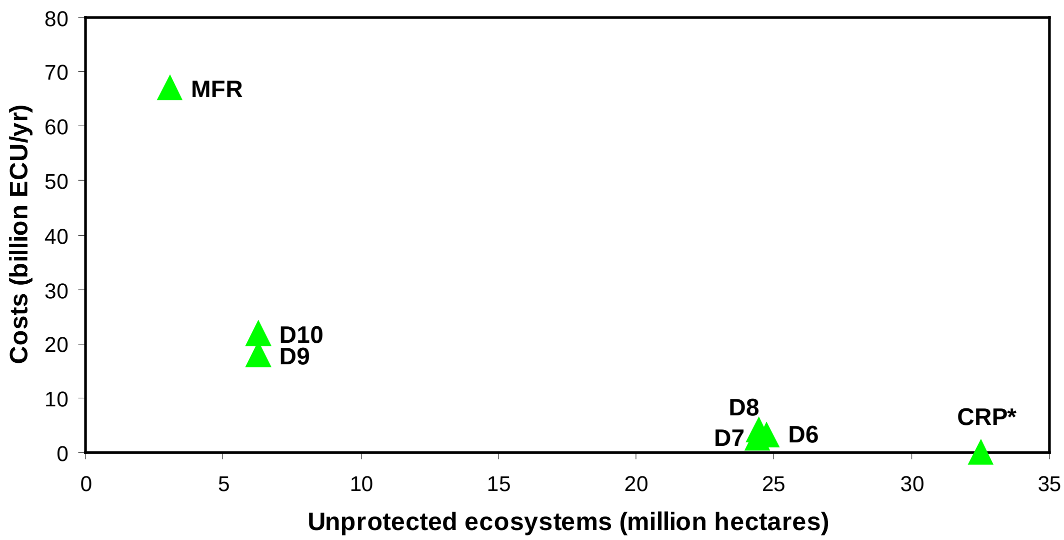

Figure 7.7: Cost-effectiveness of the scenarios for the protection of ecosystems against acidification

8 Summary of the Scenarios and Conclusions

8.1 Summary of the Scenarios

The scenarios presented in this report provide an assessment of the main features of ozone-related emission control strategies. Although there is ample space for further improvement of models and databases and a wide scope for robustness analysis, it is already possible to draw some initial conclusions from the work performed so far.

The currently available models support the theory that at the moment there are two different regimes of ozone formation in Europe. At sufficiently high ambient levels of NO_x, which occur at present in the north-western part of Europe, the ozone formation shows a clearly non-linear behavior. As a consequence, limited reductions of NO_x emissions in this area result in increased ozone concentrations. However, with more stringent NO_x control, the chemistry enters the 'linear' range , which prevails in most other parts of Europe, where additional NO_x reductions cause a decline in ozone levels.

Using the EMEP ozone model, the non-linear effect (increasing ozone) is predicted for some single grid cells as a result of the currently planned measures for NO_x emissions. On an aggregated (national) level, however, this effect is greatly diminished and almost all countries will show decreased average ozone levels after implementation of the present policies. Reducing NO_x emissions beyond the current plans will diminish ozone concentrations everywhere.

The analysis also demonstrates that the technically possible emission control measures (the maximum technically feasible emission reductions) will not be sufficient to achieve all the desired long-term environmental targets everywhere. Consequently, there is a need for the application of non-technical measures if these targets are to be met.

Given the fact that full achievement of the environmental long-term targets does not appear to be immediately feasible, the selection of appropriate interim targets is crucial for the design of acceptable emission control strategies. The target-setting process is a genuinely political task and requires judgments about political priorities. However, in order to produce illustrative scenario results from the available modelling framework, a number of alternative environmental targets have been selected to serve as examples for possible approaches.

For practical purposes, the AOT60 has been used as a health-related indicator of ozone exposure. There is a clear downward trend of the five-year mean AOT60 resulting from the current policy. A cumulative population exposure index (which combines the population densities with predicted ozone levels) is expected to decrease by 40% compared to 1990, and could be brought down further by implementing the maximum control (-90% compared to 1990).

The inter-annual meteorological variability of ozone formation is important. Analysis shows that on a grid level the AOT60 levels from a constant emission pattern may differ for different meteorological conditions by more than a factor of two. On average across Europe, the cumulative exposure index for the five years investigated shows a relative standard deviation of 36%.

It is essential to decide about the protection target, i.e., whether a certain protection level must be achieved even under the worst conditions, or whether a certain excess (or frequency of excess) is acceptable. If no violations at all are allowed, the analysis shows that a strategy based on this principle will be driven by a few extreme events at some single sites, which are not necessarily typical for the overall ozone situation. This implies that the optimized response measures will suit these extreme situations best, but they may turn out to be less efficient for reducing the large-scale excess exposure.

As an alternative, an approach was tested where (for each grid individually) the achievement of the environmental target for the year with the most unfavorable meteorological conditions out of the five available years was disregarded. Following this line of target setting, the gap between the long-term environmental target and the situation in 1990 (i.e., the excess exposure of the year 1990) could in theory be reduced by about 60%.

