THIRD INTERIM REPORT

Cost-effective Control of Acidification and Ground-Level Ozone

Third Interim Report to the
European Commission, DG-XI

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October 1997

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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. The cost-effectiveness of alternative strategies will be determined along the anticipated environmental improvement of the measures. While the earlier two Interim Reports to the European

Commission focused on acidification related strategies, this Third Interim Report puts its main emphasis on ground-level ozone.

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 discusses the main data used for the analysis. Section 4 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 5 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 6 addresses the improvement of a vegetation-related ozone criterion. The calculations use the 'AOT40', integrating the hourly day-light ozone in excess of a 40 ppb threshold over a three-months period. Section 7 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 8 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 9 summarizes the main points of the study, 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 for strategy development.

2.1 The General Approach for an Integrated Assessment

The Regional Air Pollution INformation and Simulation (RAINS)-model developed at the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria) provides a consistent framework for the analysis of emission reduction strategies, focusing on acidification, eutrophication and tropospheric ozone. RAINS comprises modules for emission generation (with databases on current and future economic activities, energy consumption levels, fuel characteristics, etc.), for emission control options and costs, for atmospheric dispersion of pollutants and for environmental sensitivities (i.e., databases on critical loads). In order to create a consistent and comprehensive picture of the options for simultaneously addressing the three environmental problems (acidification, eutrophication and tropospheric ozone), the model considers emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC). A detailed description of the RAINS model can be found in Alcamo *et al*., 1990. A schematic diagram of the RAINS model is displayed in Figure 2.1.

The European implementation of the RAINS model incorporates databases on energy consumption for 38 regions in Europe, distinguishing 22 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010 (Bertok *et al*., 1994). Emissions of SO_2, NO_x, NH_3 and VOC for 1990 are estimated based on information collected by the CORINAIR inventory of the European Environmental Agency (EEA, 1996) and on national information. Options and costs for controlling emissions of the various substances are represented in the model by considering the characteristic technical and economic features of the most important emission reduction options and technologies. Atmospheric dispersion processes over Europe for sulfur and nitrogen compounds are modeled based on results of the European EMEP model developed at the Norwegian Meteorological Institute (Barret and Sandnes, 1996). For tropospheric ozone, source-receptor relationships between the precursor emissions and the regional ozone concentrations are derived from the EMEP photo-oxidants model (Simpson, 1992, 1993). The RAINS model incorporates databases on critical loads and critical levels compiled at the Coordination Center for Effects (CCE) at the National Institute for Public Health and Environmental Protection (RIVM) in the Netherlands (Posch *et al*., 1997).

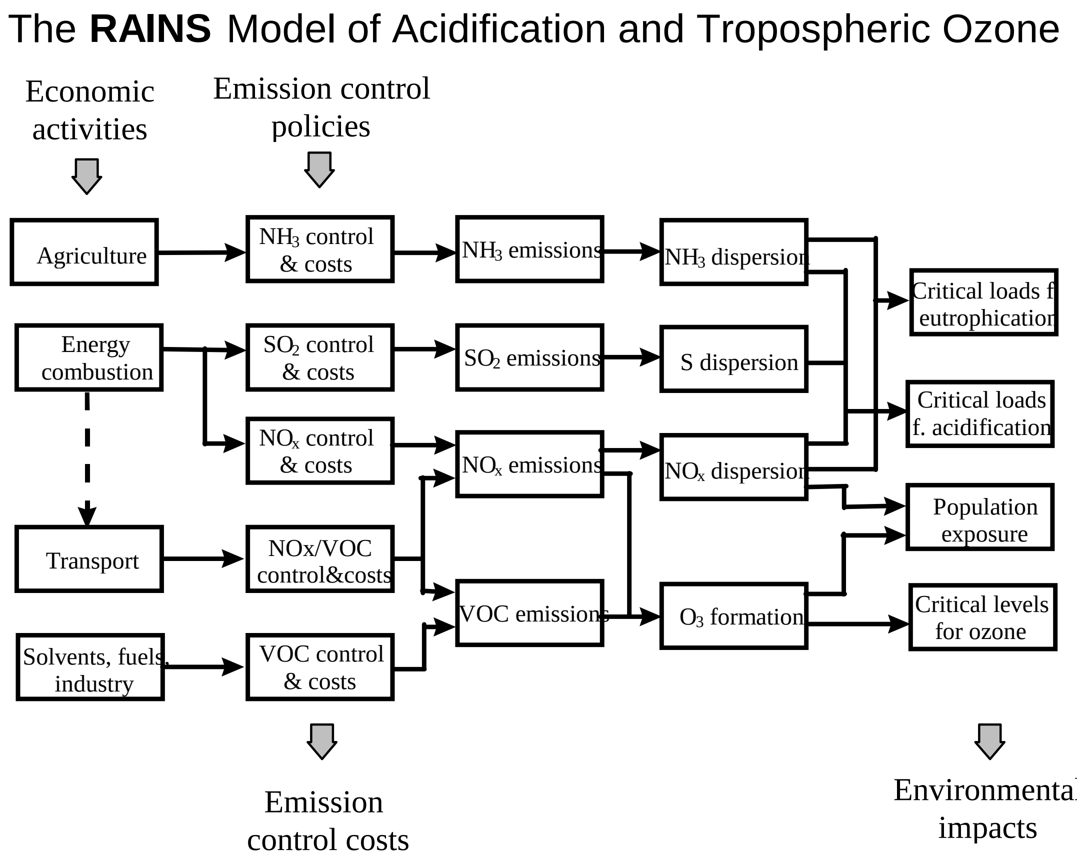

Figure 2.1: Schematic flowchart of the RAINS model framework

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

2.2 Scenarios of Emission Generating Anthropogenic Activities

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

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

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

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

2.3 Emission Estimates

The RAINS model estimates current and future levels of SO_2, NO_x, VOC and NH_3 emissions based on information provided by the energy- and economic scenario as exogenous input and on emission factors derived from the CORINAIR emission inventory (EEA, 1996), national reports as well as contacts with national experts. Emission estimates are performed on a disaggregated level, which is determined by the available details of the available energy and agricultural projection and the CORINAIR emission inventory. The relations between CORINAIR categories and the RAINS sectors are shown in Table 2.1 to Table 2.4. Due to the differences in the format of the energy and agricultural statistics and CORINAIR, a direct and full comparison of RAINS estimates with CORINAIR data is only possible at a more aggregated level.

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

1. Contribution to total emissions (compared to total European emissions and to emissions for a particular country). It was decided to aim for individual source categories in a share from 0.5 to 2 percent of total anthropogenic emissions;
2. Possibility to define uniform activity rates and emission factors;
3. Possibility to construct forecasts of future activity levels. Since the emphasis of the cost estimates is on future years, it is crucial that reasonable projections of the activity rates be constructed or derived;
4. Availability and applicability of ‘similar’ control technologies;
5. Availability of relevant data. Ultimately, the successful implementation of a VOC module will only be possible if the required data are available. As far as possible, emission related data should be compatible with the CORINAIR emission inventory.

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

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

Table 2.2: Main activity groups distinguished in the CORINAIR inventory and their relation to the sectors of the RAINS NH_3 model

CORINAIR'90 category	CORINAIR'90 SNAP code	RAINS sectors
Agriculture -animal breeding (excretions)	1005	Livestock
- Dairy cows	100501	- Dairy cows
- Other cattle	100502	- Other cattle
- Fattening pigs and sows	100503, 100504	- Pigs
- Laying hens	100507	- Laying hens
- Broilers and other poultry	100508, 100509	- Other poultry
- Sheep	100505	- Sheep
- Fur animals	100510	- Fur animals
- Horses	100506	- Horses
Agriculture - cultures with fertilizers (except animal manure)	1001-100106	Fertilizer use
Production processes - inorganic chem. Industry	040403-040408	Fertilizer production
Production processes - nitric acid	040402	Other
Waste treatment and disposal	0901-0904	Waste treatment and disposal

[1] Excluding processes with and without contact treated separately as process emissions.
[2] Including processes with and without contact treated separately as process emissions.
[3] Emissions are not directly attributed to fuel consumption. Production processes covered: oil refineries, coke, sinter, pig iron, non-ferrous metals (zinc, lead and copper), cement, lime, sulfuric acid, nitric acid, pulp mills. Other processes are covered in 'Industry-Other combustion'.

Table 2.3: Sectors in the RAINS VOC module for mobile sources

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

Table 2.4: Sectors in the RAINS VOC module for stationary sources

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

2.3.1 Comparison of RAINS Emission Estimates for 1990 with other Inventories

Table 2.5 compares the 1990 estimates for SO_2 and NO_x emissions incorporated into the RAINS model with the results from the CORINAIR 1990 inventory and with the EMEP database. As indicated above, RAINS generally uses information on emission factors provided by the CORINAIR'90 inventory. Consequently, SO_2 and NO_x emission levels calculated by RAINS are usually in good agreement with CORINAIR'90 with the largest differences below five percent. The only exception is Greece, where CORINAIR estimates for SO_2 and NO_x are more than 20 percent higher than RAINS. The reason is that the Greek submission to CORINAIR includes emissions from the total marine bunker fuel purchased in Greece, whereas the energy balances used in RAINS exclude marine bunkering from gross inland energy consumption. In reality, only a small portion of fuel purchased by sea vessels in Greece is used in the Greek coastal zone. EMEP estimates for the land-based sources in Greece (UN/ECE, 1995b) are much lower than CORINAIR results and are close to the RAINS estimates. Emission estimates for other economic sectors in Greece are in good agreement. Obviously, this issue requires further explanation with participation of national CORINAIR experts.

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

Table 2.6 compares the 1990 estimates for NH_3 and VOC emissions incorporated into the RAINS model with the results from the CORINAIR 1990 inventory and EMEP database. The agreement between RAINS and CORINAIR/EMEP emission estimates for the majority of countries lies within a range of ten percent (20 countries below five percent and nine countries between five and ten percent). For the EU countries, with the exception of Greece and the United Kingdom, RAINS and CORINAIR/EMEP estimates differ by not more than five percent. The Greek submission to CORINAIR contains an unreasonably high number of emissions from fertilizer use (about 100 times higher on a per-area basis than emissions in, e.g., Germany). Correcting this value to a reasonable range brings the total emissions down to 84 kilotons, which is close to the EMEP estimate.

Table 2.5: Comparison of RAINS 1990 emission estimates of SO_2 and NO_x and with results from the CORINAIR 1990 inventory and the EMEP database (in kilotons).

	SO_2 (kt)			NO_x (kt)		
	RAINS	EMEP	CORINAIR'90	RAINS	EMEP	CORINAIR'90
Albania	72	120	n.a.	24	30	n.a.
Austria	93	90	93	242	222	227
Belarus	845	710	n.a.	402	285	n.a.
Belgium	317	317	317	363	352	343
Bosnia-H	482	480	n.a.	80	54	n.a.
Bulgaria	1842	2020	2008	354	376	361
Croatia	178	180	n.a.	83	83	n.a.
Czech R.	1872	1876	1863	522	742	773
Denmark	190	180	198	271	269	273
Estonia	273	275	275	84	72	72
Finland	237	260	227	279	300	269
France	1300	1298	1298	1619	1585	1585
Germany	5271	5331	5257	2985	3071	2980
Greece	509	510	640	392	306	543
Hungary	913	1010	906	214	238	191
Ireland	180	178	178	107	115	116
Italy	1699	1678	1683	2009	2047	2041
Latvia	122	115	115	114	93	93
Lithuania	213	222	223	151	158	158
Luxembourg	14	14	14	21	23	23
Netherlands	197	205	200	539	575	537
Norway	54	54	54	231	230	232
Poland	3001	3210	3273	1209	1279	1445
Portugal	286	283	283	208	215	215
Moldova	197	91	n.a.	87	35	n.a.
Romania	1335	1311	1311	513	546	546
Russia	5046	4460	n.a.	3485	2675	n.a.
Slovakia	549	543	542	207	227	227
Slovenia	199	195	196	60	57	57
Spain	2234	2266	2206	1176	1178	1247
Sweden	115	136	105	345	411	345
Switzerland	45	43	44	161	165	159
Macedonia	106	10	n.a.	39	2	n.a.
Ukraine	3708	2782	n.a.	1888	1097	n.a.
United Kingdom	3754	3752	3787	2664	2702	2773
F.Yugoslavia	581	508	n.a.	211	66	n.a.
Atlantic Sea	641	641	n.a.	910	910	n.a.
Baltic Sea	73	73	n.a.	80	80	n.a.
North Sea	439	439	n.a.	638	638	n.a.
Total	39182	37866	n.a.	24967	23509	n.a.

Table 2.6: Comparison of RAINS 1990 emission estimates of NH_3 and VOC with results from the CORINAIR 1990 inventory and the EMEP database (in kilotons)

	NH_3 (kt)			VOC including all emissions from agriculture (kt)		
	RAINS	EMEP	CORINAIR'90	RAINS	EMEP	CORINAIR'90
Albania	31	30	n.a.	29	n.a.	n.a.
Austria	92	91	87	447	430	419
Belarus	219	257	n.a.	336	533	n.a.
Belgium	86	95	79	349	333	365
Bosnia-H	31	36	n.a.	45	n.a.	n.a.
Bulgaria	141	323	324	222	217	218
Croatia	40	37	n.a.	88	105	97
Czech R.	115	105	91	281	435	253
Denmark	126	140	126	188	186	169
Estonia	29	29	29	48	n.a.	50
Finland	42	41	41	193	209	165
France	692	700	700	2406	2404	2404
Germany	741	759	739	3106	3155	2937
Greece	78	78	471	308	n.a.	325
Hungary	110	176	62	172	205	148
Ireland	124	126	126	174	180	180
Italy	384	416	383	1865	2498	2396
Latvia	39	38	38	63	63	49
Lithuania	79	84	84	91	111	111
Luxembourg	7	7	7	19	19	19
Netherlands	229	236	196	506	444	457
Norway	37	39	38	266	299	270
Poland	505	508	539	721	831	1005
Portugal	91	93	93	201	206	206
R. of Moldova	47	50	n.a.	70	11	n.a.
Romania	290	300	300	628	616	619
Russia	1283	1191	n.a.	3335	3566	0
Slovakia	61	62	60	144	149	150
Slovenia	23	27	27	47	35	35
Spain	353	353	331	1111	1134	1119
Sweden	62	61	74	448	528	451
Switzerland	62	62	69	293	292	297
FYRMacedonia	17	18	n.a.	14	n.a.	n.a.
Ukraine	325	320	468	1065	1079	n.a.
United Kingdom	729	926	n.a.	2760	2703	2602
F.Yugoslavia	90	99	n.a	96	n.a.	n.a.
Total	**7410**	**7913**	**n.a.**	**22135**	**n.a.**	**n.a.**

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

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

It is believed that the forthcoming CORINAIR'94 emission inventory, which should be available by the end of this year, will provide up-to-date estimates and contribute to a better understanding of VOC emission sources. It is envisaged to further update the RAINS emission calculation using this new data.

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

2.4 Emission Control Options and Costs

Although there is a large variety of options to control emissions, an integrated assessment model focusing on the pan-European scale has to restrict itself to a manageable number of typical abatement options in order to estimate future emission control potentials and costs. Consequently, the RAINS model identifies for each of its application areas (i.e., emission source categories considered in the model) a limited list of characteristic emission control options 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 (1991b).

The databases on emission control costs have been constructed based on the actual operating experience of various emission control options documented in a number of national studies (e.g., Schärer, 1993) as well as in reports of international organizations (e.g., OECD, 1993; Takeshita, 1995; Rentz *et al.*, 1987). Country-specific information has been extracted from relevant national and international statistics (UN/ECE, 1996). In Fall 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.

2.4.1 Control Options for Reducing SO_2 Emissions and their Costs

The national potentials and costs of emission reductions are estimated based on a detailed data base of the most common emission control techniques. For a given energy scenario, reduction options for SO_2 emissions considered in RAINS are the use of low sulfur fuel, fuel desulfurization, combustion modification (e.g., lime stone injection processes and fluidized bed combustion) and flue gas desulfurization (e.g., wet limestone scrubbing processes). Structural changes, such as fuel substitution and energy conservation can also be evaluated, although only in interaction with an appropriate energy model.

Table 2.7 to Table 2.9 presents, for the major source categories, the available control options and the data used for the analysis. The basic input data for the SO_2 control technologies used in RAINS have been reviewed in the process of the negotiations for the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution and have recently been updated to take latest operating experience into account.

Table 2.7: Emission control options in the power plant and industrial sector for SO_2 considered in RAINS

Sector/control option	Removal efficiency [%]	Costs[4] Investment [1000 ECU/MW_{th}]	Operating and maintenance [%/year][5]
Power plants - retrofits			
Limestone injection	50	30	4
Wet flue gas desulfurization (FGD)	95	69	4
Regenerative FGD	98	165	4
Power plants - new			
Limestone injection	50	22	4
Wet flue gas desulfurization (FGD)	95	49	4
Regenerative FGD	98	119	4
Industrial boilers and furnaces			
Limestone injection	50	35	4
Wet flue gas desulfurization (FGD)	85	72	4

Table 2.8: Options for low sulfur fuels considered in RAINS

Fuel type	Price difference [ECU / GJ / %S][6]	Costs [ECU / t SO_2][7]
Hard coal and coke, 0.6 % S	0.28	397
Heavy fuel oil, 0.6 %S	0.44	905
Gas oil, 0.2% S	0.68	1444
Gas oil, 0.05 % S	2.04	4333

Table 2.9: Emission control options for industrial process emissions of SO_2 considered in RAINS

Control option	Removal efficiency [%]	Costs [ECU / t SO_2]
Stage 1	50	350
Stage 2	70	407
Stage 3	80	513

[4] Values are for typical hard coal fired boilers for each source category.
[5] Percent of investment cost per year
[6] percent S reduced compared to original fuel.
[7] Per ton of SO_2 removed; Calculated for a typical heating value of each fuel.

2.4.2 Control Options for Reducing NO_x Emissions and their Costs

Table 2.10 to Table 2.14 present the options for controlling NO_x emissions as contained in the RAINS database. For stationary sources, data are based on the same literature listed above for SO_2. Data for mobile sources have been derived from various reports developed within the Auto/Oil program (European Commission, 1996, Touche-Ross & Co., 1995) and from other national and international sources (i.a., Gorißen, 1992, HSMO, 1994, McArragher *et al*., 1994, Rodt *et al*., 1995, UN/ECE, 1994a, UN/ECE 1994b). The assistance of consultants participating in the Auto/Oil study helped to incorporate also the suggested measures on fuel quality improvement and inspection and maintenance schemes into the RAINS model in a fully consistent way (Barrett, 1996).

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

Table 2.10: Control options for NO_x emissions from the power plant sector considered in RAINS

Sector/control option	Removal efficiency [%]	Costs[8]	
		Investment [ECU/MW_{th}]	Operating and maintenance [%/year][9]
Retrofits of existing boilers:			
<u>Combustion modification and primary measures (CM)</u>[10]			
Brown coal and lignite	65	6.8	-
Hard coal	50	3.9	-
Heavy fuel oil	65	4.7	-
Gas	65	5	-
<u>CM + selective cat. reduction (SCR)</u>			
Brown coal and lignite	93	24.8	6
Hard coal	90	19.6	6
Heavy fuel oil	90	21.8	6
Gas	93	23.6	6
New boilers *(low-NO_x burners are assumed by default)**:***			
<u>SCR</u>			
Brown coal and lignite	80	10.0	6
Hard coal	80	8.8	6
Heavy fuel oil	80	8.7	6
Gas	80	11.8	6

[8] Values are for typical boilers for each source category.
[9] Percent of investment cost per year
[10] Combination of various measures (e.g., low NO_x burners, overfire air, etc.)

Table 2.11: Control options for NO_x emissions from industrial boilers considered in RAINS

Sector/control option	Removal efficiency [%]	Costs[11] Investment [ECU/MW_{th}]	Operating and maintenance [%/year][12]
Combustion modification and primary measures (CM)			
Brown coal and lignite	50	5.6	-
Hard coal	50	5.6	-
Heavy fuel oil	50	5.0	-
Medium distillates and gas	50	5.7	-
CM + Selective Non-catalytic Reduction (SNCR)			
Brown coal and lignite	70	11.0	6
Hard coal	70	11.0	6
Heavy fuel oil	70	9.1	6
Gas	70	10.6	6
CM + Selective Catalytic Reduction (SCR)			
Brown coal and lignite	80	21.9	6
Hard coal	80	21.9	6
Heavy fuel oil	80	17.4	6
Gas	80	20.3	6

Table 2.12: Control options for NO_x emissions from the residential and commercial sector and from ships

Sector/control option	Removal efficiency [%]	Costs[13] Investment [ECU/MW_{th}]	Operating and maintenance [%/year][14]
Residential and commercial sector[15]			
Combustion modification, low-NO_x burners (CM)			
Heavy fuel oil	50	5.6	-
Medium distillates	30	12	-
Natural gas	50	16.3	-
Ships			
SCR	80	25	6

[11] Values are for typical boilers for each source category.
[12] Percent of investment cost per year
[13] Values are for typical boilers for each source category.
[14] Percent of investment cost per year.
[15] Weighted average for residential and commercial sector. Unit control costs for gas and gas oil fired boilers in commercial sector are 40 - 50 % lower.

Table 2.13: Control options for NO_x emissions from industrial processes

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

Table 2.14: Control options for NO_x emissions from mobile sources considered in RAINS

Fuel/vehicle type/control technology	**Removal efficiency [%]**	**Costs**	
		Investments [ECU/vehicle]	**Operating and maintenance [%/year]**[16]
Gasoline passenger cars and LDV[17]			
3-way catalytic converter - 1992 standards	77	250	24
3-way catalytic converter - 1996 standards	88	300	20
Advanced converter with maintenance schemes - EU 2000 standard	94	715	8.4
Advanced converter with maintenance schemes - EU 2005 standard (**)	97	*	*
Diesel passenger cars and LDV			
Combustion modification - 1992 standards	30	150	36.0
Combustion modification - 1996 standards	49	275	19.5
Advanced combustion modification with maintenance schemes - EU 2000 standards	59	780	6.9
NO_x converter(**)	80	*	*
Heavy duty vehicles			
Euro I - 1993 standards	32	600	46
Euro II - 1996 standards	42	1800	15
Euro III - EU 2000 standards with maintenance schemes	59	4047	6.8
Euro IV (NO_x converter) (**)	85	*	*

(**) - Not yet commercially available, without cost estimates.

[16] Percent of investment cost per year.
[17] LDV - light duty vehicles.

2.4.3 Options for Reducing Ammonia Emissions and their Costs

For each of the major sources of ammonia emissions (livestock farming, fertilizer use, and chemical industry), RAINS considers a number of emission control options (Klaassen, 1991b; UN/ECE, 1996; EEA,1996; Menzi *et al*., 1996).

Ammonia emissions from livestock occur at four stages, i.e., in the stable, during storage of manure, its application and during the grazing period. At every stage emissions can be controlled by applying various techniques. Obviously RAINS cannot distinguish all of the several hundred available control options, but considers groups of techniques with similar technical and economic characteristics. The major categories considered in RAINS are

- low nitrogen feed (dietary changes), e.g., multi-phase feeding for pigs and poultry, use of synthetic amino acids (pigs and poultry), and the replacement of grass and grass silage by maize for dairy cattle;
- biofiltration (air purification), i.e., by treatment of ventilated air, applicable mostly for pigs and poultry, using biological scrubbers to convert the ammonia into nitrate or biological beds where ammonia is absorbed by organic matter;
- stable adaptation by improved design and construction of the floor (applicable for cattle, pigs and poultry), flushing the floor, climate control (for pigs and poultry), or wet and dry manure systems for poultry;
- covered outdoor storage of manure (low efficiency options with floating foils or polystyrene, and high efficiency options using tension caps, concrete, corrugated iron or polyester);
- low ammonia application techniques, distinguishing high efficiency (immediate incorporation, deep and shallow injection of manure) and medium to low efficiency techniques, including slit injection, trailing shoe, slurry dilution, band spreading, sprinkling (spray boom system).

Ammonia emissions from the chemical industry can be reduced by introducing stripping and absorption techniques (Tangena, 1985; Technica, 1984).

The main technical and economic characteristics of the control options are presented in Table 2.15 and Table 2.16. It should be mentioned that, compared to the control options for SO_2 and NO_x, the cost estimates for ammonia abatement techniques are more uncertain, mainly due to the lack of practical operating experience with many of the techniques in most European countries.

Table 2.15: Emission control options for NH_3 considered in the RAINS model and their removal efficiencies

Abatement option	Application areas	Removal efficiency [%]			
		Stables	Storage	Application	Meadow
Low nitrogen feed (LNF)	Dairy cows	15	15	15	20
	Pigs	20	20	20	n.a.
	Laying hens	20	20	20	n.a.
	Other poultry	10	10	10	n.a.
Biofiltration (BF)	Pigs, poultry	80		n.a,	n.a.
Stable adaptation (SA)	Dairy cows, Other cattle	50	80	n.a.	n.a.
	Pigs	50	80	n.a.	n.a.
	Laying hens	70	80	n.a.	n.a.
	Other poultry	80	80	n.a.	n.a.
Covered storage (CS - low/high)	Dairy cows, other cattle, pigs, poultry	n.a.	60/80	n.a.	n.a.
Low NH_3 application (LNA- low/high)	Dairy cows, other cattle, pigs, poultry, sheep	n.a.	n.a.	40/80	n.a.
Stripping/adsorption	Industry	50			

n.a.: not applicable

Table 2.16: Costs of emission control options for NH_3 considered in the RAINS model

Abatement option	Application area	Investments [ECU/animal-place] Stable size ** small	typical	Total costs* [ECU/animal/year] small	typical
Low nitrogen feed	Dairy cows	n.a.		45	
	Pigs	2.7		8	
	Laying hens	n.a.		0.1	
	Other poultry	n.a.		0.12	
Bio-filtration and bio-scrubbers	Pigs	200-300	170	50-70	38-40
	Laying hens	4.7		1.5-2.0	
	Other poultry	4.7		2.0-2.5	
Stable adaptation	Dairy cows, Other cattle	450-550	400	90-110	75-90
	Pigs	90-94	89	21	19
	Laying hens	0.8		0.2-0.25	
	Other poultry	1.8		0.28	
Covered storage - high efficiency	Dairy cows	200-400	160	40-60	18-40
	Other cattle	100-150	70	15-25	7-12
	Pigs	2-5	1	0.4-1	0.3
	Laying hens	0.4		0.06	
Covered storage - low efficiency	Dairy cows	100-200	80	20-30	9-20
	Other cattle	50-75	35	7-13	3-6
	Pigs	1-3	0.5	0.2-0.5	0.15
	Laying hens	0.2		0.03	
Low NH_3 application	Dairy cows	n.a.		50-70	
	Other cattle	n.a.		18-40	
	Pigs	n.a.		5-8	
	Laying hens	n.a.		0.15-0.3	
	Other poultry	n.a.		0.04-0.06	
	Sheep	n.a.		3-4	
Stripping/adsorption	Industry	625 ECU/t NH_3 removed			

n.a.: not applicable
* - Taking into account fixed and variable operating costs
** - The following stable sizes are assumed:
Pigs - small (<50 animals/stable), typical (~170)
Dairy cows - small (<20 animals/stable), typical (~35)
Other cattle - small (<30 animals/stable), typical (~40)

2.4.4 Options for Reducing VOC Emissions and their Costs

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

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

Commonly employed methods for reducing VOC emissions from stationary sources include modification of the production process or storage tanks, improvement of the management practices (e.g., good housekeeping, leak monitoring and repair programs), solvent substitution, and finally add-on technologies, such as thermal or catalytic incineration, adsorption, absorption, condensation/ refrigeration, and biooxidation. Major reduction measures and RAINS-VOC sectors to which they apply are listed in Table 2.17. Note that the listed efficiencies refer to the assumed technical efficiency of the option. In reality, the most efficient options in a sector often have only limited applicability.

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

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

Table 2.17: Major categories of abatement measures for stationary sources distinguished in the current RAINS-VOC model

Sector	*Technology*	*Efficiency [%]*	*Cost range [ECU/t VOC]*
Solvent use			
Dry Cleaning	Good housekeeping and adsorption	60	700
	Closed circuit conventional or new machines	75-95	150-1800
Metal degreasing	Basic emission management techniques	25	400
	Carbon adsorption	80	1600-2500
	Low temperature plasma process	98	1900-2400
	Conveyored degreaser with integrated adsorption	95	2000-2800
	Water based systems	95	3000-4000
Domestic solvent	Substitution, Propelant insert	5-30	3500-4500
Non-industrial paint use	Water based paints	80	500-800
	High solids	40-60	1800-2300
	Powder paints	100	1300-1500
Industrial paint use	Application technique modification	20-45	<2000
	Process modification and substitution	70	1500-2500
	Adsorption, Incineration	95	2500-8000
Products incorporating solvents	Substitution	50	<100
	Basic emission management and end-of-pipe	70-95	1000-1500
Products not incorporating solvents	Solvent management plan and substitution	40	<500
	Basic emission management and end-of-pipe	70-90	1500-2300
Printing	Good housekeeping	<10	<50
	Water based inks	90	<100
	Adsorption, Incineration	80-90	300-1700
Glues and adhesives in industry	Good housekeeping	15	<50
	Substitution	85	500
	Incineration	80	800-1000
Preservation of wood	Double vacuum impregnation & dryer enclosure	40	2500-3000
	Adsorption, Incineration	60	4000-14000
Other industrial use of solvents	Process modification and biofiltration	70-75	500-600
Chemical industry	Quarterly inspection and maintenance programs	60	500-1600
	Monthly inspection and maintenance programs	70	4000-6000
	Flaring	85	300-400
	Incineration	95	700-800
	Internal floating covers and secondary seals	90	2500-3000
	Vapor recovery units	95-99	5000-7000
Refineries	Quarterly inspection and maintenance programs	60	0-100
	Monthly inspection and maintenance programs	70	800-2000
	Internal floating covers and secondary seals	85	10-400
	Vapor recovery units	95-99	500-2000
Fuel distribution & gasoline evaporation	Internal floating covers and secondary seals	85	10-400
	Vapor recovery units	95-99	500-2000
	Small carbon canister	85	100-400
	Stage II	80	1500-3500
	Stage IB	95	5-250
	Vapor balancing on tankers and loading facilities	70	500-2500
Miscellaneous			
Food and drink industry	End-of-pipe	90	14000
Agriculture	Ban on burning waste	100	60
Other industrial	Good housekeeping	20	<100
	End-of-pipe	95	10000
Waste disposal	Improved landfills	20	400

2.5 Atmospheric Transport

2.5.1 Modelling 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. The time scale of ozone production is such that ozone concentrations build up in polluted air over several days under suitable weather conditions, and this pollutant and its precursors can be transported over considerable distances and across national boundaries. An integrated assessment model for ozone needs to be able to relate ozone exposure to changes in the emissions of ozone precursors.

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

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

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

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

Ozone Isopleth Diagrams

Before starting the development of the simplified model, the EMEP ozone model was used to investigate the relationships in different areas of Europe between mean boundary layer ozone concentrations and changes in the emissions of NO_x and VOCs. A convenient way to illustrate the results of these investigations is by means of ozone isopleth diagrams (Figure 2.2). Such diagrams have been most commonly used, particularly in North America, to show how maximum ozone concentrations depend on the initial concentrations of NO_x and VOCs on a particular day at a specific location. Lines of constant value, or isopleths, of the maximum ozone concentrations are constructed by connecting points having the same ozone concentration but corresponding to various initial conditions. Ozone isopleth diagrams in this form provide a concise representation of the effect of reducing initial NO_x and VOC concentrations on peak ozone concentrations and, in the past, they have been used quantitatively to develop ozone control strategies as part of the U.S. EPA's empirical kinetic modeling approach (EKMA) (Gipson et al., 1981).

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

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

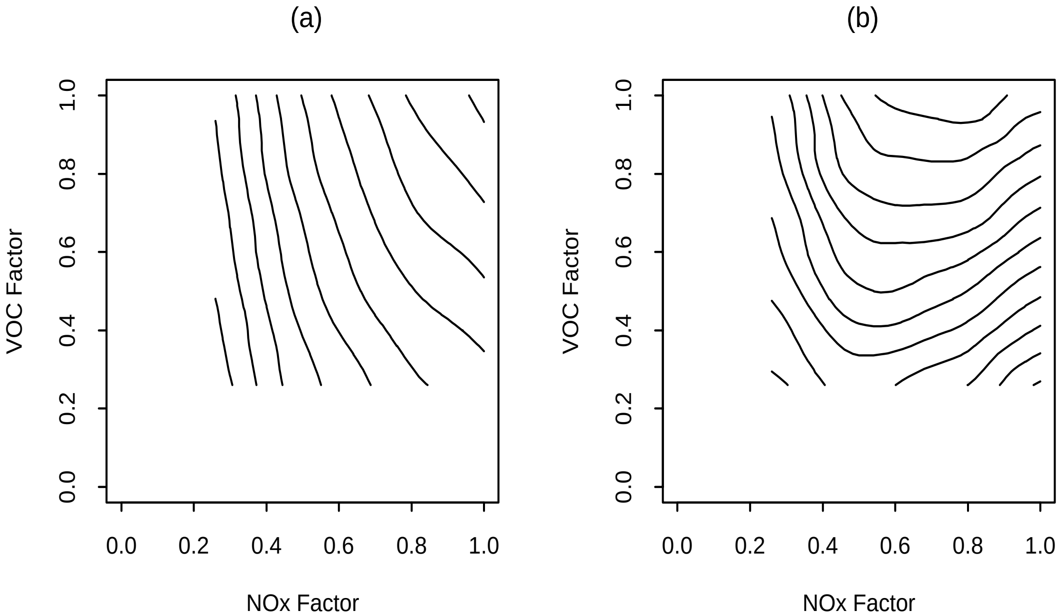

Figure 2.2: Typical patterns of ozone behaviour in Europe

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

A 'Reduced Form' Model of Ozone Formation

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

v_i	-	annual national emissions of non-methane VOCs from emitter country i
n_i	-	annual national emissions of NO_x from emitter country i
ev_j	-	"effective" emissions of VOCs, including natural sources, at receptor j
en_j	-	"effective" emissions of NO_x, including natural sources, at receptor j
evn_j	-	"effective" natural emissions of VOCs at receptor j
enn_j	-	"effective" natural emissions of NO_x at receptor j

The long-term ozone 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 and VOCs), en_j and ev_j, experienced at the receptor over the period in question. The general model formulation adopted is:

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

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

$$V = \{v1, v2, ..., vM\}, \qquad (2)$$

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

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

or by:

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

The mean "effective" emissions are given by:

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

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

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

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

$$\overline{[O_3]}_j = k_j + \sum_{i=1}^{M}(a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^2) + \alpha_j \overline{en}_j^2 + \overline{en}_j \sum_{i=1}^{M} d_{ij}v_i \qquad (7)$$

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

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

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

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

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

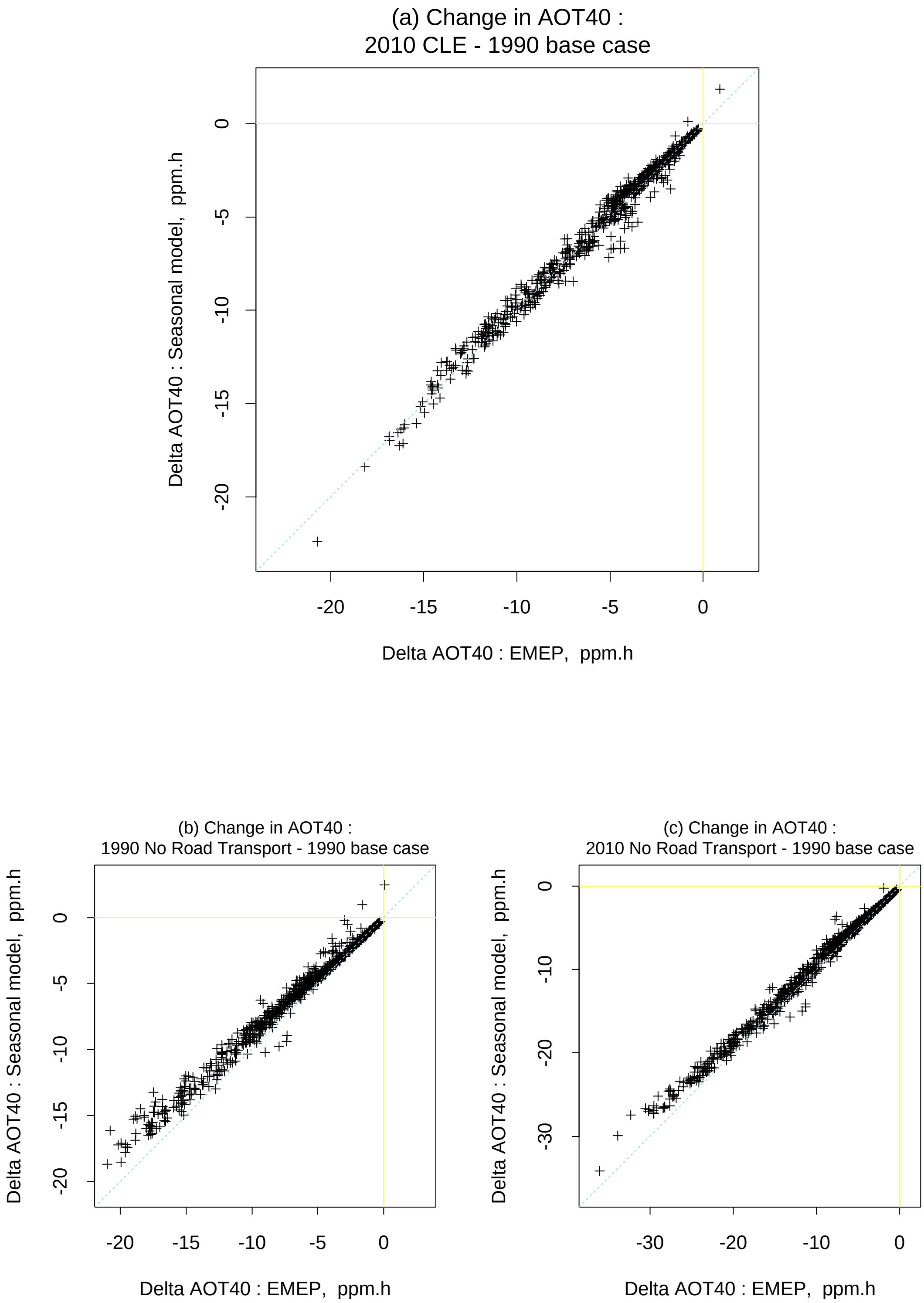

Figure 2.3: Comparison of the results from the reduced-form model for three scenarios with the corresponding EMEP model calculations

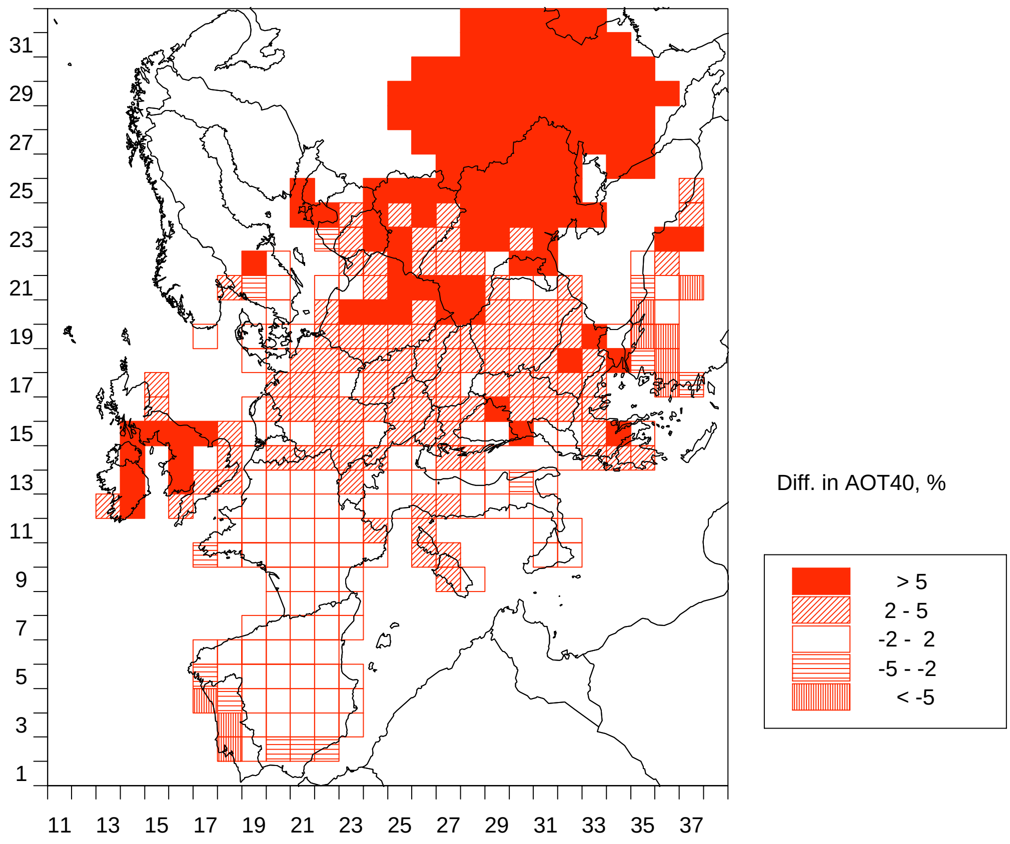

Figure 2.4: Spatial distribution of differences between a reduced-form and the full EMEP models for those receptor grids at which the 1990 base case AOT40 value for forests - as calculated using the 1995 version of the EMEP model - exceeds the critical level of 10 ppm.hours.

2.6 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.

Critical loads of sulfur have been used in the negotiations of the 1994 Second Sulfur Protocol, the first international agreement on emission reductions taking explicitly into account environmental vulnerability, in addition to technological and economic considerations (UN/ECE 1994). However, acidification is caused by the deposition of both sulfur and nitrogen, and both compounds "compete" for the counteracting (neutralizing) base cations, which are mostly provided by deposition and weathering. And, in contrast to sulfur, for nitrogen there are additional natural (sources and) sinks such as uptake by vegetation, immobilization and denitrification. Consequently, it is not possible to define a single critical load for acidity, as was the case when looking at sulfur alone, but a (simple) function, called critical load function. This function defines pairs of sulfur and nitrogen deposition for which there is no risk of damage to the ecosystem under consideration, thus replacing the single critical load value used earlier. The critical load function for each ecosystem has a trapezoidal shape and is defined by three quantities: $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$: $CL_{max}(S)$ is essentially the critical load of acidity (as defined earlier), $CL_{min}(N)$ summarizes the net nitrogen sinks, and $CL_{max}(N)$ is the maximum deposition of nitrogen (in case of zero sulfur deposition) taking into account CLmax(S) and deposition-dependent nitrogen processes ($CL_{max}(N) >= CL_{min}(N) + CL_{max}(S)$).

In addition to acidification, nitrogen deposition also acts as a nutrient for ecosystems. Consequently, in order to avoid eutrophication, critical loads for nutrient nitrogen, $CL_{nut}(N)$, have been defined and calculated for various ecosystems. If one wants to consider the multi-effect aspect of nitrogen deposition, the critical loads of nutrient nitrogen have to be introduced as additional aspects (and eventually as constraints) in the integrated assessment of reductions of NO_x and NH_3 emissions.

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. As an example, Figure 2.5 shows the fifth percentile of $CL_{max}(S)$ for the EMEP modeling domain.

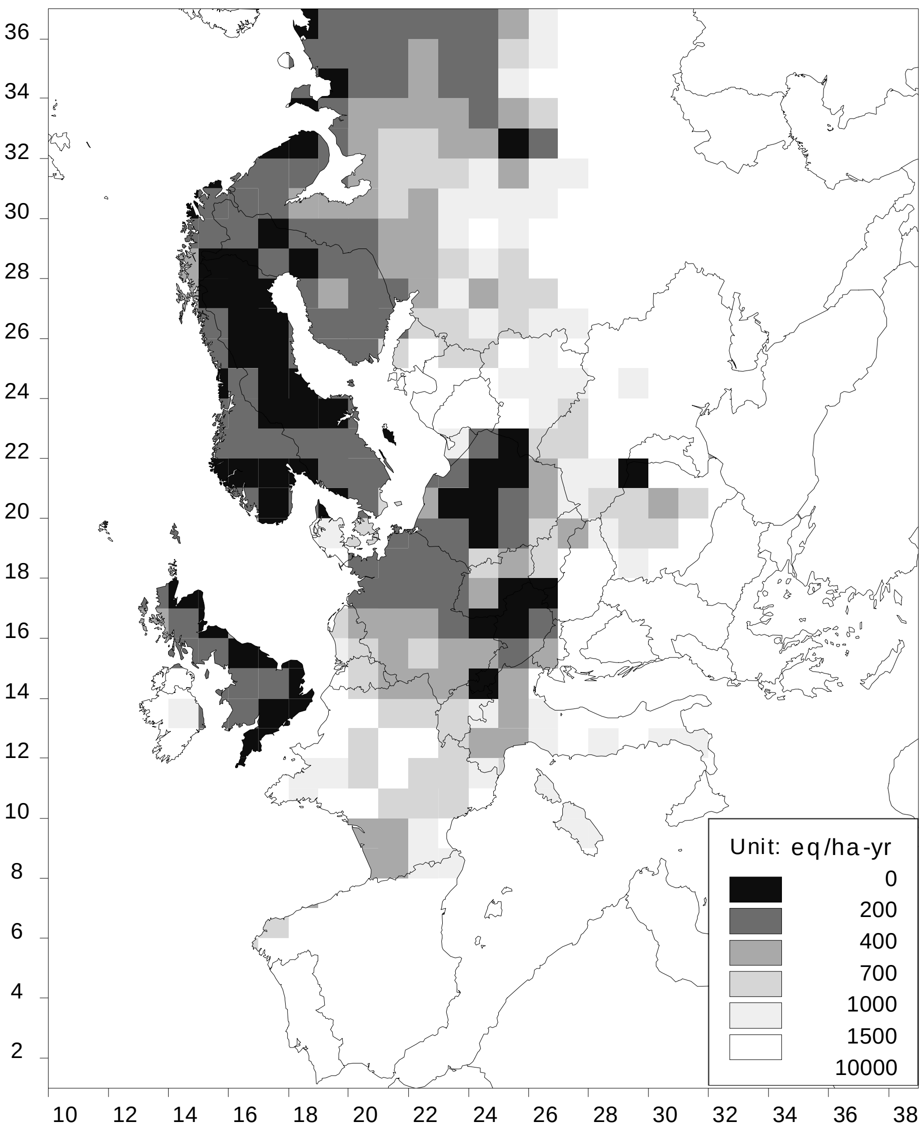

Figure 2.5: The fifth percentile of the critical loads for acidity ($CL_{max}(S)$)

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. While more difficult to present in a map format, these isolines - and simplifications thereof - can be used in integrated assessment models, such as RAINS, to evaluate emission reduction strategies for both sulfur and nitrogen. Due 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 percent of ecosystem's 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

$$\sum_{i=1}^{N} c_i \rightarrow \min \tag{8}$$

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

$$c_i = f\left(n_i, v_i\right) \tag{9}$$

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

$$AOT40_j = f'(n_i, v_i, \dots) \leq f''(AOT40_{\lim}, \dots) \tag{10}$$

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. Depending on the type of the function in Equation 8 and the number of emitter countries and receptor sites to be considered, the optimization task becomes a large-scale non-linear problem. To solve such a problem, the function derivatives (the Jacobian matrix) must also be available.

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.

2.7.1 Cost Curves as Input to the Optimization

Inputs to the optimization package include cost curves (Equation 10) 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 and NH_3 and VOC. These estimates can be expressed in terms of cost curves, providing - for a given emission source (country) - the least costs for achieving increasingly stringent emission reductions. They are compiled by ranking the available abatement options according to their marginal costs. Consequently, this methodology produces piece-wise linear curves, consisting typically of about 30 segments.

For each of the pollutants (NO_x, VOC) and the countries, such piece-wise linear curves can be used as input to the optimization according to Equation 10. Although the solver softwares used for this exercise are capable of dealing with piece-wise linear constraints, for reasons of increased numerical stability a smoothed approximation of the cost curves has been developed and used. Analysis demonstrated that the given piece-wise linear cost curves could be best approximated with a second-order rational function

$$y_i = \frac{a_i + b_i x_i}{1 + c_i x + d_i x_i^2} + e_i \quad , \qquad (11)$$

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

In December 1996 the cost curves for NO_x and NH_3 have been submitted to the Parties of the Convention on Long-range Transboundary Air Pollution for review. Comments received from the Parties will be fully incorporated into the cost curves in the near future. It is foreseen to present the cost curves for VOC and for SO_2 together with a detailed documentation of the methodology used to the Parties in late 1997 and early 1998, respectively.

3. Data Sources

3.1 Energy Projections

Input to the RAINS model are projections of future energy consumption on a national scale up to the year 2010. The model stores this information as energy balances for selected future years, distinguishing fuel production, conversion and consumption for 22 fuel types in 6 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.).

For the purpose of this study, energy projections for the 15 EU member states have been provided by DG-XVII and have been incorporated into the RAINS data base. These projections (Table 3.1) are extracted from the 'Conventional Wisdom Scenario' of the 'Energy 2020' Study (DG-XVII, 1996). For Denmark, however, the DG-XVII projections have been replaced by the forecast of the national energy plan recently adopted by the Danish Parliament. In the remainder of the report the resulting combination of energy scenarios (i.e., the official Danish energy scenario for Denmark and the 'Conventional Wisdom' scenario for the other 14 EU Member States) will be referred to as the 'Modified Conventional Wisdom' energy scenario
.
The energy scenario selected for this study projects for the 15 EU countries an increase of total energy consumption of 19 percent between 1990 and 2010. The demand for coal decreases by 27 percent and for liquid fuels from stationary sources by nine percent. This decline is mainly compensated by a rapid increase in the demand for natural gas (82 percent by 2010) and for other fuels (nuclear, hydropower, renewable energy) by 29 percent. The transport sector is expected to grow further, which - in spite of continuing improvement in fuel economy of new cars and trucks - results in an increase in the demand for transport fuels by 29 percent.

For the non-EU countries considered in RAINS (Table 3.3), energy projections are based on data submitted by the governments to the UN/ECE and published in the UN/ECE Energy Data Base (UN/ECE, 1995a). Where necessary, missing forecast data have been constructed by IIASA based on a simple energy projection model. These forecasts (Table 3.3) are also the basis for the scenario calculations conducted for the negotiations of the Second NO_x Protocol under the Convention on Long-range Transboundary Air Pollution.

For the non-EU countries, the scenario projects a five percent drop in total primary energy consumption. This is due to a sharp decrease in primary energy demand that occurred in the period 1990 - 1995 in the countries of the former Soviet Union and in other central and east European countries with economies in transition. Processes of economic restructuring in those countries will allow further economic development while keeping the total primary energy demand until 2010 below the 1990 level. Consumption of coal and oil by stationary sources is predicted to decrease by 23 and 33 percent, respectively. Consumption of natural gas will increase (by 12 percent). Similarly to the EU countries, the demand for transport fuels will increase (by 6 percent over the period 1990 - 2010). In spite of a fast increase in car ownership, the increase in the demand for fuels is modest because of a rapid decrease in material- and transport intensities of the former so-called planned economies. Thus, until 2010 the demand for goods transport will also remain below the 1990 level.