There are at least two ways of treating the different meteorological conditions in the optimization approach. As a simple approach, five individual optimizations could be carried out sequentially, each based on one set of meteorological conditions. The results obtained from these (five) runs could then be compared, and the most stringent emission reduction requirements be determined in order to satisfy the environmental constraints under the most unfavorable conditions. A more advanced method performs the optimization for all meteorological conditions simultaneously. The analysis shows that the costs of the resulting ‘composite’ solution are about 17% lower than those of the simple approach, where the most stringent emission reductions from five individual solutions are combined.

To explore a practical emission control strategy, a scenario has been calculated for a health-related gap closure of 50%. Owing to (a) the features of ozone chemistry responsible for peak concentrations and (b) the relative ratio of the marginal costs of the remaining measures for NO_x and VOC reductions after implementation of the current policies, the optimization gives, in most countries, priority to further VOC reductions.

A second scenario studies the basic features of optimal ozone control strategies targeted at the protection of vegetation, using the AOT40 indicator as a measure for the vegetation protection. The current legislation will reduce the cumulative vegetation exposure index by about 20% compared to 1990, and the maximum feasible emission reductions could bring it down by 70%. As for the health-related analysis, the selection of appropriate environmental interim targets is a key question for the development of acceptable emission control strategies. In order to achieve a wide geographical spread of the environmental improvement and of the measures required for this, an illustrative target of improving the ‘gap closure’ of the CRP* scenario by 10 percentage points has been established. As a result, optimized emission control measures include more NO_x control than for the health-related optimization.

For practical strategy development, the health- and vegetation-related targets should be combined to derive one single set of emission control measures. To shed light on this aspect, a joint optimization considering the AOT60- and AOT40-related targets simultaneously has been performed. The costs of emission reductions resulting from this optimization example are about 8% lower than the costs of the combined measures of the two individual strategies.

The NO_x-related measures proposed by ozone-targeted strategies should be carefully evaluated along with their impacts on acidification. The study presents a new concept for analyzing the interaction between ozone- and acidification-related strategies. In a way similar to the combined optimization performed for the AOT40- and AOT60-related strategy, a combined optimization approach was developed to consider targets on health- and vegetation-related ozone exposure simultaneously with acidification. In practice, this optimization looks for the least-cost combinations of SO_2, NO_x, NH_3 and VOC controls, satisfying regional constraints on acid deposition, AOT60 levels and AOT40 levels at the same time.

For the combination of these targets, the optimal set of emission reductions is only slightly rearranged compared to the set of the most stringent reductions of the individual problems. Further analysis is necessary to determine whether this is a general feature of combined ozone-acidification strategies, or whether this is a consequence of the particular environmental targets selected for this example run.

8.2 Caveats

It must be stressed that the assessment presented in this report is based on the currently available data sets and models. There are certainly some critical aspects, where further analysis could possibly modify some of the preliminary conclusions. Such central elements include the estimates of the maximum feasible emission reductions, the actual quantification of the non-linear effect of ozone formation and the influence of possible changes in the global background concentration of ozone in the free troposphere.

There are also a number of assumptions made for this particular report, which could possibly have direct impacts on some of the main results. One of the most important limitations of the work presented in this analysis is the exclusion of further emission controls in the transport sector. It is known from sensitivity analysis that the potential for additional emission reductions from mobile sources may significantly change the requirements for stationary sources.

8.3 Conclusions

Despite the preliminary character of some of the modelling tools and databases, some robust conclusions may be drawn from the analysis presented in this report:

- A tool has been developed and tested that can be used to support the development of cost-effective European emission control strategies targeted at ground-level ozone.

- The current information suggests that the non-linear characteristic of ozone formation leading to increased ozone levels with reduced NO_x emissions is limited to a certain region in the north-western part of Europe. Furthermore, NO_x control in addition to the currently planned measures will overcome this non-linear response and lead to effective ozone reductions.

- The presently adopted emission control policies are expected to reduce ozone levels in Europe. Given the energy scenario, the limitations of present emission control technologies and excluding the potential offered by non-technical measures, the full achievement of the long-term environmental targets does not appear to be feasible within the given time frame (2010). It will be necessary to establish interim targets.

- The selection of appropriate interim environmental targets has crucial impacts on the development of cost-effective emission control strategies. While the modelling exercise can offer a range of alternative targets to illustrate the implications of particular choices, the ultimate decision about the environmental objective requires value judgments about political priorities.
- Given the significant inter-annual variation in ozone formation due to meteorological conditions, it will be necessary to specify clearly the accepted extent of exceedances of the target levels. Preparing for the most unfavorable conditions might prove expensive and might not yield the optimal reduction for the average conditions.
- Considering health- and vegetation-related ozone strategies simultaneously offers a certain potential for cost savings.
- A number of assumptions made for this assessment require further analysis before robust quantitative conclusions are possible. The most important issues will be addressed in the near future.

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