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

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

	1990 [PJ]	2010 [PJ]	*Change 1990-2010*	GDP growth [%/year]
Austria	1236	1478	*20 %*	2.5 %
Belgium	1907	2155	*13 %*	2.2 %
Denmark	756	765	*1 %*	2.2 %
Finland	1208	1590	*31 %*	1.7 %
France	8792	11396	*30 %*	2.4 %
Germany	14536	15465	*6%*	2.6 %
Greece	910	1194	*31 %*	3.8 %
Ireland	423	534	*26 %*	3.5 %
Italy	6560	8231	*26 %*	2.0 %
Luxembourg	122	129	*6 %*	2.3 %
Netherlands	2711	3087	*14 %*	2.1 %
Portugal	699	1172	*68 %*	3.5 %
Spain	3659	4768	*30 %*	2.7 %
Sweden	2319	2520	*9 %*	1.3 %
UK	8526	10215	*20 %*	2.0 %
EU-15	54365	64699	*20 %*	2.3 %

Table 3.2: Energy projections for the EU-15 (Source: DG-XVII - Conventional Wisdom Scenario, Danish Energy Plan)

Source category/fuel Stationary combustion sources:	1990 [PJ]	2010 [PJ]	*Change 1990-2010*
Total	44338	51741	*17 %*
- Coal	11620	8460	*-27 %*
- Liquid fuels	11847	10819	*-9 %*
- Gaseous fuels	10424	19009	*82 %*
- Other	10448	13453	*29 %*
Mobile sources - total	10027	12958	*29 %*
TOTAL	54365	64699	*19 %*

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

	1990 [PJ]	2010 [PJ]	*Change* *1990-2010*	GDP growth [%/year]
Albania	128	143	*12 %*	1.3 %
Belarus	1762	1553	*-12 %*	-0.3 %
Bosnia-H..	311	297	*-5 %*	0.3 %
Bulgaria	1296	1262	*-3 %*	1.5 %
Croatia	413	447	*8 %*	0.8 %
Czech Republic	1956	1837	*-6 %*	1.8 %
Estonia	423	366	*-13 %*	0.9 %
Hungary	1109	1350	*22 %*	1.7 %
Latvia	399	359	*-10 %*	-0.3 %
Lithuania	677	565	*-17 %*	-0.3 %
Norway	1596	1750	*10 %*	2.0 %
Poland	4201	4951	*18 %*	3.4 %
R. of Moldova	394	324	*-18 %*	-0.3 %
Romania	2425	2525	*4 %*	1.3 %
Russia	18312	16617	*-9 %*	-0.3 %
Slovakia	987	982	*0 %*	1.8 %
Slovenia	231	234	*1 %*	1. 2 %
Switzerland	1119	1198	*7 %*	1.3 %
FYR Macedonia	151	138	*-9 %*	0.8 %
Ukraine	9968	8559	*-14 %*	-0.3 %
Yugoslavia	790	725	*-8 %*	0.6 %
Non-EU	48648	46183	*-5 %*	1.0 %

Table 3.4: Energy projections for the non-EU countries (Sources: UN/ECE, 1995a, RAINS estimates)

Source category/fuel	1990 [PJ]	2010 [PJ]	Change 1990-2010
Stationary combustion sources:			
Total	44057	41312	-6 %
- Coal	11540	8888	-23 %
- Liquid fuels	8540	5699	-33 %
- Gaseous fuels	18199	20440	12 %
- Other	5778	6285	9 %
Mobile sources - total	4591	4870	6 %
TOTAL	48648	46183	-5 %

3.2 Projections of Agricultural Livestock

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. IIASA has compiled a set of forecasts of European agricultural activities, based on national information (Marttila, 1995; Nemi, 1995; Pippatti, 1996; Henriksson, 1996; Riseth, 1990; Menzi, 1995; Menzi *et al.*, 1996; Davidson, 1996), on studies performed for DG-VI of the Commission of the European Communities, (EC DG-VI, 1995a-k) for Eastern Europe, and on Egmond (1995), Stolwijk (1996), Folmer *et al.* (1995) for EU countries. The forecast for the EU is based on the assumptions that (i) until 2005 the Common Agricultural Policy will essentially consist of the type of the policies adopted under MacSharry, and (ii) after 2005 the EU will gradually liberalize its agricultural policy (Stolwijk, 1996). More detailed information on the ECAM (European Community Agricultural Model) model used to derive this forecast can be found in Folmer *et al.* (1995). Projections for the Republics of the Former Soviet Union were derived from an OECD study (OECD, 1995).

Projections of livestock development are presented in Table 3.5.and Table 3.6. In these tables 'cows' include dairy cows and other cattle, 'pigs' include fattening pigs and sows, and poultry comprises laying hens, broilers and other poultry.

Table 3.5: Projection of livestock up to the year 2010 for the EU-15 (million animals)

	Cows			Pigs			Poultry		
	1990	2010		1990	2010		1990	2010	
Austria	2.6	2.5	-1%	3.8	4.5	20%	14.0	17.3	23%
Belgium	3.0	5.1	68%	6.4	4.7	-26%	35.3	27.1	-23%
Denmark	2.2	1.7	-23%	9.3	11.7	26%	16.2	17.1	5%
Finland	1.4	0.9	-34%	1.3	1.2	-11%	6.0	4.5	-25%
France	21.4	20.9	-3%	12.4	17.4	41%	236.0	279.3	18%
Germany	20.3	15.7	-23%	34.2	21.2	-38%	125.5	78.6	-37%
Greece	0.6	0.6	-1%	1.0	1.5	46%	27.4	33.0	20%
Ireland	5.9	7.7	31%	1.0	1.9	93%	8.9	13.6	52%
Italy	8.7	9.5	9%	9.3	10.5	13%	161.0	204.1	27%
Luxembourg	0.2	0.4	78%	0.1	0.1	-33%	0.1	0.1	-28%
Netherlands	4.9	4.8	-2%	13.4	11.2	-16%	93.8	79.5	-15%
Portugal	1.3	1.2	-7%	2.5	1.5	-41%	21.9	26.8	22%
Spain	5.1	5.3	3%	16.0	21.4	34%	51.0	56.1	10%
Sweden	1.7	1.9	10%	2.3	2.1	-7%	12.3	9.0	-27%
UK	11.9	9.9	-17%	7.4	4.8	-34%	141.0	120.5	-15%
EU-15	91.4	88.2	-4%	120.3	115.6	-4%	950.5	966.5	2%

Table 3.6: Projection of livestock up to the year 2010 for the non-EU countries (million animals)

	Cows			Pigs			Poultry		
	1990	2010		1990	2010		1990	2010	
Albania	0.6	0.8	21%	0.2	0.3	17%	5.0	8.4	68%
Belarus	7.2	4.3	-40%	5.2	4.0	-23%	49.8	43.3	-13%
Bosnia -H	0.9	0.7	-22%	0.6	0.6	-10%	9.0	8.0	-11%
Bulgaria	1.6	0.9	-41%	4.4	4.3	-2%	36.3	43.6	20%
Croatia	0.8	0.6	-27%	1.6	1.3	-17%	15.0	8.4	-44%
Czech Rep.	3.4	3.4	3%	4.6	5.8	26%	33.3	49.1	48%
Estonia	0.8	0.6	-28%	1.1	1.2	9%	7.0	7.8	11%
Hungary	1.6	1.6	-3%	7.7	7.9	3%	58.6	63.5	8%
Latvia	1.5	0.7	-52%	1.6	1.5	-7%	11.0	7.6	-31%
Lithuania	2.4	2.2	-7%	2.7	2.8	2%	18.0	19.2	7%
Norway	1.0	1.1	10%	0.7	0.8	10%	5.4	5.3	-2%
Poland	10.0	13.3	32%	19.5	23.8	22%	70.0	97.8	40%
R. Moldova	1.1	1.0	-13%	2.0	1.5	-27%	25.0	19.0	-24%
Romania	6.3	6.2	-2%	11.7	10.3	-12%	119.3	146.8	23%
Russia	42.2	27.3	-35%	30.5	30.5	0%	474.3	326.5	-31%
Slovakia	1.6	0.8	-49%	2.5	2.7	8%	16.5	22.0	34%
Slovenia	0.5	0.4	-22%	0.6	0.7	18%	13.5	12.9	-4%
Switzerland	1.9	1.7	-8%	1.8	1.4	-22%	6.5	6.5	0%
Macedonia	0.3	0.3	-1%	0.2	0.2	7%	22.0	22.0	0%
Ukraine	25.2	20.5	-19%	19.9	23.0	15%	255.1	260.0	2%
Yugoslavia	2.2	2.0	-8%	4.3	4.1	-5%	28.0	21.0	-25%
Non-EU	113.1	90.4	-20%	123.3	128.4	4%	1278.7	1198.8	-6%

The forecast of fertilizer consumption for EU-15, Switzerland and Norway is based on a study by the European Fertilizer Manufacturers Association (EFMA, 1996a,b). A “moderate grain price” scenario was used. The basic assumptions of this projection are (i) that there will be no change in the Common Agricultural Policy (CAP) until the year 2000; thereafter a more market oriented, less regulated CAP is expected; and (ii) that by the year 2005/2006 the Central European Countries will have joined the EU. Estimates on fertilizer consumption for the rest of Europe were derived from publications of the International Fertilizer Industry Association (Ginet, 1995). Since these forecasts do not always extend up to the year 2010, missing values were constructed based on a trend extrapolation.

Table 3.7: Projections of nitrogen fertilizer use for the EU-15 (in 1000 tons N/year)

	Nitrogen fertilizer use		
	1990	**2010**	***Change***
Austria	137	109	*-20 %*
Belgium	166	137	*-17 %*
Denmark	395	261	*-34 %*
Finland	207	153	*-26 %*
France	2493	2457	*-1 %*
Germany	1786	1545	*-14 %*
Greece	428	294	*-31 %*
Ireland	370	381	*3 %*
Italy	879	911	*4 %*
Luxembourg	20	16	*-20 %*
Netherlands	392	207	*-47 %*
Portugal	150	144	*-4 %*
Spain	1064	1052	*-1 %*
Sweden	212	219	*3 %*
UK	1516	1298	*-14 %*
EU-15	**10215**	**9184**	***-10 %***

Table 3.8: Projections of nitrogen fertilizer use for the non-EU countries (in 1000 tons N/year)

	Nitrogen fertilizer use		
	1990	**2010**	***Change***
Albania	73	60	*-18 %*
Belarus	780	676	*-13 %*
Bosnia -H	19	10	*-47 %*
Bulgaria	453	530	*17 %*
Croatia	114	190	*67 %*
Czech Rep.	441	580	*32 %*
Estonia	110	151	*37 %*
Hungary	359	639	*78 %*
Latvia	143	221	*55 %*
Lithuania	256	309	*21 %*
Norway	111	92	*-17 %*
Poland	671	855	*27 %*
R. of Moldova	123	228	*85 %*
Romania	765	780	*2 %*
Russia	3418	1994	*-42 %*
Slovakia	147	150	*2 %*
Slovenia	88	102	*16 %*
Switzerland	63	40	*-37 %*
FYRMacedonia	6	3	*-50 %*
Ukraine	1885	1599	*-15 %*
Yugoslavia	146	145	*-0 %*
Non-EU	**10171**	**9354**	***-8 %***

3.3 Changes in the Database Since the Second Interim Report

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

- The UN/ECE Working Group on Effects released the updated critical loads database (August 1997). This database was subsequently incorporated into the RAINS model.
- There is new information on the emissions from ships on the Atlantic Ocean and the North Sea. This subject is discussed in more detail in Section 0 of this Report.
- In response to comments made by Member States the removal efficiencies for emission control equipment in the industrial sector have been modified (see also Section 2.4).
- Comments made by the Parties to the Convention on Long-range Transboundary Air Pollution were partially incorporated into the database, in particular:
    - improved estimates of the current legislation scenario for Italy; revised current reduction plans for Sweden, the Netherlands, the UK, and some non-EU countries;
    - improved power plant data for Finland and the Netherlands;
    - exclusion of the energy consumption of the Canary Island from the Spanish energy balance;
    - update of the transport scenario for Switzerland.
- The VOC cost curves developed at IIASA were introduced into the model.
- The ammonia estimates were slightly revised in light of new information.

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

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

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

The 'Current Reduction Plans' (CRP) scenario is based on an inventory of officially declared national emission ceilings. Such declarations of envisaged future emissions result from the various protocols of the Convention on Long-range Transboundary Air Pollution and are collected on a routine basis by the Secretariat of the Convention. The analysis in this study uses the recent data published in UN/ECE (1995b). 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 the Current Legislation scenario has been used.

4.2 The Current Legislation (CLE) Scenario for the Year 2010

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

The starting point for the analysis is a detailed inventory of regulations on emission controls, taking into account the legislation in the individual European countries, the relevant Directives of the European Union (in particular the 'Large Combustion Plant Directive' (OJ, 1988) and the Directive on Sulfur Content of Gas Oil (Johnson & Corcelle, 1995)), as well as the obligatory clauses regarding emission standards from the protocols under the Convention on Long-range Transboundary Air Pollution (for instance, the Second Sulfur Protocol

(UN/ECE, 1994b) requires emission control according to 'Best Available Technology' (BAT) for new plants).

In addition to the emission standards for new and existing sources in each country it has been assumed that signatories to the Second Sulfur Protocol will reduce the sulfur content in gas oil for stationary sources to 0.2 percent and to 0.05 percent if used as diesel fuel for road vehicles. It is important to mention that the assumptions for the CLE scenario have not been modified since the Second Interim Report. Consequently, the limit on the sulfur content for liquid fuels contained in the Commission's Acidification Strategy is not reflected in this CLE scenario.

For the control of NO_x emissions from mobile sources, the scenario considers the implementation of the current EU standards for all new cars, light duty trucks and heavy duty vehicles (i.e., the Directives 94/12/EC, 70/220/EEC and 88/77/EEC; see McArragher, 1994) in the Member States of the European Union. Additionally, the scenario assumes for all EU countries after the year 2000 the implementation of the measures proposed by the Auto/Oil Program. They include vehicle-related measures like improved catalytic converters, engine modifications and on-board diagnostic systems. Furthermore, the impacts of the proposed improved inspection and maintenance practices and the changes in fuel quality are incorporated. The pace of the implementation of the vehicle-related measures depends on the turnover of vehicle stock and has been based on modeling work performed for the Auto/Oil study.

For non-EU members the scenario takes account of the regulations currently in force in each country.

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

For constructing the CLE scenario the emission control measures listed above were combined with the future level of energy consumption as projected by the Modified Conventional Wisdom energy scenario. Table 4.1 and Table 4.2 compare the estimates for the year 1990 with the CRP and the CLE scenarios. There is clear evidence that official long-term emission targets presented to international organizations are not always consistent with what could be expected to be achieved through current legislation. In particular, the longer-term dynamics of technology-related emission limit values induced by the turnover of the capital stock often seem to be underestimated, so that frequently technology- and activity-based forecasts yield higher emission reductions. For NO_x, however, most of the differences in the estimates for the EU countries can be explained by the stricter emission standards for mobile sources resulting from the Auto/Oil program. Whereas these new plans are considered in the CLE scenario, they are not yet taken into account in the official country submissions to the UN/ECE used for the CRP scenario.

4.3 The Reference (REF) Scenario for the Year 2010

A Reference scenario has been constructed in order to assess the likely environmental impacts of the current emission control strategies. Taking into account national and international legislation as well as commitments made within the framework of the Convention on Long-range Transboundary Air Pollution, the Reference (REF) scenario selects, for each country individually, the more stringent outcome of the Current Reduction Plans- and the Current Legislation-scenarios. Emissions of this scenario are compared with the 1990 levels in Table 4.3 and Table 4.4.

For EU-15 as a whole, SO_2 emissions will be reduced by 72 percent compared to 1990; NO_x will go down by 55 percent and ammonia by 14 percent. VOC is expected to decline by 45 percent. Lower relative reductions are foreseen for the non-EU countries with SO_2 declining by 54 percent, NO_x by 20 percent and ammonia by 17 percent.

4.4 Full Implementation of Current Control Technologies

A further scenario, the Maximum Feasible Reductions (MFR) scenario, has been constructed to illustrate the potential of a full application of current control technology and to quantify possible progress towards the ultimate target of full achievement of critical loads as stipulated by the Council of the European Commission.

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.

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

It is important to mention that the analysis presented in this Third Interim Report excludes the possible emission reductions discussed within 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-accounting 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 Third Interim Report. It is planned, however, to have the new method available for the next reports.

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. There are, however, several sensitivity runs presented in this report which identify the theoretical potential for the Auto/Oil 2 measures.

Table 4.3 and Table 4.4 list the resulting emissions for the REF and MFR scenarios. The measures assumed in MFR scenario enable a reduction of SO_2 emissions in the EU-15 by 92 percent, of NO_x by 68 percent, of ammonia by 44 percent and of VOC by 70 percent compared 1990.

Table 4.1: SO_2 and NO_x emissions for 1990, the current reduction plans for the year 2010 and for the current legislation scenario (CLE) for the year 2010 (in kilotons)

	SO_2			NO_x		
	1990	CRP	CLE	1990	CRP	CLE
Austria	93	78	**57**	242	155	**116**
Belgium	317	**215**	258	363	309	**199**
Denmark	190	90	**71**	271	192	**116**
Finland	237	**116**	160	279	224	**163**
France	1300	737	**691**	1619	1276	**895**
Germany	5271	**740**	921	2985	2130	**1289**
Greece	509	570	**361**	392	544	**282**
Ireland	180	**155**	201	107	105	**74**
Italy	1699	1042	**442**	2009	2060	**1113**
Luxembourg	14	**4**	9	21	19	**10**
Netherlands	197	**56**	115	539	270	**218**
Portugal	286	294	**194**	208	215	**206**
Spain	2234	2143	**1003**	1176	892	**843**
Sweden	115	**87**	99	345	254	**205**
UK	3754	**980**	1923	2664	1186	**1225**
EU-15	**18386**	**7307**	**6505**	**15210**	**9831**	**6954**

Table 4.2: NH_3 and VOC emissions for 1990, the current reduction plans for the year 2010 and for the current legislation scenario (CLE) for the year 2010 (in kilotons)

	NH_3			VOC		
	1990	CRP	No control	1990	CRP	CLE
Austria	92	**93**	95	420	**305**	327
Belgium	95	**96**	106	339	233	**182**
Denmark	140	**103**	121	175	136	**89**
Finland	41	**23**	30	193	**108**	133
France	692	**668**	668	2395	1681	**1381**
Germany	741	**539**	539	3106	1750	**1361**
Greece	78	**76**	76	295	205	**203**
Ireland	124	**126**	149	96	138	**42**
Italy	384	394	**391**	1852	1376	**1139**
Luxembourg	7	**6**	9	18	13	**8**
Netherlands	229	**82**	193	465	258	**258**
Portugal	91	92	**84**	197	**144**	186
Spain	353	**345**	373	1036	794	**763**
Sweden	62	**53**	63	448	**287**	353
UK	325	320	**270**	2690	**1276**	1544
EU-15	**5444**	**3016**	**3167**	**15715**	**8704**	**7969**

Table 4.3: Emissions of SO_2 and NH_3 for 1990, the Reference (REF) scenario and the maximum feasible reductions (MFR) in the year 2010 (assuming the implementation of Auto/Oil-1)

	SO_2					NH_3				
	1990	REF	*Change*	MFR	*Change*	1990	REF	*Change*	MFR	*Change*
Austria	93	57	*-39%*	37	*-60%*	92	93	*1%*	54	*-41%*
Belgium	317	215	*-32%*	49	*-84%*	95	96	*1%*	70	*-27%*
Denmark	190	71	*-63%*	17	*-91%*	140	103	*-26%*	47	*-66%*
Finland	237	116	*-51%*	55	*-77%*	41	23	*-44%*	20	*-52%*
France	1300	691	*-47%*	222	*-83%*	692	668	*-3%*	409	*-41%*
Germany	5271	740	*-86%*	334	*-94%*	741	539	*-27%*	292	*-61%*
Greece	509	361	*-29%*	49	*-90%*	78	76	*-3%*	54	*-31%*
Ireland	180	155	*-14%*	31	*-83%*	124	126	*2%*	118	*-5%*
Italy	1699	442	*-74%*	165	*-90%*	384	391	*2%*	261	*-32%*
Luxembourg	14	4	*-71%*	3	*-81%*	7	6	*-14%*	6	*-16%*
Netherlands	197	56	*-72%*	34	*-83%*	229	82	*-64%*	81	*-64%*
Portugal	286	194	*-32%*	31	*-89%*	91	84	*-8%*	63	*-31%*
Spain	2234	1003	*-55%*	175	*-92%*	353	345	*-2%*	226	*-36%*
Sweden	115	87	*-24%*	59	*-49%*	62	53	*-15%*	38	*-39%*
UK	3754	980	*-74%*	173	*-95%*	325	270	*-17%*	209	*-36%*
EU-15	18386	5172	*-72%*	1433.8	*-92%*	3454	2955	-14%	1947	-44%

Table 4.4: Emissions of NO_x and VOC for 1990, the Reference (REF) 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)

	NO_x					VOC[1)]				
	1990	REF	*Change*	MFR (AO1)	*Change*	1990	REF	*Change*	MFR (AO1)	*Change*
Austria	242	116	*-52%*	98	*-60%*	420	305	*-27%*	245	*-42%*
Belgium	363	199	*-45%*	123	*-66%*	339	182	*-46%*	90	*-73%*
Denmark	271	116	*-57%*	84	*-69%*	175	89	*-49%*	57	*-67%*
Finland	279	163	*-42%*	93	*-67%*	193	108	*-44%*	65	*-66%*
France	1619	895	*-45%*	695	*-57%*	2395	1381	*-42%*	616	*-74%*
Germany	2985	1289	*-57%*	1056	*-65%*	3106	1361	*-56%*	772	*-75%*
Greece	392	282	*-28%*	203	*-48%*	295	203	*-31%*	111	*-62%*
Ireland	107	74	*-31%*	31	*-71%*	96	42	*-56%*	10	*-90%*
Italy	2009	1113	*-45%*	738	*-63%*	1852	1139	*-38%*	582	*-69%*
Luxembourg	21	10	*-52%*	7	*-67%*	18	8	*-56%*	3	*-83%*
Netherlands	539	218	*-60%*	156	*-71%*	465	258	*-45%*	123	*-74%*
Portugal	208	206	*-1%*	130	*-38%*	197	144	*-27%*	95	*-52%*
Spain	1176	843	*-28%*	542	*-54%*	1036	763	*-26%*	294	*-72%*
Sweden	345	205	*-41%*	153	*-56%*	448	287	*-36%*	267	*-40%*
UK	2664	1186	*-55%*	703	*-74%*	2690	1276	*-53%*	744	*-72%*
EU-15	15210	6915	*-55%*	4812	*-68%*	13725	7546	-45%	4074	-70%

Note: [1]) Excluding agricultural emissions

5. Ground-level ozone: AOT60

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 recently reviewed and updated the Air Quality Guidelines for Europe (WHO 1997a, WHO 1997b). This update suggests an eight-hours maximum value of 60 ppb as a level at which acute adverse effects in the population are present. Although chronic exposure to ozone has the capability to cause 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 (1997b). 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 five percent 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 relations between these exposure indices vary greatly with space, time and the concentrations of precursor emissions over Europe. Consequently, optimized strategies will crucially depend on the target exposure index (whether giving preference to peak or long-term exposure), and will not necessarily also 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 6. Subsequently, Section 7 explores the potential for optimized strategies meeting both types of targets simultaneously.

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

Following the revised WHO Air Quality Guidelines for Europe, the Draft Position Paper on Ozone prepared by the Commission's Services proposes a maximum eight-hour average concentration of 60 ppb (120 μg) as the long-term environmental objective for the EU ozone strategy[18]. The ultimate goal would be to eliminate all excess of this criterion.

The modelling of European abatement strategies for individual days over a multi-months 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 maximum eight hours mean concentrations) was converted into an AOT index, which could be handled in a similar way to the AOT40 for vegetation. As a result, an AOT60 (i.e., the cumulative excess exposure over 60 ppb, for practical reasons over a six-month period) of zero is considered as equivalent to the full achievement of the WHO criterion. Any violation of this WHO guideline will consequently result in an AOT60 of larger than zero.

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

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

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 5.3.1, the inter-annual meteorological variability may vary actual long-term ozone concentrations by more than a factor of two, keeping emissions constant. 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 REF scenario) and the possible (from the MFR scenario) changes in AOT60 between 1990 and 2010. In doing so, the analysis uses the mean meteorological conditions of the five years 1989, 1990, 1992, 1993 and 1994. Obviously, the data displayed in the maps cannot be directly compared with real observations, since these incorporate the specific meteorological conditions for the selected year.

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

Figure 5.2 illustrates that for the emissions of 1990 and assuming the five-years mean meteorology, the highest (rural) AOT60 of more than 6 ppb.hours occurred 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 and Austria 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.

Although the AOT60 is a convenient index to model, it might be a difficult one to interpret and to link with generally understandable notions. A better measure in this respect is obviously the number of days on which the WHO criterion is exceeded. Figure 5.1 displays (for the mean meteorology) 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, a fact which is important to take into account when designing emission control strategies.

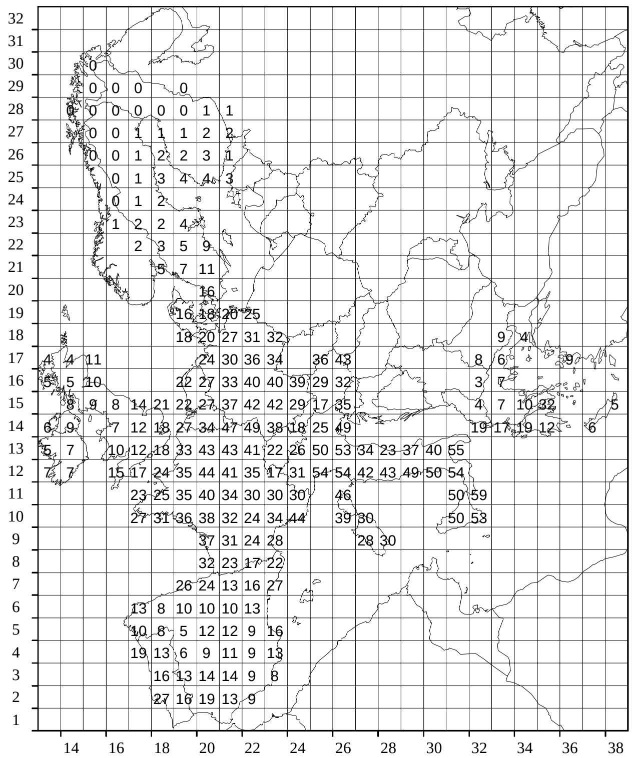

Figure 5.1: Number of days with ozone above 60 ppb, using 1990 emissions and mean meteorology

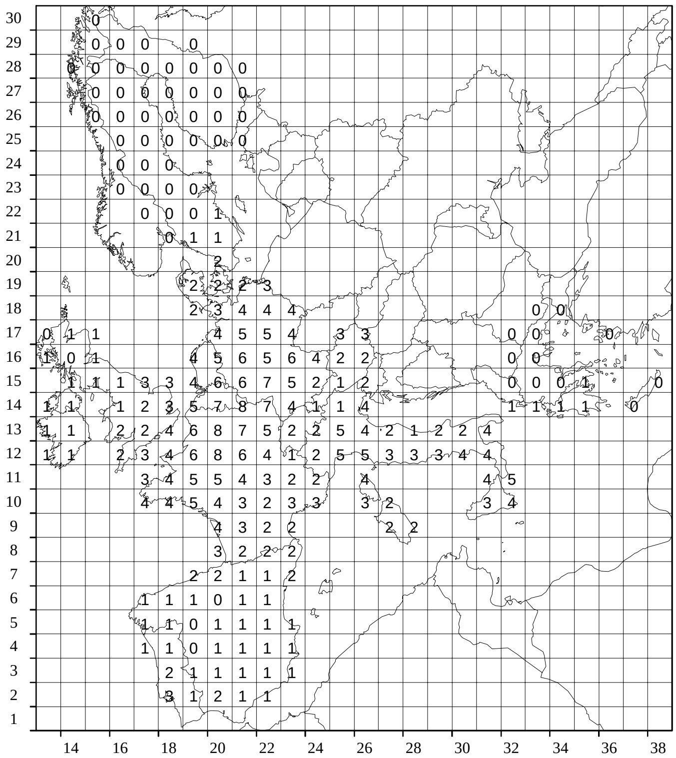

Figure 5.2: AOT60 for the emissions of the year 1990, using mean meteorology (in ppm.hours)

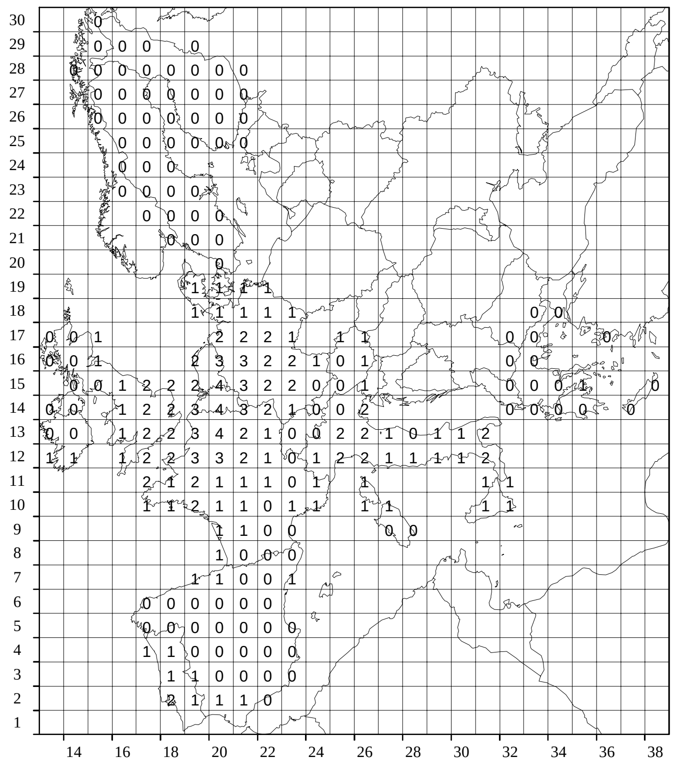

Figure 5.3: AOT60 for the REF scenario in the year 2010, using mean meteorology (in ppm.hours)

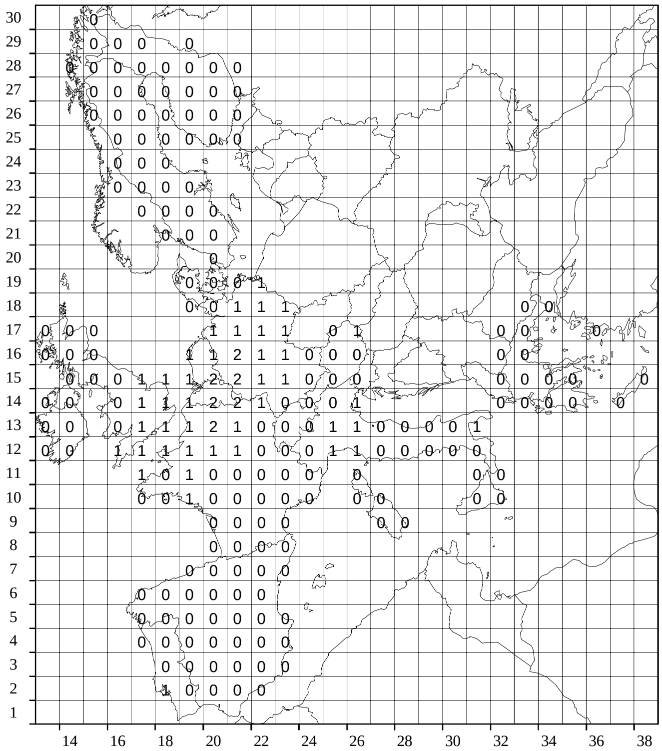

Figure 5.4: : AOT60 for the maximum feasible emission reductions (assuming the measures of Auto/Oil 1) in the year 2010, using mean meteorology (in ppm.hours)

The emission controls assumed in the REF scenario for the year 2010 (NO_x -55%, VOC -45% compared to 1990) are expected to have profound impacts on ozone exposure (Figure 5.3). Assuming mean meteorological conditions, the highest AOT60 in Europe would decline to about 4 ppm.hours, i.e., by about 50 percent. In many other regions there would be even higher improvements, leading to an average drop of the AOT60 by 60 percent.

Even further cuts in the AOT60 could be achieved by the maximum feasible emission reductions (Figure 5.4). Excluding the emission control potential offered by Auto/Oil 2, a 68 percent decline of NO_x emissions accompanied by a 70 percent decrease of VOC emissions would bring highest AOT60 levels in Europe to about two ppm.hours, which is 70-80 percent below the 1990 levels. Since most of Europe would be able to achieve the WHO guideline, the average AOT60 would be 83 percent lower than in 1990.

Table 5.1 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 with the total population. The RAINS model calculates these indices on a grid basis (using gridded data on AOT60 and population); in a second step these grid values are aggregated to the country level. The indices presented in this report use the AOT60 concentrations per grid, representing the rural ozone concentrations, and the total population per grid in 1990. Inaccuracies may occur for grids with major urban areas, where the rural ozone concentrations used for these analysis present an upper bound for the concentrations in the cities, and are lower than the concentrations occurring in the city plumes. The ‘average’ indicator reflects the average exposure of a person in a country, calculated from gridded data. It is important to stress that these indices may not be used to derive estimates of health damage, for which more detailed information is deemed necessary. In the context of this report, these indices provide relative measures to enable a comparison of different scenarios.

Table 5.1: Population exposure indices (AOT60) for 1990, the Reference (REF) scenario and the maximum feasible emission reductions (MFR), using the mean meteorology. The table presents the cumulative population exposure for each country (in million person.ppm.hours) and the average exposure per person in each country (in ppm.hours). Note that the environmental long term target is proposed at a level of zero.

	Cumulative population exposure (million person. ppm.hours)			Average population exposure (ppm.hours)		
	1990	REF	MFR	1990	REF	MFR
Austria	18	5	2	2.2	0.6	0.3
Belgium	67	37	19	6.3	3.5	1.8
Denmark	7	3	1	1.9	0.7	0.3
Finland	1	0	0	0.1	0.1	0.0
France	294	108	44	5.0	1.8	0.8
Germany	365	140	73	5.0	1.9	1.0
Greece	8	4	2	0.7	0.3	0.2
Ireland	4	2	0	0.8	0.3	0.1
Italy	177	62	19	3.2	1.1	0.4
Luxembourg	3	1	1	8.2	3.2	1.7
Netherlands	72	43	22	4.6	2.8	1.4
Portugal	16	9	4	1.6	0.9	0.4
Spain	35	13	3	1.0	0.3	0.1
Sweden	6	2	1	0.6	0.2	0.1
UK	113	80	31	2.0	1.4	0.6
EU-15	820	367	150	2.9	1.3	0.5

As shown in the table, in 1990 the average exposure was highest in France, Luxembourg, , Belgium and Germany, the highest cumulative exposure (due to the large population) occurred in Germany, France, Italy and the UK. The cumulative exposure of the population in the EU-15 countries is expected to decline by 55 percent as a result of the current policy. Larger improvements occur in Austria (-71 percent) and the Scandinavian countries (60-70 percent), while for the UK and Netherlands a decrease in AOT60 between 30 and 40 percent could be expected. The maximum feasible emission reductions would reduce the exposure indices by 82 percent.

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

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

molecules. As indicated in Figure 5.6, reducing NO_x will lead for some time to increased ozone. Beyond a certain NO_x reduction level, however, ozone will decline again.

Figure 5.5 supports this explanation by illustrating the emission densities in 1990. It is important to realize that the emissions in the areas where the increase occurs (UK, Belgium, Netherlands, etc.) are up to a factor of 10 higher than in other industrialized European regions (compare e.g., southern Germany).

In general, Figure .., 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 all other region this phenomenon does not occur (due to lower NO_x emissions), and a reduction of NO_x will always result in lower ozone.

It is also important to realize that this ozone increase disappears for the maximum feasible emission reductions (see Figure 5.4). This means that sufficiently high NO_x reductions (which are considered as technically feasible) can overcome the temporary ozone increase everywhere.

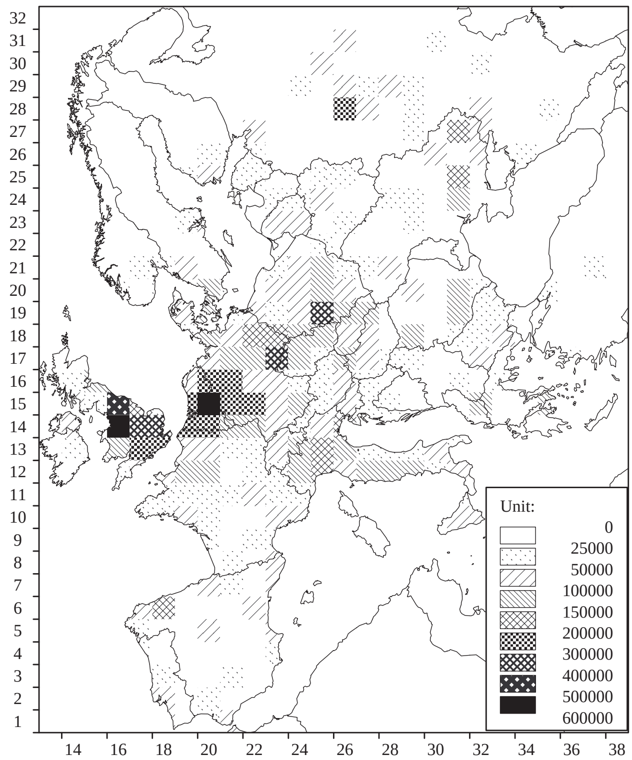

Figure 5.5: NO_x emissions per EMEP grid cell in 1990 (in kilotons)

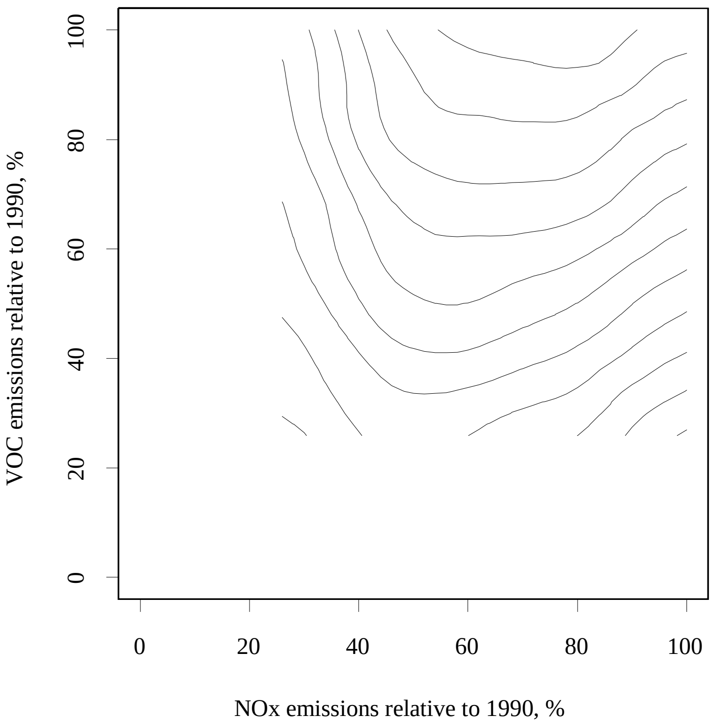

Figure 5.6: A typical ozone isopleth for the non-linear region. The isopleths indicate the ozone concentrations (e.g., in terms of AOT60) as a function of NO_x and VOC emissions. Starting from the level in 1990 (the upper right corner), NO_x reductions (along the x-axis, to the left) will initially increase ozone and only after a certain reduction level lead to an ozone decline.

5.3 Optimized Scenarios for the AOT60

The scenarios outlined in the preceding section illustrate the range of possible improvement of ozone exposure evaluated along the AOT60 criterion. It is obvious from the analysis that the currently planned emission reductions (the REF 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-years mean meteorology. In reality, ozone formation is highly dependent on the meteorological conditions, and it can be expected that at least in some years the situation will be worse than suggested using the mean meteorology. 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.

5.3.1 Dealing with the Inter-annual Meteorological Variability

Figure 5.7 to Figure 5.11 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 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, etc.

Table 5.2 lists the population exposure indices for the emissions of the year 1990 derived with the five meteorological conditions. Compared to the mean meteorology, the cumulative population exposure index varies for the EU-15 in a range of ± 40 percent.

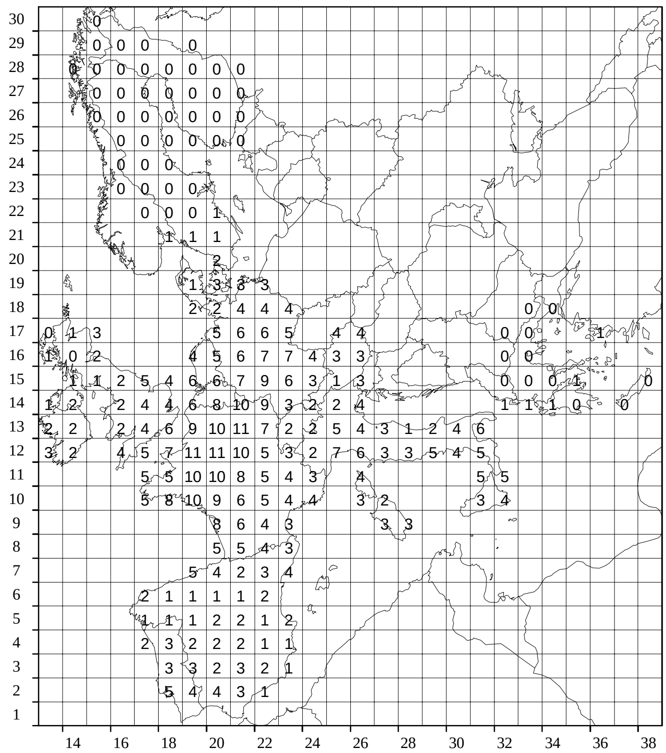

Figure 5.7: AOT60 for the emissions of the year 1990, using the meteorology of 1989 (in ppm.hours)

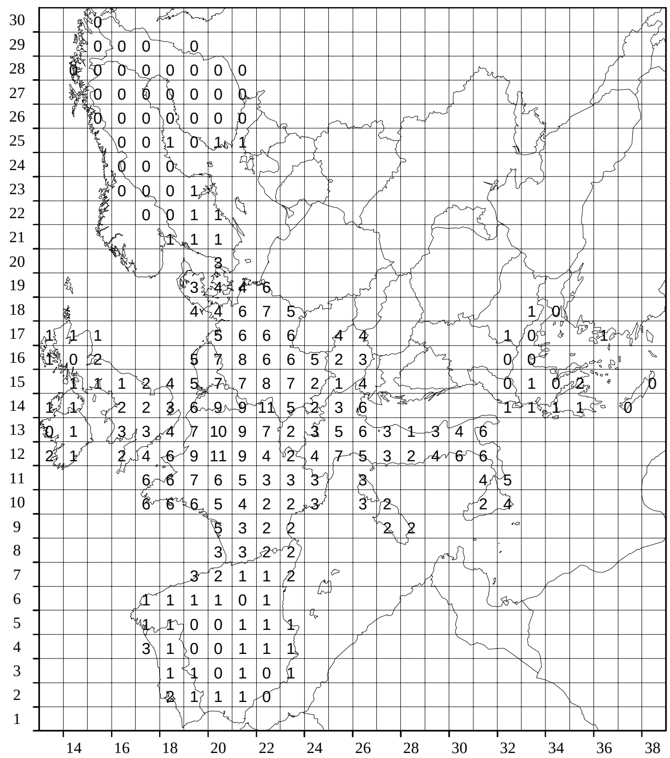

Figure 5.8: AOT60 for the emissions of the year 1990, using the meteorology of 1990 (in ppm.hours)

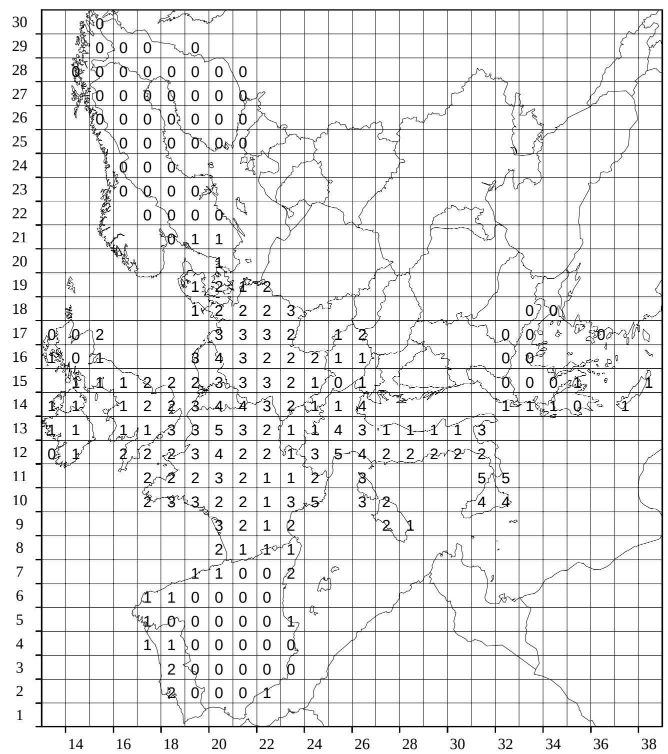

Figure 5.9: AOT60 for the emissions of the year 1990, using the meteorology of 1992 (in ppm.hours)

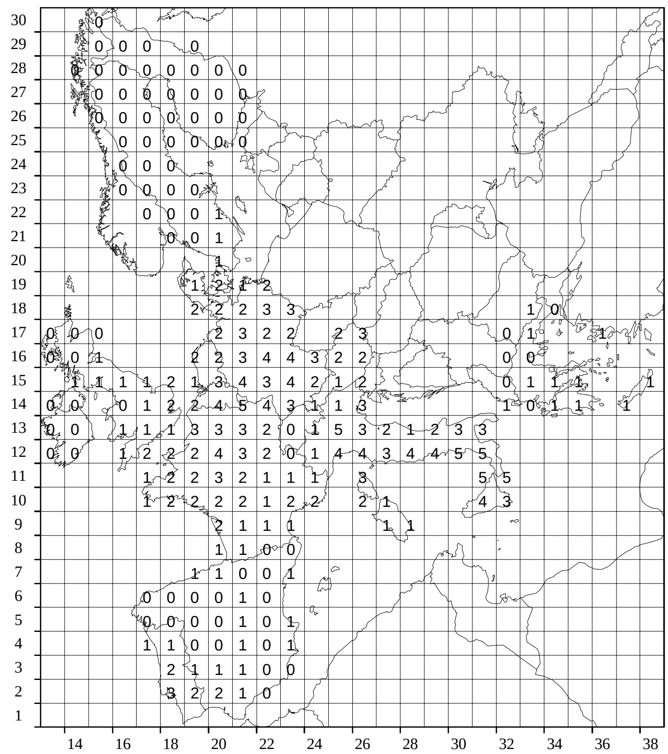

Figure 5.10 AOT60 for the emissions of the year 1990, using the meteorology of 1993 (in ppm.hours)

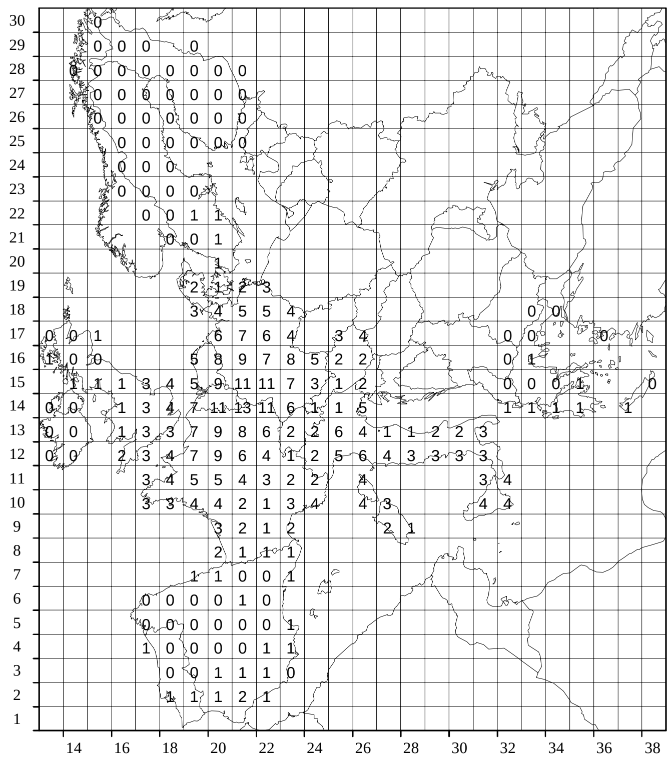

Figure 5.11: AOT60 for the emissions of the year 1990, using the meteorology of 1994 (in ppm.hours)

Table 5.2: Population exposure indices for the emissions of the year 1990, for the five meteorological conditions

	Cumulative population exposure index (million person.ppm.hours)					Average population exposure index (ppm.hours)				
	1989	1990	1992	1993	1994	1989	1990	1992	1993	1994
Austria	24	23	9	14	20	2.9	2.8	1.1	1.6	2.4
Belgium	76	81	37	33	102	7.1	7.5	3.5	3.1	9.5
Denmark	7	12	5	5	8	1.8	3.0	1.3	1.2	2.0
Finland	1	1	1	0	1	0.2	0.2	0.2	0.1	0.1
France	444	376	165	133	329	7.6	6.4	2.8	2.3	5.6
Germany	420	472	185	215	532	5.7	6.4	2.5	2.9	7.3
Greece	6	10	6	8	8	0.5	0.9	0.5	0.7	0.7
Ireland	9	4	3	1	1	1.9	0.8	0.7	0.2	0.2
Italy	202	210	140	161	175	3.7	3.8	2.5	2.9	3.2
Luxembourg	3	3	1	1	4	9.6	9.3	3.7	4.7	13.1
Netherlands	84	92	43	31	106	5.5	6.0	2.8	2.0	6.9
Portugal	32	16	11	15	6	3.2	1.6	1.1	1.6	0.6
Spain	80	34	19	21	22	2.2	0.9	0.5	0.6	0.6
Sweden	8	11	4	4	5	0.7	1.0	0.4	0.4	0.5
UK	177	127	77	55	127	3.2	2.3	1.4	1.0	2.3
EU-15	1154	999	521	483	911	4.0	3.5	1.8	1.7	3.2

5.3.2 Setting Environmental Targets for the Optimization

As explained in the Introduction, the goal of the report is to analyze 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 5.2), 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 before, the extent to which ground-level ozone exceeds the long-term environmental targets also shows great variations over the area of the European Union. A strategy solely targeted 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 over Europe, since regions with less excess exposure would be excluded from the concern of the strategy. One way to ascertain 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 it was the goal, e.g., of the EU acidification strategy, 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.

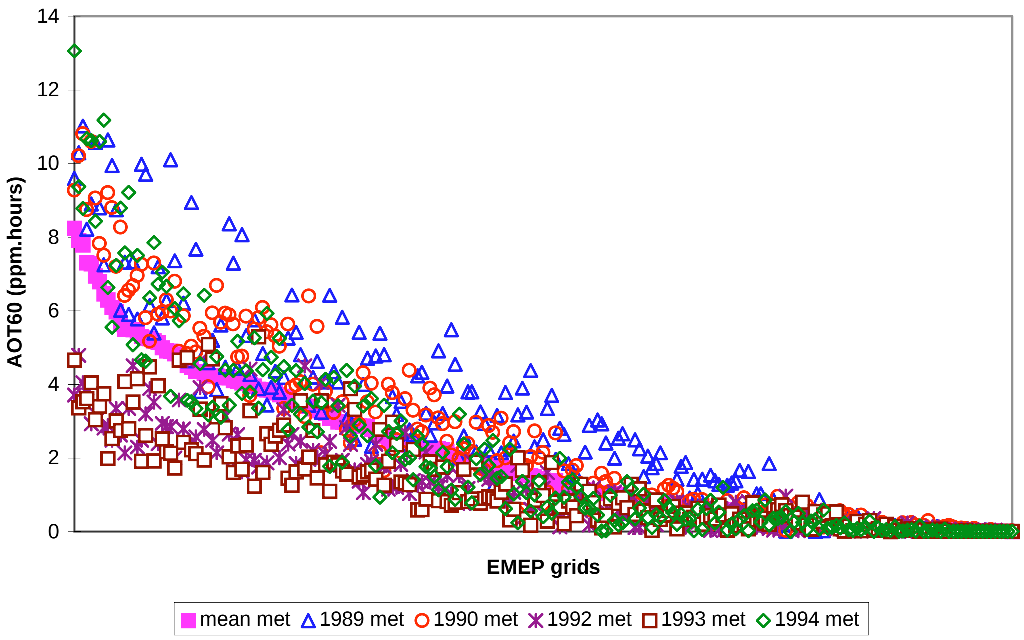

Figure 5.12: AOT60 for the emissions of 1990, using mean meteorological conditions and the meteorologies for the five individual years

Determining a target and designing a strategy that only considers mean meteorology might result in the situation that in some years the environmental targets will not be met. As an illustration, Figure 5.12 displays the AOT60 (on the y-axis) for the 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 explicitly address the question of the meteorological variations in the process of target setting.

Figure 5.13 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, for two grids in the UK for the meteorology of 1990 only a 40 percent gap closure is possible; a similar low improvement is possible for two grids in the Netherlands for the meteorological conditions of 1993, and the improvement is limited to 50 percent around Athens for the 1992 meteorology. Applying the ‘flat gap closure’ principle to the full set of data would limit the ambition level to somewhat less than a 40 percent gap closure for all EU grids, although for most grids - and even for these ‘difficult’ grids for other meteorological conditions - a much higher improvement would be easily 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.

The decision about the appropriate ambition level for the target setting must be left to the political process. However, there are some methodological aspects important to consider. From Figure 5.13 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.

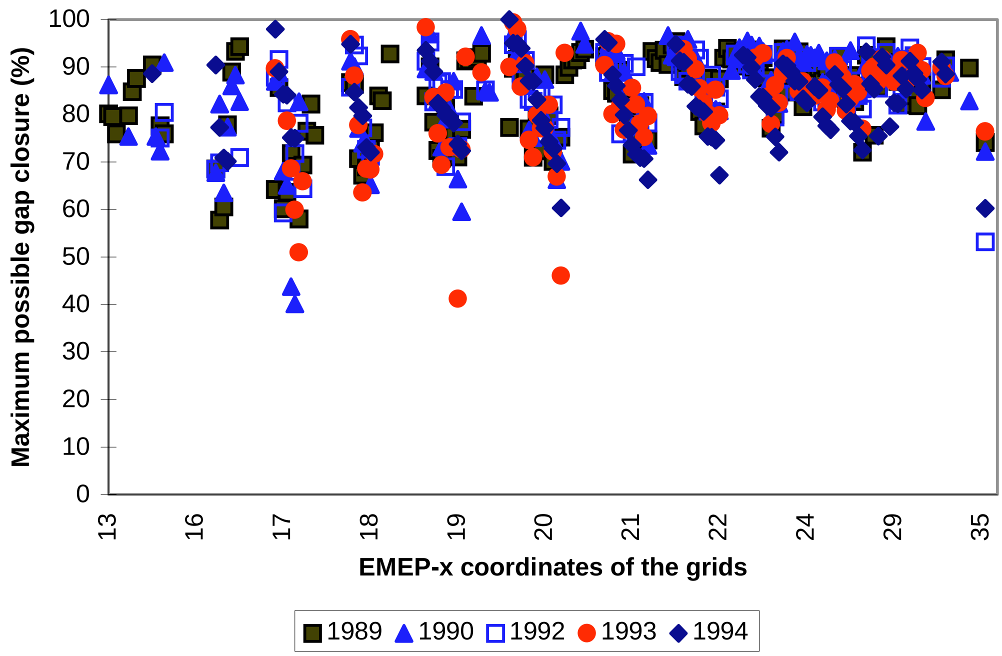

Figure 5.13: Maximum possible gap closure for the EMEP grids for the different meteorological conditions

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 an (interim step) 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 becomes 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 5.14 displays for each grid the year for which the target has been excluded.

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

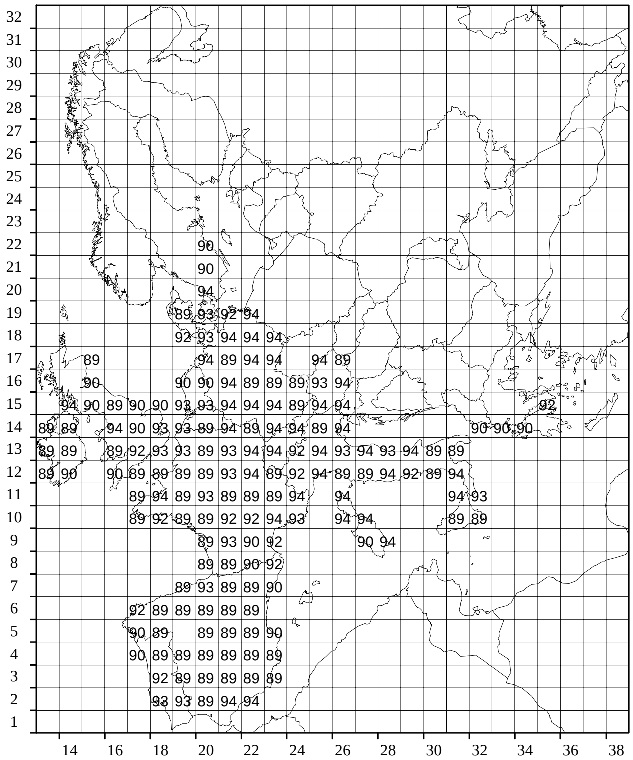

Figure 5.14: Year with the lowest gap closure of the maximum feasible emission reductions. These grid-year combinations have been excluded from the optimization

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 to accurately 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 is on 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.hours 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 already in 1990 the AOT60 was relatively low (one ppm.hours, 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 they could not drive the optimization. Of course, measures targeted at the remaining receptors in these countries will also improve the situation at these sites.

The RAINS ozone optimization module was used to identify three alternative interim gap closure targets: a 45 percent, a 50 percent and a 55 percent gap closure. Figure 5.15 identifies the grids for which the gap closure achieved by the Reference scenario is less than the targets set for the optimization. For these grids the optimization forces an improvement of the situation, or put in other words, the optimization is driven by the required improvements for these grids only..

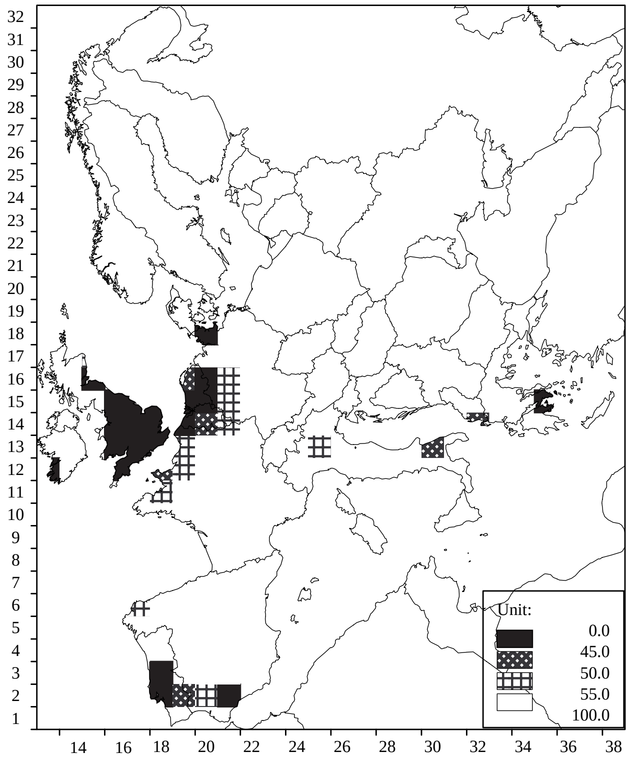

Figure 5.15: Gap closures achieved by the Reference scenario (in percent of the 1990 gap). The graph indicates that setting a gap closure target of 45 percent forces an environmental improvement only in the fully filled grid cells. If the gap closure target is increased to 50 and 55 percent, additional grids in other countries enter the optimization.

5.3.3 Main Assumptions for the Optimization Analysis

Before interpreting the results of the optimization analysis it might be useful to briefly review the main exogenous assumptions made for the scenarios:

- under no circumstances may emissions exceed those of the Reference scenario described in Section 4.3;
- energy consumption will follow the Conventional Wisdom scenario (see Section 3.1);
- agricultural activities develop along the lines described in Section 3.2;
- measures discussed within the Auto/Oil 2 programme are excluded from the analysis (see also Section 4.4).

These assumptions are maintained throughout this paper, except for the sensitivity analysis carried out in Section 5.3.7, which explores the potential role of Auto/Oil 2 measures.

5.3.4 Scenario C1: 50 Percent Gap Closure for AOT60

Scenario C1 establishes 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 C1/1 to C1/5). As discussed before, 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 C1/C). This means that this 'composite' optimization identified the least-cost set of measures which will achieve all specified environmental targets (i.e., the 50 percent gap closure of AOT60 in four out of five years).

Table 5.3 to Table 5.5 compare emission reductions of NO_x, VOC and the emission control costs for the 50 percent gap closure scenarios. It is interesting to note that reducing the AOT60 puts main pressure on VOC emissions. Compared to the level of the REF scenario (7546 kt VOC), the optimization suggests for the individual meteorological conditions a range between 5905 kt for 1989 and 6802 kt in 1993. Compared with the minimum emissions over all countries (5665 kt), the composite optimization for all years results in 5776 kt, while achieving the same environmental targets. The reductions for NO_x emissions are much smaller: compared to the level of 6915 kt of the REF scenario, the 1994 optimization results in 6697 kt, while the 1990 meteorology yields 6859 kt. The cumulative minimum emissions are 6590, while the composite optimization suggest only two-thirds of the reduction (at 6705 kt). Emission control costs (on top of REF) range between 1773 in 1993 and 3287 million ECU/year for the 1989 meteorology. As a result of the composite optimization costs are 15 percent lower (3405 million ECU/year) than the cumulative maximum over all countries (4003 million ECU/year).

Figure 5.16 displays the 'binding' grids for the 50 percent gap closure scenario, 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 percent cap closure scenario binding grid cells occur in the UL, Belgium/Netherlands/Germany, Portugal, Italy and Greece.

Looking at the measures of individual countries, it is interesting to note that for NO_x emissions only Belgium, France, Ireland and Portugal would take action, depending on the meteorological conditions (Figure 5.17). While for France and Portugal the composite optimization results at the maximum NO_x reduction spanned by the solutions for the individual years, for Ireland the composite ends at the lowest point, and for Belgium in the middle of the range. For VOC (Figure 5.18) all countries except Austria, Italy, Denmark, Sweden and Finland would take action at least in one year. The composite optimization ends typically close to the lowest emissions spanned by the individual years.

Table 5.3: NO_x emissions for a 50 percent gap closure scenario for AOT60 (Scenario C1)

	NO_x emissions (kilotons)								Change compared to 1990							
Meteorology		1989	1990	1992	19.93	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C1/1	C1/2	C1/3	C1/4	C1/5	*1989-94*	C1/C	REF	C1/1	C1/2	C1/3	C1/4	C1/5	*1989-94*	C1/C
Austria	116	116	116	116	116	116	*116*	116	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Belgium	199	199	199	199	161	138	*138*	175	-45%	-45%	-45%	-45%	-56%	-62%	*-62%*	-52%
Denmark	116	116	116	116	116	116	*116*	116	-57%	-57%	-57%	-57%	-57%	-57%	*-57%*	-57%
Finland	163	163	163	163	163	163	*163*	163	-42%	-42%	-42%	-42%	-42%	-42%	*-42%*	-42%
France	895	798	870	860	859	775	*775*	785	-45%	-51%	-46%	-47%	-47%	-52%	*-52%*	-52%
Germany	1289	1289	1289	1282	1289	1252	*1252*	1289	-57%	-57%	-57%	-57%	-57%	-58%	*-58%*	-57%
Greece	282	282	282	282	282	282	*282*	282	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Ireland	74	74	43	74	57	74	*43*	74	-31%	-31%	-60%	-31%	-47%	-31%	*-60%*	-31%
Italy	1113	1113	1113	1113	1113	1113	*1113*	1113	-45%	-45%	-45%	-45%	-45%	-45%	*-45%*	-45%
Luxembourg	10	10	10	10	10	10	*10*	10	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Netherlands	218	218	218	218	218	218	*218*	218	-60%	-60%	-60%	-60%	-60%	-60%	*-60%*	-60%
Portugal	206	130	206	165	137	206	*130*	130	-1%	-38%	-1%	-21%	-34%	-1%	*-38%*	-38%
Spain	843	843	843	843	843	843	*843*	843	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Sweden	205	205	205	205	205	205	*205*	205	-41%	-41%	-41%	-41%	-41%	-41%	*-41%*	-41%
UK	1186	1186	1186	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	-55%	-55%	-55%	*-55%*	-55%
EU-15	6915	6742	6859	6832	6755	6697	*6590*	6705	-48%	-49%	-48%	-48%	-49%	-49%	*-50%*	-49%

Table 5.4: VOC emissions for a 50 percent gap closure scenario for AOT60 (Scenario C1)

	VOC emissions (kilotons)								Change compared to 1990							
Meteorology		1989	1990	1992	1993	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C1/1	C1/2	C1/3	C1/4	C1/5	*1989-94*	C1/C	REF	C1/1	C1/2	C1/3	C1/4	C1/5	*1989-94*	C1/C
Austria	305	305	305	305	305	305	*305*	305	-27%	-27%	-27%	-27%	-27%	-27%	*-27%*	-27%
Belgium	182	109	118	119	182	109	*109*	107	-46%	-68%	-65%	-65%	-46%	-68%	*-68%*	-68%
Denmark	89	89	89	89	89	89	*89*	89	-49%	-49%	-49%	-49%	-49%	-49%	*-49%*	-49%
Finland	108	108	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1381	997	1116	1012	1381	899	*899*	928	-42%	-58%	-53%	-58%	-42%	-62%	*-62%*	-61%
Germany	1361	1058	1084	1082	1135	991	*991*	1010	-56%	-66%	-65%	-65%	-63%	-68%	*-68%*	-67%
Greece	203	203	203	203	203	149	*149*	155	-31%	-31%	-31%	-31%	-31%	-49%	*-49%*	-47%
Ireland	42	42	24	42	39	42	*24*	42	-56%	-56%	-75%	-56%	-59%	-56%	*-75%*	-56%
Italy	1139	1139	1139	1139	1136	1139	*1136*	1139	-38%	-38%	-38%	-38%	-39%	-38%	*-39%*	-38%
Luxembourg	8	8	8	8	8	8	*8*	8	-56%	-56%	-56%	-56%	-56%	-56%	*-56%*	-56%
Netherlands	258	146	150	161	150	149	*146*	144	-45%	-69%	-68%	-65%	-68%	-68%	*-69%*	-69%
Portugal	144	95	144	144	117	144	*95*	95	-27%	-52%	-27%	-27%	-41%	-27%	*-52%*	-52%
Spain	763	502	763	763	763	763	*502*	510	-26%	-52%	-26%	-26%	-26%	-26%	*-52%*	-51%
Sweden	287	287	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	-36%	-36%	*-36%*	-36%
UK	1276	817	837	916	899	1247	*817*	849	-53%	-70%	-69%	-66%	-67%	-54%	*-70%*	-68%
EU-15	7546	5905	6375	6378	6802	6429	*5665*	5776	-48%	-55%	-52%	-52%	-49%	-51%	*-57%*	-56%

Table 5.5: Costs for a 50 percent gap closure scenario for AOT60 (C1), in million ECU/year

Meteorology	Total costs REF	Additional costs on top of REF 1989 C1/1	1990 C1/2	1992 C1/3	1993 C1/4	1994 C1/5	*maximum 1989-94*	composite C1/C
Austria	951	0	0	0	0	0	*0*	0
Belgium	1062	148	103	95	64	331	*331*	198
Denmark	475	0	0	0	0	0	*0*	0
Finland	672	0	0	0	0	0	*0*	0
France	6577	387	196	294	20	563	*563*	496
Germany	10625	437	378	386	293	699	*699*	578
Greece	683	0	0	0	0	48	*48*	36
Ireland	485	0	44	0	7	0	*44*	0
Italy	7380	0	0	0	3	0	*3*	0
Luxembourg	74	0	0	0	0	0	*0*	0
Netherlands	2011	177	162	123	161	165	*177*	189
Portugal	1032	372	0	18	170	0	*372*	372
Spain	4115	200	0	0	0	0	*200*	191
Sweden	1257	0	0	0	0	0	*0*	0
UK	5754	1566	1423	974	1055	49	*1566*	1345
EU-15	43152	3287	2306	1890	1773	1855	*4003*	3405

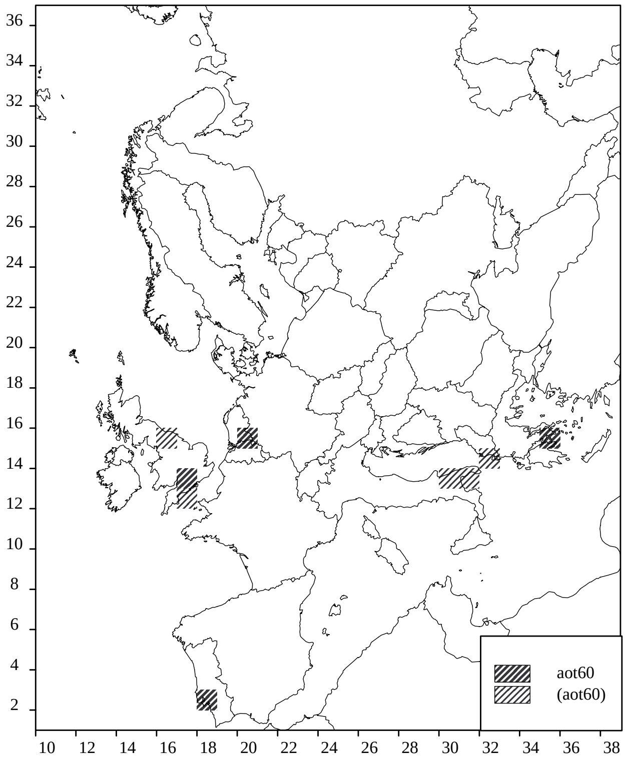

Figure 5.16: Binding grids for the C1/C scenario. The map indicates where the AOT60 after the optimization is exactly at (grids indicated with 'aot60') or is very close to [indicated with '(aot60)'] the target level. At all other grids the optimized AOT60 is below the specified target.

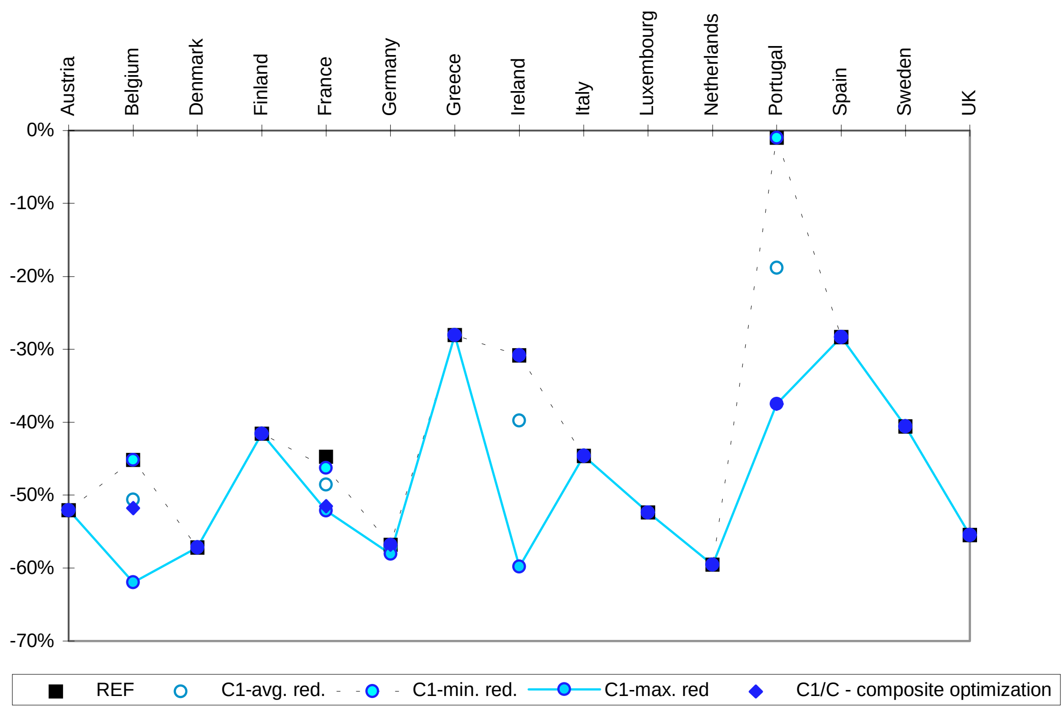

Figure 5.17: NO_x reductions for the 50 percent gap closure scenarios for the AOT60 (Scenarios C1), compared to 1990

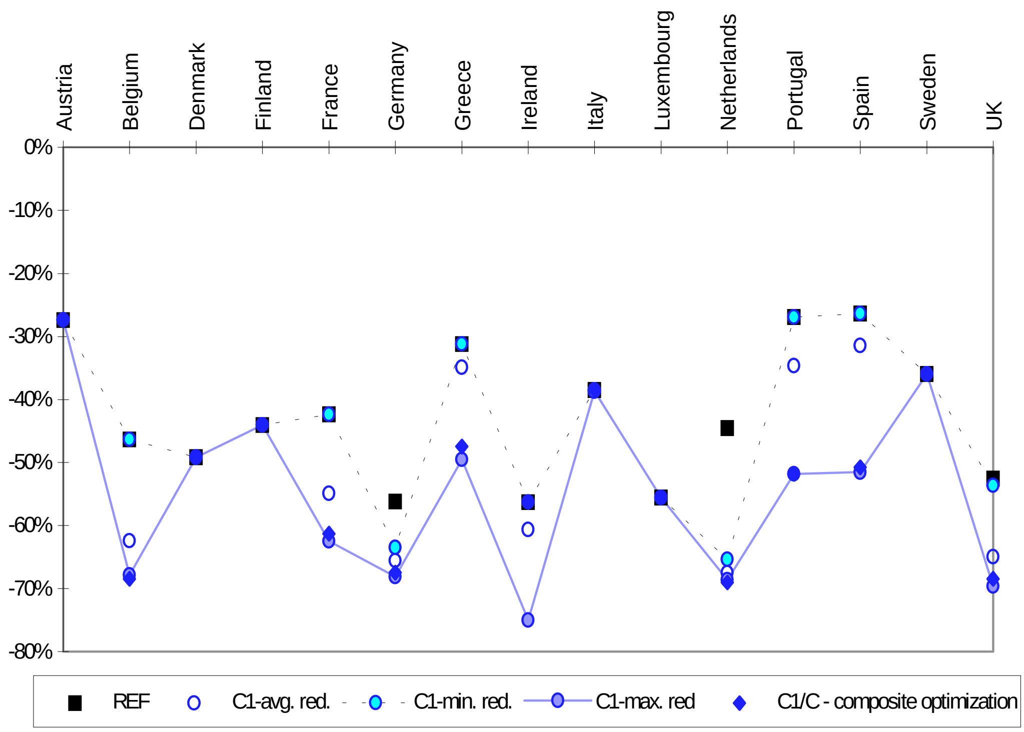

Figure 5.18: VOC reductions for the 50 percent gap closure scenarios for the AOT60 (Scenarios C1), compared to 1990

5.3.5 Scenario C2: 45 Percent Gap Closure for AOT60

For comparison Scenario C2 explores the changes in emission reductions if the gap closure target is set to 45 percent. All other assumptions (four out of five years, exclusion of grids with AOT60 in 1990 below 1 ppm.hours, the REF scenario as the upper bounds for emissions, etc.) are the same as for Scenario C1.

Obviously, a less ambitious environmental target results in less emission reductions (Table 5.7 and Table 5.8). As in scenario C1 there is a strong preference towards further reductions of VOC emissions (-16 percent compared to REF),while NO_x emissions are reduced by two percent only compared to REF. The costs (Table 5.6) are only two thirds of Scenario C1/C.

Table 5.6: Costs for a 45 percent gap closure scenario for AOT60 (C2), in million ECU/year

	Total costs REF	Additional costs on top of REF						
		1989 C2/1	1990 C2/2	1992 C2/3	1993 C2/4	1994 C2/5	*maximum 1989-94*	composite C2/C
Austria	951	0	0	0	0	0	*0*	0
Belgium	1062	109	77	76	46	150	*150*	90
Denmark	475	0	0	0	0	0	*0*	0
Finland	672	0	0	0	0	0	*0*	0
France	6577	177	0	166	5	323	*323*	85
Germany	10625	282	275	275	179	310	*310*	381
Greece	683	0	0	0	0	16	*16*	11
Ireland	485	0	23	0	0	0	*23*	0
Italy	7380	0	0	0	0	0	*0*	0
Luxembourg	74	0	0	0	0	0	*0*	0
Netherlands	2011	138	141	100	124	96	*141*	148
Portugal	1032	275	0	0	81	0	*275*	276
Spain	4115	89	0	0	0	0	*89*	91
Sweden	1257	0	0	0	0	0	*0*	0
UK	5754	1138	1303	725	818	9	*1303*	1189
EU-15	43152	2208	1819	1342	1253	904	*2630*	2271

5.3.6 Scenario C3: 55 Percent Gap Closure for AOT60

To explore the changes in emission control costs for stricter targets than laid down for the C1 scenario, an alternative set of optimizations was performed aiming at a 55 percent gap closure of AOT60. As for C2, all other assumptions (four out of five years, exclusion of grids with AOT60 in 1990 below 1 ppm.hours, the REF scenario as the upper bounds for emissions, etc.) were maintained constant. As a result, costs increase compared to Scenario C1/C by almost 70 percent (Table 5.9 to Table 5.11).

Table 5.7: NO_x emissions for a 45 percent gap closure scenario for AOT40 (Scenario C2)

Meteorology	NO_x emissions (kilotons)								Change compared to 1990							
		1989	1990	1992	19.93	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C2/1	C2/2	C2/3	C2/4	C2/5	*1989-94*	C2/C	REF	C2/1	C2/2	C2/3	C2/4	C2/5	*1989-94*	C2/C
Austria	116	116	116	116	116	116	*116*	116	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Belgium	199	199	199	199	167	158	*158*	199	-45%	-45%	-45%	-45%	-54%	-56%	*-56%*	-45%
Denmark	116	116	116	116	116	116	*116*	116	-57%	-57%	-57%	-57%	-57%	-57%	*-57%*	-57%
Finland	163	163	163	163	163	163	*163*	163	-42%	-42%	-42%	-42%	-42%	-42%	*-42%*	-42%
France	895	816	895	876	884	805	*805*	858	-45%	-50%	-45%	-46%	-45%	-50%	*-50%*	-47%
Germany	1289	1289	1289	1289	1289	1289	*1289*	1289	-57%	-57%	-57%	-57%	-57%	-57%	*-57%*	-57%
Greece	282	282	282	282	282	282	*282*	282	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Ireland	74	74	49	74	74	74	*49*	74	-31%	-31%	-54%	-31%	-31%	-31%	*-54%*	-31%
Italy	1113	1113	1113	1113	1113	1113	*1113*	1113	-45%	-45%	-45%	-45%	-45%	-45%	*-45%*	-45%
Luxembourg	10	10	10	10	10	10	*10*	10	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Netherlands	218	218	218	218	218	218	*218*	218	-60%	-60%	-60%	-60%	-60%	-60%	*-60%*	-60%
Portugal	206	130	206	206	149	206	*130*	130	-1%	-38%	-1%	-1%	-28%	-1%	*-38%*	-38%
Spain	843	843	843	843	843	843	*843*	843	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Sweden	205	205	205	205	205	205	*205*	205	-41%	-41%	-41%	-41%	-41%	-41%	*-41%*	-41%
UK	1186	1186	1186	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	-55%	-55%	-55%	*-55%*	-55%
EU-15	6915	6760	6890	6896	6815	6784	*6683*	6802	-48%	-49%	-48%	-48%	-48%	-49%	*-49%*	-49%

Table 5.8: VOC emissions for a 45 percent gap closure scenario for AOT60 (Scenario C2)

Meteorology	VOC emissions (kilotons)								Change compared to 1990							
		1989	1990	1992	1993	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C2/1	C2/2	C2/3	C2/4	C2/5	*1989-94*	C2/C	REF	C2/1	C2/2	C2/3	C2/4	C2/5	*1989-94*	C2/C
Austria	305	305	305	305	305	305	*305*	305	-27%	-27%	-27%	-27%	-27%	-27%	*-27%*	-27%
Belgium	182	116	124	125	182	124	*116*	121	-46%	-66%	-63%	-63%	-46%	-63%	*-66%*	-64%
Denmark	89	89	89	89	89	89	*89*	89	-49%	-49%	-49%	-49%	-49%	-49%	*-49%*	-49%
Finland	108	108	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1381	1211	1381	1150	1381	1049	*1049*	1281	-42%	-49%	-42%	-52%	-42%	-56%	*-56%*	-47%
Germany	1361	1132	1137	1135	1200	1120	*1120*	1084	-56%	-64%	-63%	-63%	-61%	-64%	*-64%*	-65%
Greece	203	203	203	203	203	172	*172*	178	-31%	-31%	-31%	-31%	-31%	-42%	*-42%*	-40%
Ireland	42	42	30	42	42	42	*30*	42	-56%	-56%	-69%	-56%	-56%	-56%	*-69%*	-56%
Italy	1139	1139	1139	1139	1139	1139	*1139*	1139	-38%	-38%	-38%	-38%	-38%	-38%	*-38%*	-38%
Luxembourg	8	8	8	8	8	8	*8*	8	-56%	-56%	-56%	-56%	-56%	-56%	*-56%*	-56%
Netherlands	258	157	156	171	161	173	*156*	153	-45%	-66%	-66%	-63%	-65%	-63%	*-66%*	-67%
Portugal	144	107	144	144	128	144	*107*	107	-27%	-46%	-27%	-27%	-35%	-27%	*-46%*	-46%
Spain	763	620	763	763	763	763	*620*	617	-26%	-40%	-26%	-26%	-26%	-26%	*-40%*	-40%
Sweden	287	287	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	-36%	-36%	*-36%*	-36%
UK	1276	883	855	975	951	1271	*855*	874	-53%	-67%	-68%	-64%	-65%	-53%	*-68%*	-68%
EU-15	7546	6407	6729	6644	6947	6794	*6161*	6393	-48%	-52%	-49%	-50%	-47%	-49%	*-53%*	-52%

Table 5.9: NO_x emissions for a 55 percent gap closure scenario for AOT60 (Scenario C3)

Meteorology	NO_x emissions (kilotons)								Change compared to 1990							
		1989	1990	1992	19.93	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C3/1	C3/2	C3/3	C3/4	C3/5	*1989-94*	C3/C	REF	C3/1	C3/2	C3/3	C3/4	C3/5	*1989-94*	C3/C
Austria	116	116	116	116	116	116	*116*	116	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Belgium	199	199	199	199	154	126	*126*	136	-45%	-45%	-45%	-45%	-58%	-65%	*-65%*	-63%
Denmark	116	116	116	116	116	116	*116*	116	-57%	-57%	-57%	-57%	-57%	-57%	*-57%*	-57%
Finland	163	163	163	163	163	163	*163*	163	-42%	-42%	-42%	-42%	-42%	-42%	*-42%*	-42%
France	895	774	828	841	836	738	*738*	748	-45%	-52%	-49%	-48%	-48%	-54%	*-54%*	-54%
Germany	1289	1289	1289	1261	1289	1203	*1203*	1240	-57%	-57%	-57%	-58%	-57%	-60%	*-60%*	-58%
Greece	282	282	282	282	282	282	*282*	282	-28%	-28%	-28%	-28%	-28%	-28%	*-28%*	-28%
Ireland	74	74	39	74	48	74	*39*	74	-31%	-31%	-64%	-31%	-55%	-31%	*-64%*	-31%
Italy	1113	1113	1113	1113	1113	1113	*1113*	1113	-45%	-45%	-45%	-45%	-45%	-45%	*-45%*	-45%
Luxembourg	10	10	10	10	10	10	*10*	10	-52%	-52%	-52%	-52%	-52%	-52%	*-52%*	-52%
Netherlands	218	218	218	218	218	187	*187*	218	-60%	-60%	-60%	-60%	-60%	-65%	*-65%*	-60%
Portugal	206	130	206	152	130	206	*130*	130	-1%	-38%	-1%	-27%	-38%	-1%	*-38%*	-38%
Spain	843	611	781	843	843	843	*611*	620	-28%	-48%	-34%	-28%	-28%	-28%	*-48%*	-47%
Sweden	205	205	205	205	205	205	*205*	205	-41%	-41%	-41%	-41%	-41%	-41%	*-41%*	-41%
UK	1186	1186	1186	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	-55%	-55%	-55%	*-55%*	-55%
EU-15	6915	6486	6751	6779	6709	6568	*6225*	6357	-48%	-51%	-49%	-49%	-49%	-50%	*-53%*	-52%

Table 5.10: VOC emissions for a 55 percent gap closure scenario for AOT60 (Scenario C3)

Meteorology	VOC emissions (kilotons)								Change compared to 1990							
		1989	1990	1992	1993	1994	*minimum*	composite		1989	1990	1992	19.93	1994	*maximum*	composite
	REF	C3/1	C3/2	C3/3	C3/4	C3/5	*1989-94*	C3/C	REF	C3/1	C3/2	C3/3	C3/4	C3/5	*1989-94*	C3/C
Austria	305	305	305	305	305	305	*305*	305	-27%	-27%	-27%	-27%	-27%	-27%	*-27%*	-27%
Belgium	182	101	109	113	165	96	*96*	96	-46%	-70%	-68%	-67%	-51%	-72%	*-72%*	-72%
Denmark	89	89	89	89	76	89	*76*	89	-49%	-49%	-49%	-49%	-57%	-49%	*-57%*	-49%
Finland	108	108	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1381	852	923	916	1381	788	*788*	791	-42%	-64%	-61%	-62%	-42%	-67%	*-67%*	-67%
Germany	1361	976	1022	1026	1079	891	*891*	907	-56%	-69%	-67%	-67%	-65%	-71%	*-71%*	-71%
Greece	203	184	194	203	203	129	*129*	135	-31%	-38%	-34%	-31%	-31%	-56%	*-56%*	-54%
Ireland	42	42	18	42	30	42	*18*	42	-56%	-56%	-81%	-56%	-69%	-56%	*-81%*	-56%
Italy	1139	1139	1139	1139	1065	1090	*1065*	1082	-38%	-38%	-38%	-38%	-42%	-41%	*-42%*	-42%
Luxembourg	8	8	8	8	8	8	*8*	8	-56%	-56%	-56%	-56%	-56%	-56%	*-56%*	-56%
Netherlands	258	135	143	152	140	131	*131*	130	-45%	-71%	-69%	-67%	-70%	-72%	*-72%*	-72%
Portugal	144	95	144	132	111	144	*95*	95	-27%	-52%	-27%	-33%	-44%	-27%	*-52%*	-52%
Spain	763	370	763	763	675	763	*370*	375	-26%	-64%	-26%	-26%	-35%	-26%	*-64%*	-64%
Sweden	287	287	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	-36%	-36%	*-36%*	-36%
UK	1276	748	818	854	843	1111	*748*	792	-53%	-72%	-70%	-68%	-69%	-59%	*-72%*	-71%
EU-15	7546	5439	6070	6137	6476	5982	*5115*	5242	-48%	-59%	-54%	-54%	-51%	-55%	*-61%*	-60%

Table 5.11: Costs for a 55 percent gap closure scenario for AOT60 (C3), in million ECU/year

Meteorology	Total costs REF	Additional costs (on top of REF) 1989 C3/1	1990 C3/2	1992 C3/3	1993 C3/4	1994 C3/5	*maximum 1989-94*	composite C3/C
Austria	951	0	0	0	0	0	*0*	0
Belgium	1062	222	146	124	98	634	*634*	484
Denmark	475	0	0	0	8	0	*8*	0
Finland	672	0	0	0	0	0	*0*	0
France	6577	638	421	417	41	949	*949*	880
Germany	10625	694	535	555	429	1359	*1359*	1120
Greece	683	8	3	0	0	118	*118*	91
Ireland	485	0	78	0	24	0	*78*	0
Italy	7380	0	0	0	64	42	*64*	49
Luxembourg	74	0	0	0	0	0	*0*	0
Netherlands	2011	238	192	155	207	394	*394*	276
Portugal	1032	372	0	63	248	0	*372*	372
Spain	4115	734	27	0	52	0	*734*	692
Sweden	1257	0	0	0	0	0	*0*	0
UK	5754	2230	1561	1310	1383	324	*2230*	1773
EU-15	43152	5136	2963	2624	2554	3820	*6940*	5737

Figure 5.19 visualizes the emission reductions of the AOT60-related gap closure scenarios beyond those of the REF scenario and illustrates the preference for further VOC reductions. Only Portugal and, with increasing stringency of the environmental target Spain, France and Germany, embark on additional measures to control NO_x emissions. This strong priority for VOC is partially caused by sometimes lower marginal costs for further VOC measures after the implementation of the Reference scenario, but mainly by the atmospheric chemistry responsible for the reduction of the higher ozone concentrations.

Table 5.12 lists the population exposure indices of the three AOT60 gap closure scenarios using the five-year mean meteorology. For the EU-15, the gap closure scenarios achieve a reduction of the cumulative exposure index in a range from 22 to 41 percent compared to the Reference scenario. Figure 5.20 compares the costs of the three gap closure scenarios against the improvements in the cumulative population exposure index.

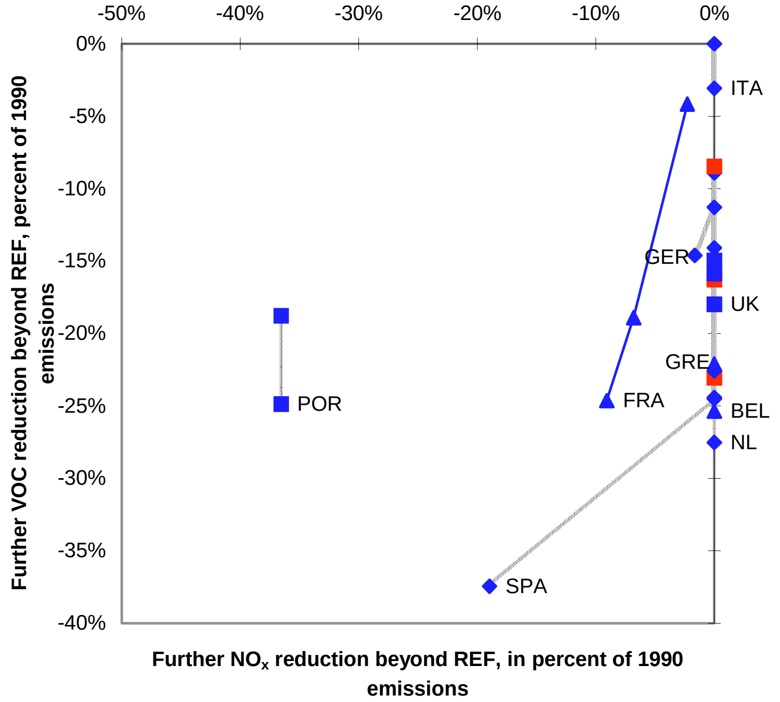

Figure 5.19: Further NO_x and VOC reductions (beyond the REF scenario) for theAOT60 gap closure scenarios (C1/C, C2/C and C3/C), in percent of the 1990 emissions

Table 5.12: Population exposure indices for the AOT60 gap closure scenario

Gap closure Scenario	Cumulative population exposure index (million person.ppm.hours) REF	45% C2/C	50% C1/C	55% C3/C	MFR	Average population exposure index (ppm.hours) REF	45% C2/C	50% C1/C	55% C3/C	MFR
Austria	5	4	4	3	2	0.6	0.5	0.4	0.4	0.3
Belgium	37	30	26	23	19	3.5	2.7	2.4	2.1	1.8
Denmark	3	2	2	2	1	0.7	0.5	0.5	0.4	0.3
Finland	0	0	0	0	0	0.1	0.0	0.0	0.0	0.0
France	108	84	69	57	44	1.8	1.4	1.2	1.0	0.8
Germany	140	115	102	92	73	1.9	1.6	1.4	1.3	1.0
Greece	4	3	3	3	2	0.3	0.3	0.3	0.2	0.2
Ireland	2	1	1	1	0	0.3	0.2	0.2	0.2	0.1
Italy	62	58	55	51	19	1.1	1.1	1.0	0.9	0.4
Luxembourg	1	1	1	1	1	3.2	2.7	2.4	2.1	1.7
Netherlands	43	34	30	27	22	2.8	2.2	1.9	1.7	1.4
Portugal	9	6	5	4	4	0.9	0.6	0.5	0.5	0.4
Spain	13	9	7	4	3	0.3	0.2	0.2	0.1	0.1
Sweden	2	1	1	1	1	0.2	0.1	0.1	0.1	0.1
UK	80	52	45	39	31	1.4	0.9	0.8	0.7	0.6
EU-15	367	286	249	215	150	1.3	1.0	0.9	0.7	0.5

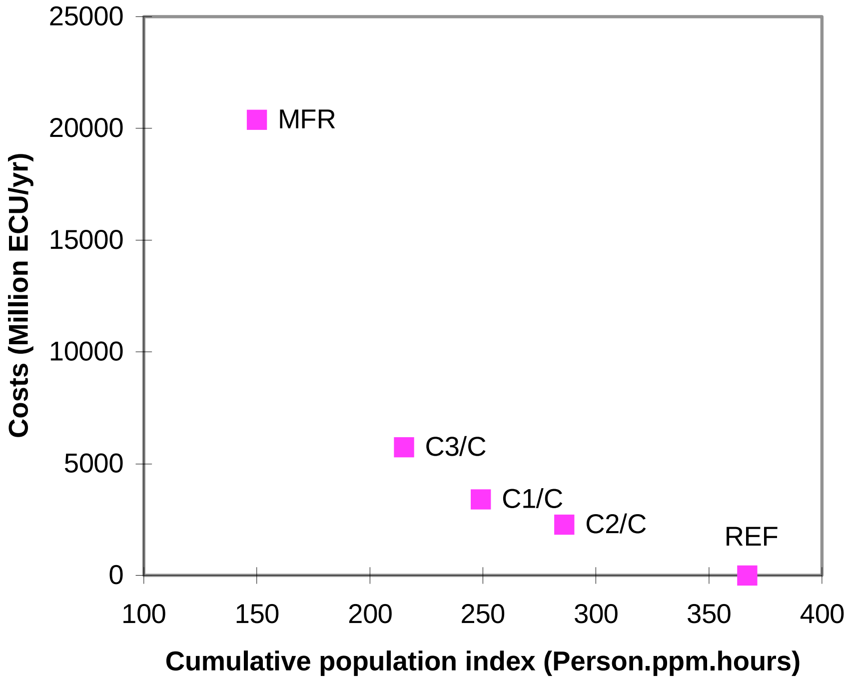

Figure 5.20: Cost-effectiveness of the gap closure scenarios for the AOT60

5.3.7 Gap Closure Scenarios for the AOT60 Assuming the Implementation of the Measures Discussed under Auto/Oil 2

For the reasons discussed in the Methodology Section, the cost curves used for the scenarios above exclude the emission reduction potential of the measures currently discussed under the Auto/Oil 2 programme. Consequently, the Scenarios C1 to C3 optimize only for stationary sources and keep the emissions from mobile sources at the level resulting from the implementation of the Auto/Oil 1 programme.

Obviously, this exclusion of further measures in the transport sector is a serious limitation for a comprehensive ozone control strategy. Work is underway to overcome this problem and to include also further measures for the transport sector into the optimization analysis. It is expected that it will be possible to address this issue in full detail in the next Interim Report.

In the meantime a sensitivity analysis was carried out to determine - in the absence of accepted cost estimates for the Auto/Oil 2 measures - the potential scope for further measures in the transport sector within the overall context of an ozone strategy. To this end the optimization runs for the AOT60 were repeated with the assumption that the Auto/Oil 2 measures would be implemented - independent from the ozone strategy. Consequently, the optimization identifies the possible scope for reactions of stationary sources to further reductions of the emissions from mobile sources, while keeping the environmental targets constant.

The sensitivity analysis explored two cases:

- Optimizing the 50 percent gap closure scenario (C1/C) with further measures in the transport sector identifies for a 'realistic scenario' a relaxation of measures at stationary sources and the possible cost-savings at these sources. Later on, these costs could be compared with the additional costs involved by the Auto/Oil 2 measures (Scenario C4).
- Revisiting the 55 percent gap closure scenario (C3/C) checks the implications of stricter emission control in the transport sector in a situation of stringent environmental targets, where in the absence of such measures sometimes rather expensive measures for stationary sources would be necessary (Scenario C5).

The results of the analysis are presented in Table 5.13 and Table 5.14. It is important to note that adoption of the Auto/Oil 2 measures would cause expected emission levels of the current legislation (CLE) scenario to be lower, and subsequently also the maximum feasible reductions (for the stationary sources). For Scenario C4 (50 percent gap closure with Auto/Oil 2) the resulting NO_x emissions would be eight percent lower than without the measures in the transport sector, although starting from a lower level of the REF scenario. In contrast to this, overall VOC emissions would be five percent higher than without the Auto/Oil 2 measures. Stationary sources would reduce their NO_x abatement by 28 percent and their VOC reductions by 25 percent. For stationary sources, the costs would be about 750 million ECU/year or 22 percent lower than in Scenario C1/C (Table 5.15). As to be expected, the cost saving effect of further measures in the transport sector becomes more pronounced with more stringent environmental targets. For the 55 percent gap closure scenario, stationary sources would reduce costs by 1.7 billion ECU/year (31 percent).

Table 5.13: NO_x emissions for REF, MFR and for the optimized 50% gap closure scenarios for AOT60, assuming the implementation of the measures discussed within the Auto/Oil 2 programme

	NO_x emissions (kilotons)					Change compared to 1990				
	REF (AO2)	50% gap closure C4	55% gap closure C5	MFR (AO2)	C1/C	REF (AO2)	50% gap closure C4	55% gap closure C5	MFR AO2	C1/C
Austria	100	100	100	82	116	-59%	-59%	-59%	-66%	-52%
Belgium	183	173	148	107	175	-50%	-52%	-59%	-71%	-52%
Denmark	109	109	109	77	116	-60%	-60%	-60%	-72%	-57%
Finland	152	152	152	82	163	-46%	-46%	-46%	-71%	-42%
France	772	725	654	572	785	-52%	-55%	-60%	-65%	-52%
Germany	1135	1135	1135	902	1289	-62%	-62%	-62%	-70%	-57%
Greece	274	274	274	196	282	-30%	-30%	-30%	-50%	-28%
Ireland	71	59	71	28	74	-34%	-45%	-34%	-74%	-31%
Italy	1033	1033	1033	657	1113	-49%	-49%	-49%	-67%	-45%
Luxembourg	9	9	9	6	10	-57%	-57%	-57%	-71%	-52%
Netherlands	194	194	194	132	218	-64%	-64%	-64%	-76%	-60%
Portugal	197	121	121	121	130	-5%	-42%	-42%	-42%	-38%
Spain	801	794	694	500	843	-32%	-32%	-41%	-57%	-28%
Sweden	189	189	189	137	205	-45%	-45%	-45%	-60%	-41%
UK	1102	1102	1102	580	1186	-59%	-59%	-59%	-78%	-55%
EU-15	6321	6169	5985	4179	6705	-52%	-53%	-55%	-68%	-49%

Table 5.14: VOC emissions for REF, MFR and for the optimized 50% gap closure scenarios for AOT60, assuming the implementation of the measures discussed within the Auto/Oil 2 programme

	VOC emissions (kilotons)					Change compared to 1990				
	REF (AO2)	50% gap closure C4	55% gap closure C5	MFR (AO2)	C1/C	REF (AO2)	50% gap closure C4	55% gap closure C5	MFR AO2	C1/C
Austria	305	305	305	241	305	-27%	-27%	-27%	-43%	-27%
Belgium	177	114	100	85	107	-48%	-66%	-71%	-75%	-68%
Denmark	87	87	87	55	89	-50%	-50%	-50%	-69%	-49%
Finland	108	108	108	63	108	-44%	-44%	-44%	-67%	-44%
France	1351	1176	881	586	928	-44%	-51%	-63%	-76%	-61%
Germany	1326	1040	963	737	1010	-57%	-67%	-69%	-76%	-67%
Greece	194	157	134	101	155	-34%	-47%	-55%	-66%	-47%
Ireland	40	40	40	9	42	-58%	-58%	-58%	-91%	-56%
Italy	1080	1080	1073	523	1139	-42%	-42%	-42%	-72%	-38%
Luxembourg	8	8	8	3	8	-56%	-56%	-56%	-83%	-56%
Netherlands	254	147	136	118	144	-45%	-68%	-71%	-75%	-69%
Portugal	144	100	92	92	95	-27%	-49%	-53%	-53%	-52%
Spain	740	562	449	271	510	-29%	-46%	-57%	-74%	-51%
Sweden	287	287	287	261	287	-36%	-36%	-36%	-42%	-36%
UK	1276	829	795	726	849	-53%	-69%	-70%	-73%	-68%
EU-15	7377	6040	5458	3871	5776	-46%	-56%	-60%	-72%	-58%

Table 5.15: Emission control costs for AOT60-related scenarios (for non-mobile sources) assuming the implementation of the measures of Auto/Oil 2 (AO2). Note that these cost estimates exclude the costs for the Auto/Oil 2 measures.

	Total costs	Additional costs on top of REF		
	REF (AO2)	50% gap closure C4	55% gap closure C5	MFR (AO2)
Austria	949	0	0	435
Belgium	1084	107	240	788
Denmark	515	0	0	271
Finland	704	0	0	394
France	6578	145	539	3163
Germany	10625	402	615	3992
Greece	683	20	60	495
Ireland	691	3	0	218
Italy	7381	0	6	3462
Luxembourg	87	0	0	30
Netherlands	2808	153	206	933
Portugal	1028	309	376	376
Spain	4206	119	299	1554
Sweden	1241	0	0	414
UK	5711	1387	1630	3942
EU-15	44291	2647	3973	20469

6. Ground-level Ozone: AOT40

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

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

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

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

6.1 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 6.1 displays the excess AOT40 (over the critical level of 3 ppm.hours) calculated for the emissions of the year 1990 using the five years mean meteorology. The map clearly shows that in most countries of the EU-15 the AOT60 was exceeded. The only exceptions are the 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 important to note that ozone levels in many areas, which do not experience significant excess of the AOT60, exceed the AOT40 criterion significantly. This applies particularly to the Mediterranean countries and some Alpine regions.

The emission reductions of the Reference scenario will generally lead to a decline of the excess AOT40, but will not significantly increase the protected area (Figure 6.2). The maximum feasible emission reductions are expected to achieve a 50 percent and higher cut of the excess AOT40 in most regions (Figure 6.3).

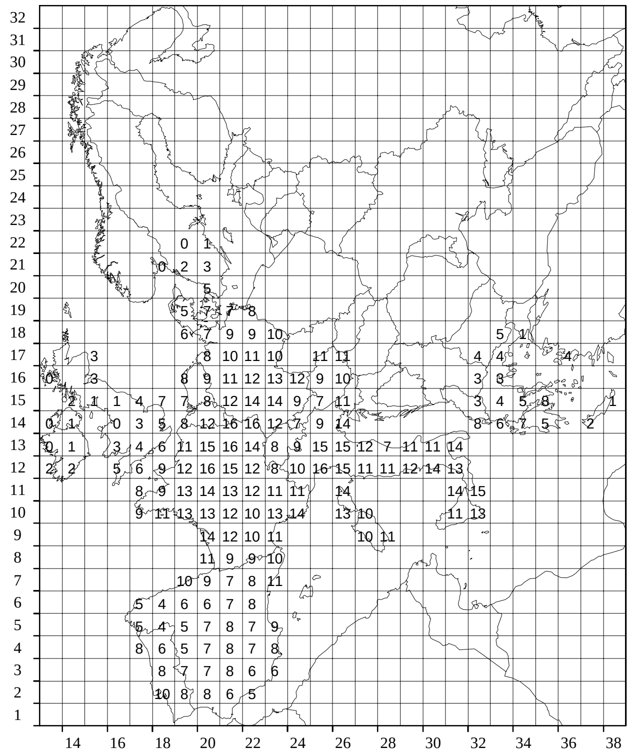

Figure 6.1: Excess AOT40 above the critical level of 3 ppm.hours for the year 1990 (using five years mean meteorology), in ppm.hours. Land area left blank had no excess in 1990 (or does not belong to the EU).

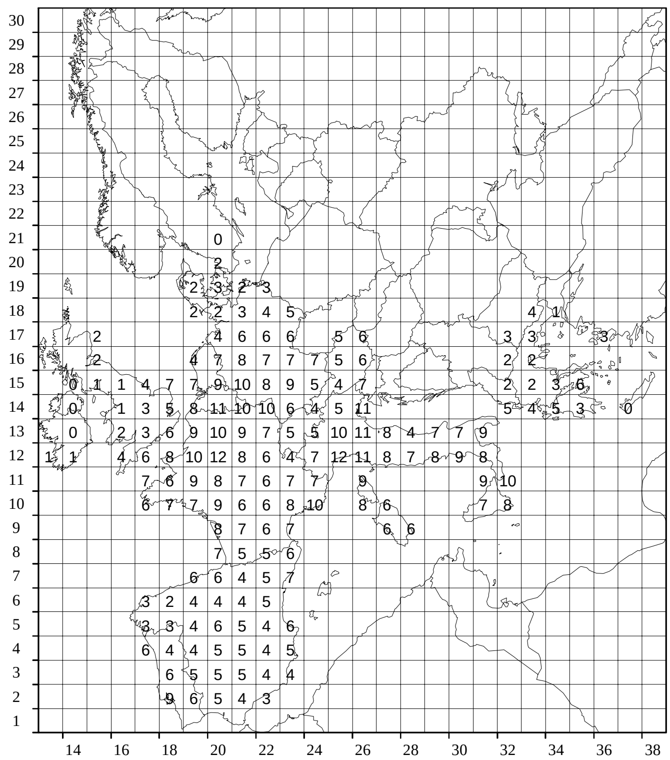

Figure 6.2: Excess AOT40 above the critical level of 3 ppm.hours for the Reference scenario in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario.

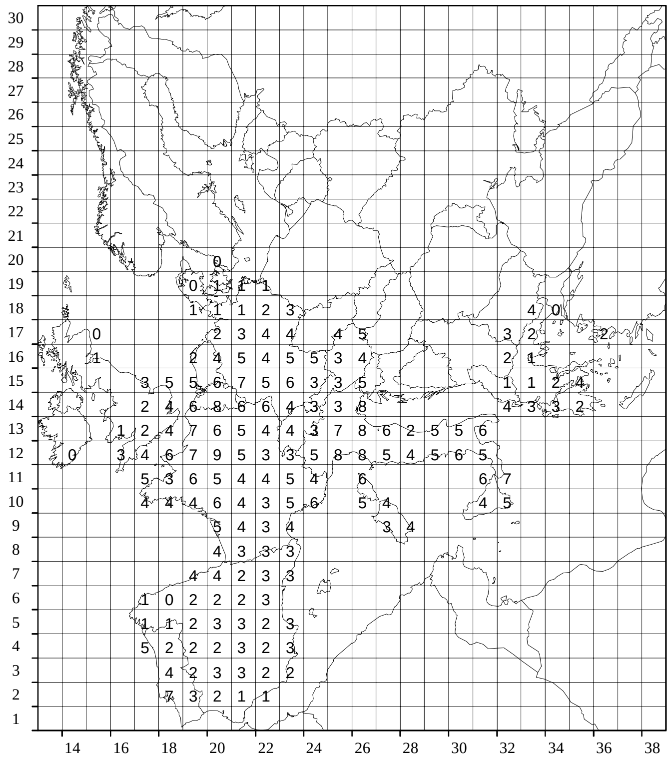

Figure 6.3: Excess AOT40 above the critical level of 3 ppm.hours for the maximum feasible emission reductions in 2010 (using five years mean meteorology), in ppm.hours. Areas left blank had no excess in this scenario.

Table 6.1: Vegetation exposure indices for 1990, the Reference Scenario in 2010 and the maximum feasible emission reductions

	Cumulative vegetation exposure index (million hectares.excess ppm.hours)			Average vegetation exposure index (excess ppm.hours)		
	1990	REF	MFR	1990	REF	MFR
Austria	48	27	19	9.4	5.2	3.7
Belgium	18	15	11	11.3	9.8	6.9
Denmark	14	5	2	4.7	1.8	0.6
Finland	0	0	0	0.0	0.0	0.0
France	405	252	158	12.5	7.8	4.9
Germany	235	132	82	11.1	6.2	3.9
Greece	24	15	11	4.4	2.8	2.0
Ireland	2	1	0	1.0	0.4	0.0
Italy	181	122	82	11.5	7.7	5.2
Luxembourg	2	1	1	15.9	10.0	6.4
Netherlands	10	9	6	8.0	6.6	4.4
Portugal	37	29	17	6.4	4.9	3.0
Spain	203	134	65	6.6	4.4	2.1
Sweden	13	2	0	0.4	0.1	0.0
UK	21	20	11	2.6	2.4	1.4
EU-15	980	632	384	5.9	3.8	2.3

Table 6.1 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, while, for instance, the UK had a significantly lower value. Per ecosystem, the highest exposure was experienced in France, Luxembourg, Belgium, Germany and Italy. The current reduction measures are expected to decrease the indices for the EU-15 by 35 percent, which is significantly lower than the expected decline of the health-related exposure indices (- 55 percent). While areas with already low indices achieve a 60 - 85 percent reduction (Ireland, Sweden, etc.), the expected improvement in Belgium, the Netherlands and the UK ranges only between five and 15 percent. Again, as for the AOT60 this low improvement is caused by the features of the ozone chemistry in high-NO_x regions. The maximum feasible reductions would overcome these effects and lead to a 60 percent reduction for the EU-15 as a whole.

6.2 Optimized Scenarios for the AOT40

Keeping in mind the possible scope for improvement, the selection of an appropriate (interim) 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 Reference 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 with already lower excess ozone.

Similar situations have occurred for other environmental problems, such as acidification and the AOT60. In both cases the use of a gap-closure principle, i.e., establishing a relative measure for the excess exposure, offered useful solutions.

Figure 6.4 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 REF 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 REF scenario, i.e., where the excess AOT40 of the REF 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, as discussed before. 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 15-20 percent. Unfortunately, these grids show the high(est) ozone and should, therefore, not be eliminated from the improvement strategy. This means that a conventional ‘uniform’ gap closure target, as applied for acidification and the AOT60, would be limited to, realistically, 15 percent. On the other hand, the graph also clearly shows that for about 90 percent of the grid cells the

REF scenario will result in more than a 15 percent improvement, so that such a gap closure target would not force wide-spread environmental improvement over the region of the EU-15.

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 than in other countries.
- Alternatively, the gap could be defined as the difference between, e.g., the 1990 situation (or the REF 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 be always 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 one of the most uncertain model elements as one of the major driving forces 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 percent in relation to 1990), but in relation, e.g., to the Reference scenario, which reflects much of the different characteristics of ozone formation. As shown in Figure 6.4 the REF scenario achieves gap closures between -30 and +100 percent. For most grids there is the possibility for an additional 20-30 percent improvement on top of the REF scenario. A practical target could, e.g., aim at increasing the gap closure by 10 percentage points compared to the REF 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 interim target for the ozone strategy is a political decision. Without prejudging such a decision, the analysis adopted the last principle to provide some illustrative results for AOT40-related optimization scenarios. Arbitrarily, a 10 percent improvement has been selected for the illustrative scenarios. Furthermore, for areas with very low (or even negative) gap closures of the REF scenario (where much more than a 10 percent improvement is achievable by the maximum feasible emission reductions), a minimum 15 percent gap closure (related to 1990) has been specified as an additional criterion. The selected target gap closure is indicated in Figure 6.4 by the black line.

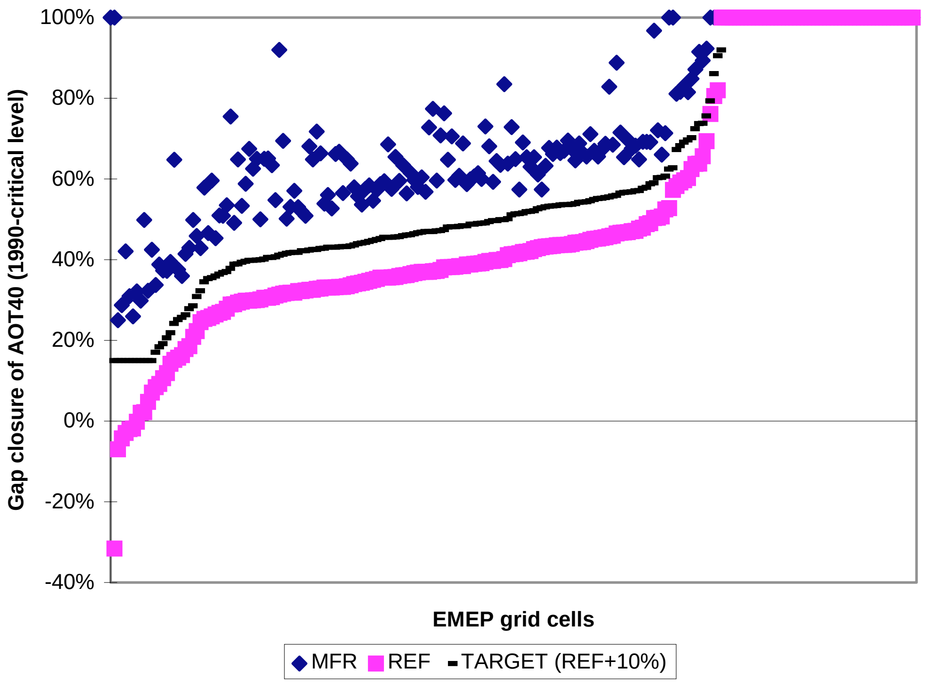

Figure 6.4: The possible gap closure of AOT40 (on the y-axis) for the EMEP grids (along the x-axis, ordered according to their gap closure of the REF scenario). The maximum possible gap closure is essentially determined by the maximum feasible emission reductions (MFR). Meaningful targets for the optimization should lie between the gap closure achieved by the Reference (REF) scenario and the MFR. TARGET indicates the illustrative choice made for this analysis.

Furthermore, in order to analyze the diminishing return for increasingly stringent environmental targets, an attempt was made to formulate two alternative sets of targets. Instead of modifying the required percentage point improvement (on top of REF) from 10 percent to perhaps eight or 12 percent, the 10 percent target was interpreted once in a strict sense and alternatively in a more relaxed context. In practice, the strict target (Scenario C8) requires everywhere an improvement of <u>at least</u> 10 percent on top of REF, while the relaxed interpretation (Scenario C7) aims for an <u>average</u> improvement of 10 percent, allowing grids where it is most expensive to reduce ozone by only nine percent, if compensated by additional reductions at other sites.

6.2.1 Scenarios C7 and C8: Improving the AOT40 Gap Closure Achieved by the REF scenario by 10 Percent

Table 6.2 to Table 6.4 present emission reductions and control costs for the two AOT40-related gap closure scenarios. Although comparable in terms of overall costs, there are much more NO_x reductions than for the AOT60-related scenarios, while the total VOC for all EU-15 countries are in a similar range. Most interesting, however, are the country-wise differences in costs. Comparing Scenario C7 and C1/C (the costs of the AOT40-related Scenario C7 are four percent higher than the AOT60 scenario), the AOT40 scenario suggests more expensive measures in Austria, Germany, France, the Netherlands and Greece, while Belgium, Spain, Portugal and the UK end up with less expensive measures. For the UK, the costs of the AOT40 scenario are 80 percent lower than those of the AOT60. One important reason for these differences is the different nature of the gap closure target (the AOT40 scenario aimed at further improvement (beyond REF) everywhere, while the AOT60 gap closure target is already partly achieved by the Reference scenario); another reason is the different ozone regime contributing to the AOT40 index.

Figure 6.6 and Figure 6.7 illustrate the NO_x and VOC reductions, respectively, implied by the AOT40 scenarios and compares them with the AOT60 gap closure scenario. Figure 6.8 demonstrates the larger role of NO_x reductions for reducing the AOT40.

Table 6.5 presents the vegetation exposure indices for the scenarios. Compared to REF, Scenario C7 achieves a 19 percent decline of the vegetation index. The further measures of Scenario C8 extend this decline to 21 percent. Largest improvements occur for Ireland and Sweden, where significant parts of their ecosystems will achieve the critical levels.

Finally, Figure 6.9 assesses the cost-effectiveness of the AOT40 scenarios, using the cumulative vegetation exposure index.

Table 6.2: NO_x emissions for the AOT40-related gap closure scenarios

	NO_x emissions (kilotons)			Change compared to 1990		
	REF	Gap closure REF + 10% avg. C7	Gap closure REF + 10% min. C8	REF	Gap closure REF + 10% avg. C7	Gap closure REF + 10% min. C8
Austria	116	98	98	-52%	-60%	-60%
Belgium	199	199	199	-45%	-45%	-45%
Denmark	116	110	106	-57%	-59%	-61%
Finland	163	163	163	-42%	-42%	-42%
France	895	785	772	-45%	-52%	-52%
Germany	1289	1185	1174	-57%	-60%	-61%
Greece	282	249	251	-28%	-36%	-36%
Ireland	74	74	74	-31%	-31%	-31%
Italy	1113	945	882	-45%	-53%	-56%
Luxembourg	10	10	10	-52%	-52%	-52%
Netherlands	218	218	218	-60%	-60%	-60%
Portugal	206	135	130	-1%	-35%	-38%
Spain	843	813	803	-28%	-31%	-32%
Sweden	205	205	205	-41%	-41%	-41%
UK	1186	1186	1186	-55%	-55%	-55%
EU-15	6915	6375	6271	-48%	-52%	-53%

Table 6.3: VOC emissions for the AOT40-related gap closure scenarios

	NO_x emissions (kilotons)			Change compared to 1990		
	REF	Gap closure REF + 10% avg. C7	Gap closure REF + 10% min. C8	REF	Gap closure REF + 10% avg. C7	Gap closure REF + 10% min. C8
Austria	305	256	247	-27%	-39%	-41%
Belgium	182	132	153	-46%	-61%	-55%
Denmark	89	78	75	-49%	-55%	-57%
Finland	108	108	108	-44%	-44%	-44%
France	1381	853	818	-42%	-64%	-66%
Germany	1361	944	913	-56%	-70%	-71%
Greece	203	160	156	-31%	-46%	-47%
Ireland	42	42	42	-56%	-56%	-56%
Italy	1139	862	774	-38%	-53%	-58%
Luxembourg	8	8	8	-56%	-56%	-56%
Netherlands	258	137	138	-45%	-71%	-70%
Portugal	144	106	105	-27%	-46%	-47%
Spain	763	604	599	-26%	-42%	-42%
Sweden	287	287	287	-36%	-36%	-36%
UK	1276	1140	1155	-53%	-58%	-57%
EU-15	7546	5717	5578	-45%	-58%	-59%

Table 6.4: Emission control costs for the AOT40-related scenarios C7 and C8 (million ECU/year)

	Total costs	Additional costs on top of REF	
	REF	Gap closure REF + 10% avg. C7	Gap closure REF + 10% min. C8
Austria	951	308	411
Belgium	1062	54	20
Denmark	475	13	22
Finland	672	0	0
France	6577	605	709
Germany	10625	1098	1362
Greece	683	62	66
Ireland	485	0	0
Italy	7380	565	944
Luxembourg	74	0	0
Netherlands	2011	226	221
Portugal	1032	248	288
Spain	4115	113	122
Sweden	1257	0	0
UK	5754	256	224
EU-15	43152	3548	4389

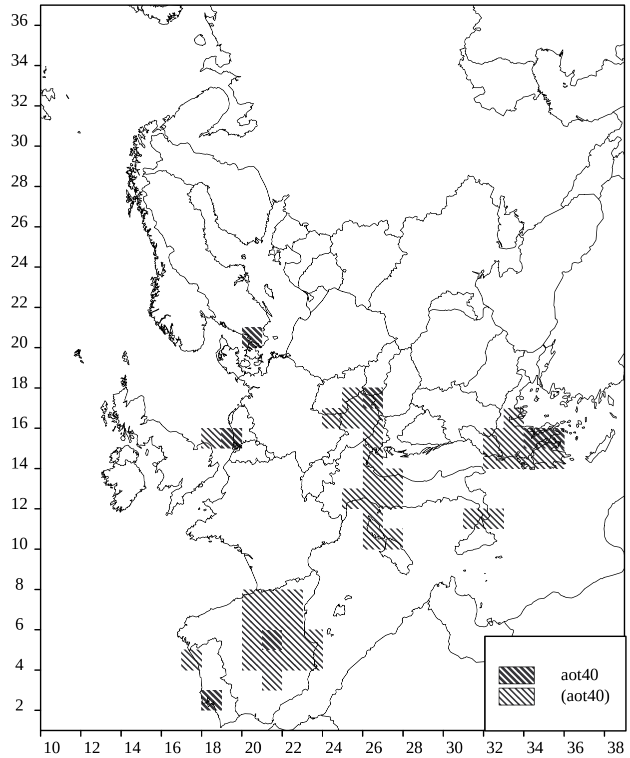

Figure 6.5: Binding grids for the C7 scenario. The map indicates where the AOT40 after the optimization is exactly at (grids indicated with 'aot40') or very close to [indicated with '(aot40)'] the target level. At all other grids the optimized AOT40 level is below the specified target.

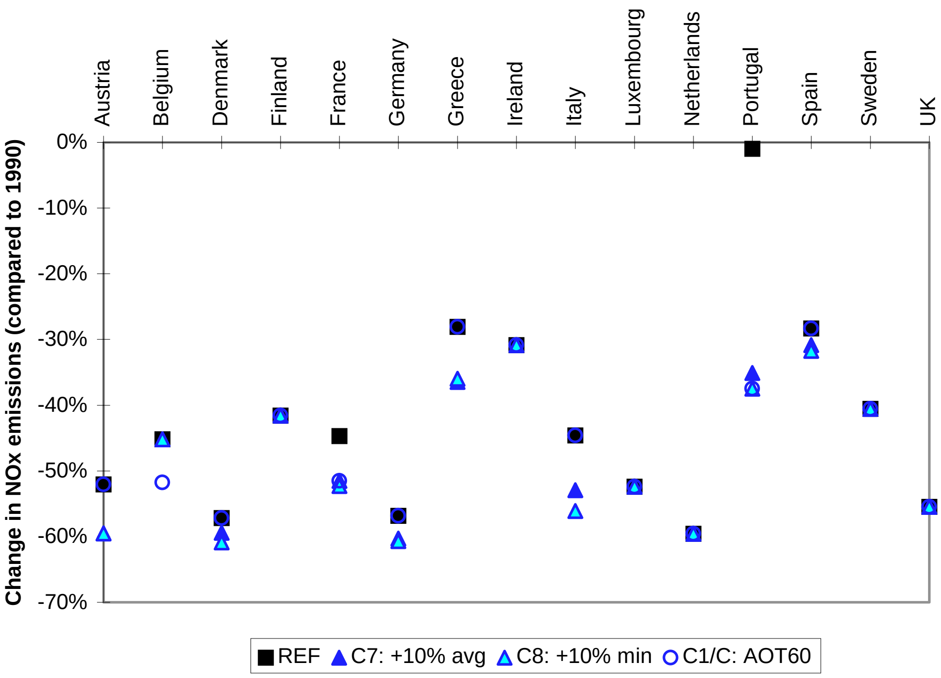

Figure 6.6: Change in NO_x emissions for the AOT40-related gap-closure scenarios

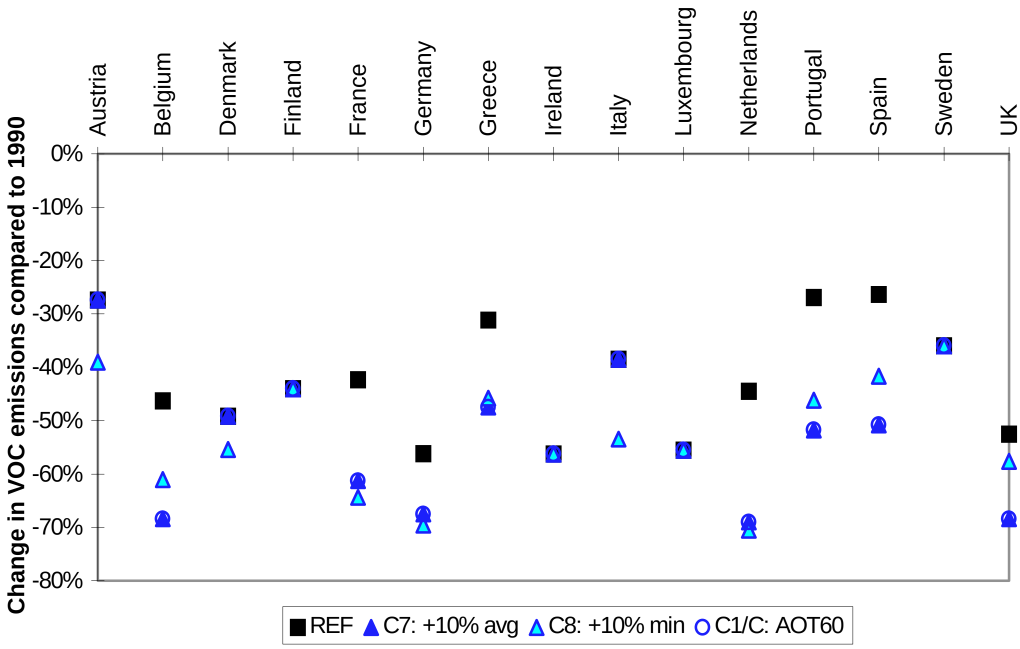

Figure 6.7: Change in VOC emissions for the AOT40-related gap-closure scenarios

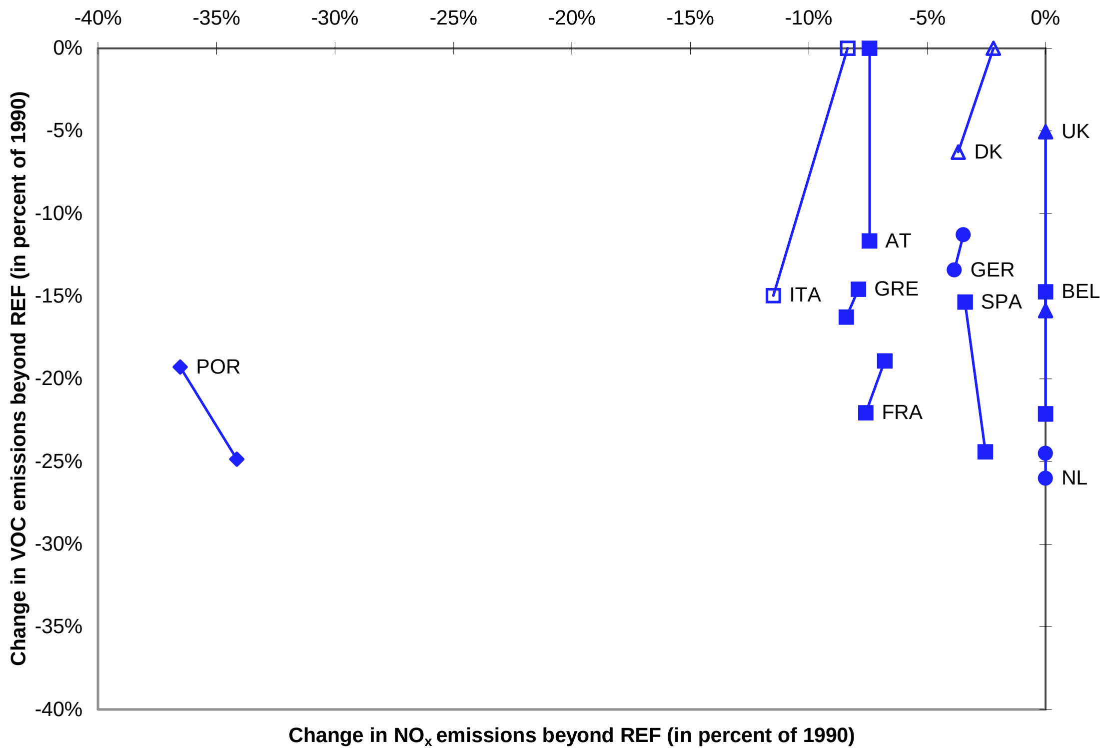

Figure 6.8: Change in NO_x and VOC emissions beyond the REF scenario for the AOT40-related gap closure scenarios

Table 6.5: Vegetation exposure indices for the optimized AOT40 scenarios

Gap closure	Cumulative vegetation exposure index (million hectares. excess ppm.hours)				Average vegetation exposure index (excess ppm.hours)			
		REF +10%				REF +10%		
	REF	avg. C7	min. C8	MFR	REF	avg. C7	min. C8	MFR
Austria	27	22	22	19	5.2	4.3	4.2	3.7
Belgium	15	12	12	11	9.8	7.9	7.9	6.9
Denmark	5	4	4	2	1.8	1.3	1.2	0.6
Finland	0	0	0	0	0.0	0.0	0.0	0.0
France	252	200	197	158	7.8	6.2	6.1	4.9
Germany	132	101	99	82	6.2	4.7	4.7	3.9
Greece	15	13	13	11	2.8	2.5	2.4	2.0
Ireland	1	0	0	0	0.4	0.2	0.2	0.0
Italy	122	102	97	82	7.7	6.5	6.2	5.2
Luxembourg	1	1	1	1	10.0	8.0	7.9	6.4
Netherlands	9	6	6	6	6.6	5.0	5.0	4.4
Portugal	29	23	22	17	4.9	3.9	3.9	3.0
Spain	134	110	108	65	4.4	3.6	3.5	2.1
Sweden	2	1	1	0	0.1	0.0	0.0	0.0
UK	20	15	15	11	2.4	1.8	1.8	1.4
EU-15	632	510	499	384	3.8	3.1	3.0	2.3

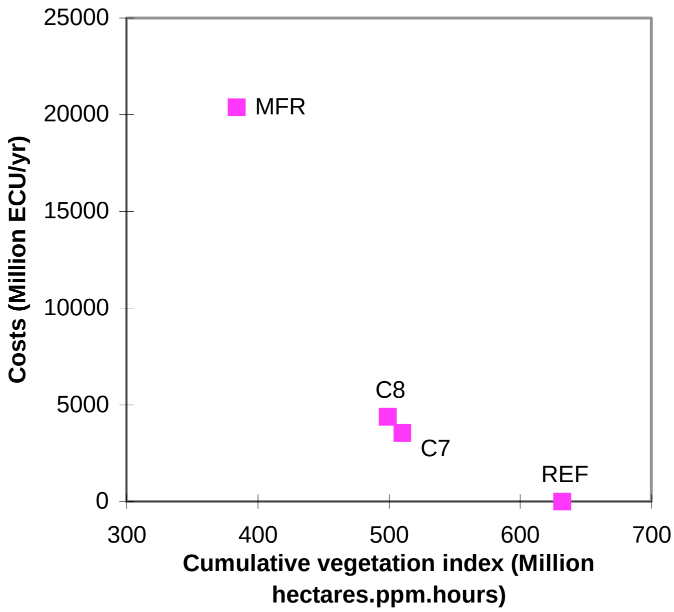

Figure 6.9: Cost-effectiveness of the AOT40-related gap closure scenarios

6.2.2 Reducing the Excess AOT40 Assuming the Implementation of the Measures Discussed under Auto/Oil 2

As for the AOT60, the above optimization scenarios C7 and C8 exclude further control measures in the transport sector beyond those included in the Auto/Oil 1 package. Obviously, such an analysis excluding the emission control potential of an important source category is incomplete. It is envisaged that the next Interim Report will extend the optimization analysis to also include mobile sources.

To this end, a sensitivity analysis explores the implications for emission control at stationary sources if the measures currently discussed within the Auto/Oil 2 programme were implemented. The sensitivity runs were carried out for the AOT40 targets of Scenario C7 and C8 and are labeled as C7-2 and C8-2, respectively.

Table 6.6 to Table 6.8 present the results of the sensitivity analysis. Maintaining the environmental targets of Scenario C7 (the 10 percent average improvement of the gap closure), stationary sources could relax further NO_x control by about 40 percent and VOC control by 20 percent, if the Auto/Oil 2 measures were implemented. Consequently, the emission control costs for stationary sources decline by 33 percent (1.1 billion ECU/year). For the stricter environmental targets of the C8 scenario, the cost saving increases to 1.8 billion ECU/year.

Table 6.6: NO_x emissions for the AOT40-related gap closure scenarios assuming the measures of Auto/Oil 2

	NO_x emissions (kilotons)					Change compared to 1990				
	REF-AO2	**C7-2**	C7	**C8-2**	C8	REF-AO2	**C7-2**	C7	**C8-2**	C8
Austria	100	**93**	98	**86**	98	-59%	**-62%**	-60%	**-64%**	-60%
Belgium	183	**183**	199	**183**	199	-50%	**-50%**	-45%	**-50%**	-45%
Denmark	109	**109**	110	**109**	106	-60%	**-60%**	-59%	**-60%**	-61%
Finland	152	**152**	163	**152**	163	-46%	**-46%**	-42%	**-46%**	-42%
France	772	**676**	785	**674**	772	-52%	**-58%**	-52%	**-58%**	-52%
Germany	1135	**1087**	1185	**1078**	1174	-62%	**-64%**	-60%	**-64%**	-61%
Greece	274	**247**	249	**243**	251	-30%	**-37%**	-36%	**-38%**	-36%
Ireland	71	**71**	74	**71**	74	-34%	**-34%**	-31%	**-34%**	-31%
Italy	1033	**947**	945	**919**	882	-49%	**-53%**	-53%	**-54%**	-56%
Luxembourg	9	**9**	10	**9**	10	-57%	**-57%**	-52%	**-57%**	-52%
Netherlands	194	**194**	218	**194**	218	-64%	**-64%**	-60%	**-64%**	-60%
Portugal	197	**126**	135	**122**	130	-5%	**-39%**	-35%	**-41%**	-38%
Spain	801	**801**	813	**792**	803	-32%	**-32%**	-31%	**-33%**	-32%
Sweden	189	**189**	205	**189**	205	-45%	**-45%**	-41%	**-45%**	-41%
UK	1102	**1102**	1186	**1102**	1186	-59%	**-59%**	-55%	**-59%**	-55%
EU-15	6321	**5986**	6375	**5923**	6271	-52%	**-55%**	-52%	**-55%**	-53%

Table 6.7: VOC emissions for the AOT40-related gap closure scenarios assuming the measures of Auto/Oil 2

	VOC emissions (kilotons)					Change compared to 1990				
	REF-AO2	**C7-2**	C7	**C8-2**	C8	REF-AO2	**C7-2**	C7	**C8-2**	C8
Austria	305	**305**	256	**298**	247	-27%	**-27%**	-39%	**-29%**	-41%
Belgium	177	**112**	132	**113**	153	-48%	**-67%**	-61%	**-67%**	-55%
Denmark	87	**87**	78	**87**	75	-50%	**-50%**	-55%	**-50%**	-57%
Finland	108	**108**	108	**108**	108	-44%	**-44%**	-44%	**-44%**	-44%
France	1351	**887**	853	**880**	818	-44%	**-63%**	-64%	**-63%**	-66%
Germany	1326	**987**	944	**983**	913	-57%	**-68%**	-70%	**-68%**	-71%
Greece	194	**162**	160	**157**	156	-34%	**-45%**	-46%	**-47%**	-47%
Ireland	40	**40**	42	**40**	42	-58%	**-58%**	-56%	**-58%**	-56%
Italy	1080	**898**	862	**868**	774	-42%	**-52%**	-53%	**-53%**	-58%
Luxembourg	8	**8**	8	**8**	8	-56%	**-56%**	-56%	**-56%**	-56%
Netherlands	254	**130**	137	**131**	138	-45%	**-72%**	-71%	**-72%**	-70%
Portugal	144	**109**	106	**108**	105	-27%	**-45%**	-46%	**-45%**	-47%
Spain	740	**679**	604	**661**	599	-29%	**-34%**	-42%	**-36%**	-42%
Sweden	287	**287**	287	**287**	287	-36%	**-36%**	-36%	**-36%**	-36%
UK	1276	**1082**	1140	**1092**	1155	-53%	**-60%**	-58%	**-59%**	-57%
EU-15	7377	**5881**	5717	**5821**	5578	-46%	**-57%**	-58%	**-58%**	-59%

Table 6.8: Emission control costs for the AOT40-related gap closure scenarios assuming the measures of Auto/Oil 2

	Total costs	Additional costs on top of REF			
	REF-AO2	C7-2	C7	C8-2	C8
Austria	949	26	308	82	411
Belgium	1084	109	54	103	20
Denmark	515	0	13	0	22
Finland	704	0	0	0	0
France	6578	477	605	489	709
Germany	10625	591	1098	628	1362
Greece	683	43	62	53	66
Ireland	691	0	0	0	0
Italy	7381	272	565	355	944
Luxembourg	87	0	0	0	0
Netherlands	2808	241	226	236	221
Portugal	1028	217	248	247	288
Spain	4206	35	113	49	122
Sweden	1241	0	0	0	0
UK	5711	379	256	354	224
EU-15	44291	2392	3548	2598	4389

7. 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 in order to simultaneously satisfy constraints on the composite AOT60 (ignoring the most unfavorable year) and on the AOT40.

This section describes two optimization scenarios:

- Scenario C9 combines the composite 50 percent gap closure optimization for the AOT60 (Scenario C1/C) with the 10 percent average increase of the gap closure for the AOT40 (Scenario 7).
- Scenario C10 explores the gains offered by the joint optimization for stricter environmental ambition levels by combining the targets of the composite 55 percent gap closure scenario (C3/C) with the 10 percent minimum improvement of the AOT40 gap closure (Scenario 8).

Table 7.1 to Table 7.3 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 always 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 derived from the tables, however, the optimization is capable of identifying the potential of synergistic emission reductions serving both environmental problems optimally, and thereby relax the most stringent and expensive reduction requirements in many situations. For the EU-15 as a whole, the combined optimization leads to 14 percent less NO_x reductions and five percent less VOC reduction with a cost saving of about 10 percent (Scenario C9).

It is interesting to inspect the reactions for individual countries. Figure 7.2 and Figure 7.3 clearly indicate that for most countries the combined optimization ends with slightly less ambitious emission reductions than the individually most stringent optimization result. For some countries, however, the combined consideration of both environmental targets makes it possible to relax emission reductions to the lower end spanned by the two individual problems. This effect occurs for Denmark for both NO_x and VOC reductions, and for Belgium and Spain for NO_x emissions. The phenomenon would be even more pronounced if the optimization results for AOT60 for the individual years were included in this comparison.

Figure 7.1 displays the binding grids for the joint optimization of Scenario C9.It is interesting to note that the AOT60 targets serve as a driving force in the UK, Portugal, and around Athens, while in many other countries (Spain, Italy, Austria, Netherlands/Germany/Belgium, Sweden) the AOT40 targets are more stringent. In Greece, AOT40 targets for rural regions drive the emission reductions in addition to the AOT60 targets of the surroundings of Athens.

Table 7.1: NO_x emissions for the ozone-related optimization scenarios

	NO_x emissions (kilotons)									Change compared to 1990								
		AOT60 50%GC	AOT40 REF +10% avg.	*min. of AOT60 + AOT40 C1/C and C7*	joint optim. AOT40 + AOT60	AOT60 55%GC	AOT40 REF +10% min.	*min. of AOT60 + AOT40 C3/C and C8*	joint optim. AOT40 + AOT60		AOT60 50%GC	AOT40 REF +10% avg.	*max. of AOT60 + AOT40 C1/C and C7*	joint optim. AOT40 + AOT60	AOT60 55%GC	AOT40 REF +10% min.	*max. of AOT60 + AOT40 C3/C and C8*	joint optim. AOT40 + AOT60
Scenario	REF	C1/C	C7		C9	C3/C	C8		C10	REF	C1/C	C7		C9	C3/C	C8		C10
Austria	116	116	98	*98*	98	116	98	*98*	98	-52%	-52%	-60%	*-60%*	-60%	-52%	-60%	*-60%*	-60%
Belgium	199	175	199	*175*	199	136	199	*136*	151	-45%	-52%	-45%	*-52%*	-45%	-63%	-45%	*-63%*	-58%
Denmark	116	116	110	*110*	116	116	106	*106*	116	-57%	-57%	-59%	*-59%*	-57%	-57%	-61%	*-61%*	-57%
Finland	163	163	163	*163*	163	163	163	*163*	163	-42%	-42%	-42%	*-42%*	-42%	-42%	-42%	*-42%*	-42%
France	895	785	785	*785*	779	748	772	*748*	749	-45%	-52%	-52%	*-52%*	-52%	-54%	-52%	*-54%*	-54%
Germany	1289	1289	1185	*1185*	1202	1240	1174	*1174*	1193	-57%	-57%	-60%	*-60%*	-60%	-58%	-61%	*-61%*	-60%
Greece	282	282	249	*249*	246	282	251	*251*	247	-28%	-28%	-36%	*-36%*	-37%	-28%	-36%	*-36%*	-37%
Ireland	74	74	74	*74*	74	74	74	*74*	74	-31%	-31%	-31%	*-31%*	-31%	-31%	-31%	*-31%*	-31%
Italy	1113	1113	945	*945*	957	1113	882	*882*	941	-45%	-45%	-53%	*-53%*	-52%	-45%	-56%	*-56%*	-53%
Luxembourg	10	10	10	*10*	10	10	10	*10*	10	-52%	-52%	-52%	*-52%*	-52%	-52%	-52%	*-52%*	-52%
Netherlands	218	218	218	*218*	218	218	218	*218*	209	-60%	-60%	-60%	*-60%*	-60%	-60%	-60%	*-60%*	-61%
Portugal	206	130	135	*130*	130	130	130	*130*	130	-1%	-38%	-35%	*-38%*	-38%	-38%	-38%	*-38%*	-38%
Spain	843	843	813	*813*	841	620	803	*620*	632	-28%	-28%	-31%	*-31%*	-28%	-47%	-32%	*-47%*	-46%
Sweden	205	205	205	*205*	205	205	205	*205*	205	-41%	-41%	-41%	*-41%*	-41%	-41%	-41%	*-41%*	-41%
UK	1186	1186	1186	*1186*	1186	1186	1186	*1186*	1186	-55%	-55%	-55%	*-55%*	-55%	-55%	-55%	*-55%*	-55%
EU-15	6915	6705	6375	*6346*	6424	6357	6271	*6001*	6104	-48%	-49%	-52%	*-52%*	-51%	-52%	-53%	*-55%*	-54%

Table 7.2: VOC emissions for the ozone-related optimization scenarios

	VOC emissions (kilotons)									Change compared to 1990								
		AOT60 50%GC	AOT40 REF +10% avg.	*min. of AOT60 + AOT40 C1/C and C7*	joint optim. AOT40 + AOT60	AOT60 55%GC	AOT40 REF +10% min.	*min. of AOT60 + AOT40 C3/C and C8*	joint optim. AOT40 + AOT60		AOT60 50%GC	AOT40 REF +10% avg.	*max. of AOT60 + AOT40 C1/C and C7*	joint optim. AOT40 + AOT60	AOT60 55%GC	AOT40 REF +10% min.	*max. of AOT60 + AOT40 C3/C and C8*	joint optim. AOT40 + AOT60
Scenario	REF	C1/C	C7		C9	C3/C	C8		C10	REF	C1/C	C7		C9	C3/C	C8		C10
Austria	305	305	256	*256*	262	305	247	*247*	264	-27%	-27%	-39%	*-39%*	-38%	-27%	-41%	*-41%*	-37%
Belgium	182	107	132	*107*	117	96	153	*96*	100	-46%	-68%	-61%	*-68%*	-65%	-72%	-55%	*-72%*	-71%
Denmark	89	89	78	*78*	89	89	75	*75*	89	-49%	-49%	-55%	*-55%*	-49%	-49%	-57%	*-57%*	-49%
Finland	108	108	108	*108*	108	108	108	*108*	108	-44%	-44%	-44%	*-44%*	-44%	-44%	-44%	*-44%*	-44%
France	1381	928	853	*853*	863	791	818	*791*	781	-42%	-61%	-64%	*-64%*	-64%	-67%	-66%	*-67%*	-67%
Germany	1361	1010	944	*944*	955	907	913	*907*	889	-56%	-67%	-70%	*-70%*	-69%	-71%	-71%	*-71%*	-71%
Greece	203	155	160	*155*	161	135	156	*135*	140	-31%	-47%	-46%	*-47%*	-45%	-54%	-47%	*-54%*	-53%
Ireland	42	42	42	*42*	42	42	42	*42*	42	-56%	-56%	-56%	*-56%*	-56%	-56%	-56%	*-56%*	-56%
Italy	1139	1139	862	*862*	880	1082	774	*774*	855	-38%	-38%	-53%	*-53%*	-52%	-42%	-58%	*-58%*	-54%
Luxembourg	8	8	8	*8*	8	8	8	*8*	8	-56%	-56%	-56%	*-56%*	-56%	-56%	-56%	*-56%*	-56%
Netherlands	258	144	137	*137*	141	130	138	*130*	130	-45%	-69%	-71%	*-71%*	-70%	-72%	-70%	*-72%*	-72%
Portugal	144	95	106	*95*	95	95	105	*95*	95	-27%	-52%	-46%	*-52%*	-52%	-52%	-47%	*-52%*	-52%
Spain	763	510	604	*510*	532	375	599	*375*	383	-26%	-51%	-42%	*-51%*	-49%	-64%	-42%	*-64%*	-63%
Sweden	287	287	287	*287*	287	287	287	*287*	287	-36%	-36%	-36%	*-36%*	-36%	-36%	-36%	*-36%*	-36%
UK	1276	849	1140	*849*	865	792	1155	*792*	793	-53%	-68%	-58%	*-68%*	-68%	-71%	-57%	*-71%*	-71%
EU-15	7546	5776	5717	*5291*	5405	5242	5578	*4862*	4964	-48%	-56%	-57%	*-60%*	-59%	-60%	-58%	*-63%*	-62%

Table 7.3: Emission control costs for the ozone-related optimization scenarios

	Total costs	Additional costs on top of REF							
		AOT60	AOT40	*max. of AOT60+ AOT40*	joint optim. AOT40 + AOT60	AOT60	AOT40	*max. of AOT60+ AOT40*	joint optim. AOT40 + AOT60
		50%GC	REF +10% avg.	*C1/C and C7*		55%GC	REF +10% min.	*C3/C and C8*	
	REF	C1/C	C7		C9	C3/C	C8		C10
Austria	951	0	308	*308*	262	0	411	*411*	250
Belgium	1062	198	54	*198*	106	484	20	*484*	323
Denmark	475	0	13	*13*	0	0	22	*22*	0
Finland	672	0	0	*0*	0	0	0	*0*	0
France	6577	496	605	*605*	605	880	709	*880*	902
Germany	10625	578	1098	*1098*	954	1120	1362	*1362*	1369
Greece	683	36	62	*62*	66	91	66	*91*	109
Ireland	485	0	0	*0*	0	0	0	*0*	0
Italy	7380	0	565	*565*	506	49	944	*944*	587
Luxembourg	74	0	0	*0*	0	0	0	*0*	0
Netherlands	2011	189	226	*226*	200	276	221	*276*	300
Portugal	1032	372	248	*372*	372	372	288	*372*	372
Spain	4115	191	113	*191*	167	692	122	*692*	637
Sweden	1257	0	0	*0*	0	0	0	*0*	0
UK	5754	1345	256	*1345*	1244	1773	224	*1773*	1766
EU-15	43152	3405	3548	*4983*	4482	5737	4389	*7307*	6615

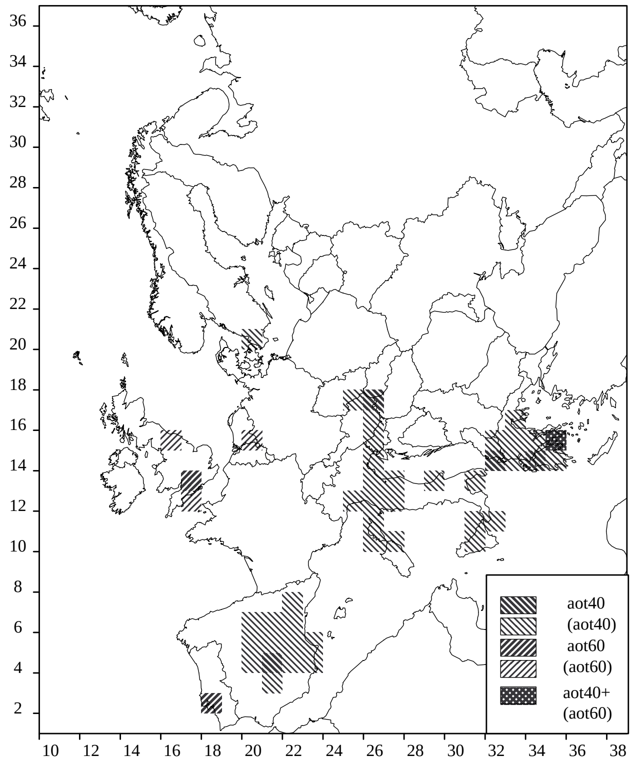

Figure 7.1: Binding grids for the Scenario C9. The map indicates where after optimization the ozone levels are at or are very close to the specified targets. The map distinguishes grids where the AOT40 is binding (indicated by 'aot40') or almost binding ['(aot40)'], where the AOT60 is binding ['aot60'] or almost binding ['(aot60)'] and where both AOT60 and AOT40 are binding.

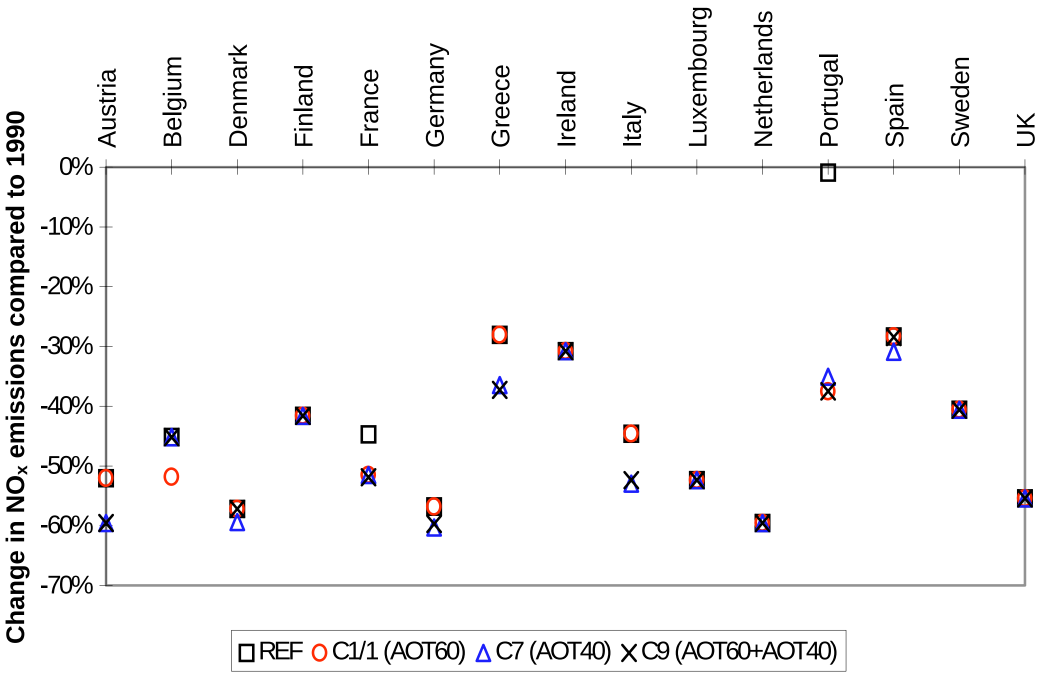

Figure 7.2: Change in NO_x emissions for the ozone-related optimization scenarios

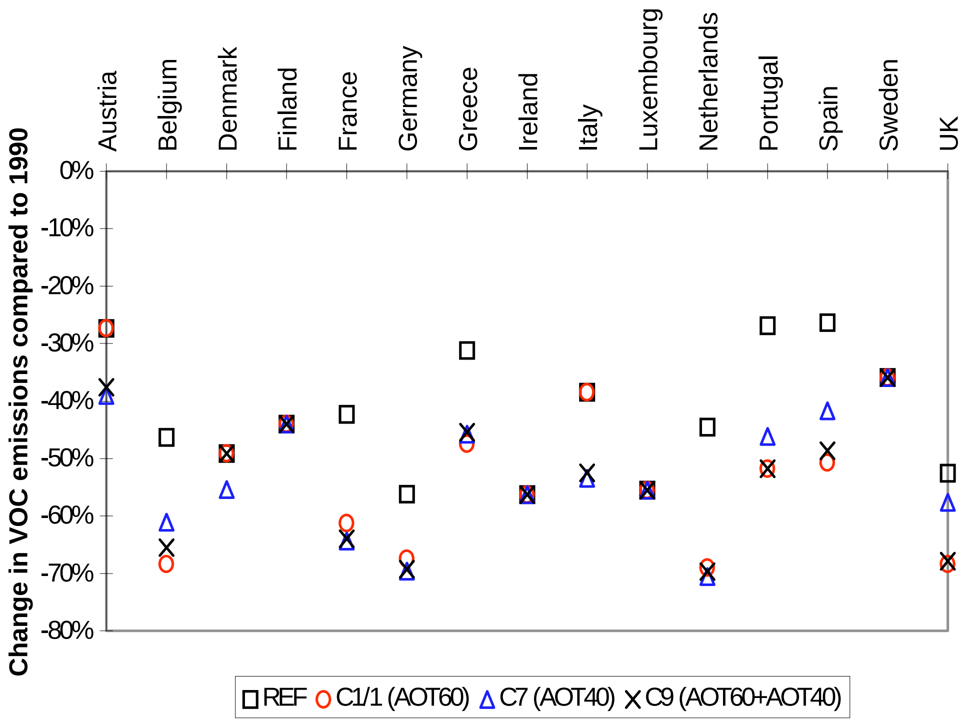

Figure 7.3: Change in VOC emissions for the ozone-optimized scenarios

8. 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 shown in the earlier Interim Reports of this study 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 environmental targets of an acidification-oriented strategy into account. This new feature will be used in this section to attempt a first analysis of the possible interaction of acidification and ozone related strategies.

It is important to stress that it is not the subject of this Interim Report to explore acidification related scenarios in great detail. Consequently, it was decided to restrict the analysis to the 50 percent gap closure scenario for acidification (Scenario B1) of the Second Interim Report of this study, which served as the basis for the Commission’s proposal on the Acidification Strategy. Further refinements of this scenario, taking into account comments made by the Member States and updated information, will be the subject of the next Interim Reports.

Although possible refinements and modifications of the B1 Scenario of the Second Interim Report are outside the scope of this report, new information on some important elements made it necessary to revise the acidification scenario to be consistent with the latest databases used for the ozone analysis. These revisions are only made in the interest of a consistent treatment of ozone- and acidification scenarios. Without any doubt there are many more interesting aspects linked with the acidification scenario, which deserve further attention and careful analysis. As mentioned above, such a detailed assessment is planned for the coming Interim Reports.

8.1 A Preliminary 50 Percent Gap Closure Scenario for Acidification (Scenario C11)

The Second Interim Report of this study presented a 50 percent gap closure scenario (Scenario B1 in that report), which served as the basis for the Acidification Strategy proposed by the Commission. In the meantime, improved information on some important elements of the analysis became available, which was subsequently incorporated into the RAINS database used for the analysis of the ozone scenarios presented in this report. As a consequence, a 50 percent gap closure scenario for acidification would, in light of the new information, look somewhat different.

The most relevant new pieces of information are:

- The new critical loads database, released by the UN/ECE Working Groups on Effects (WGE) at their August 1997 session. There are important changes in the critical loads in the following fields:
    - new (stricter) critical loads for Ireland (for the first time data supplied by Ireland);
    - new critical loads data for the UK;
    - modifications to the Swedish critical loads (with a critical load of zero for one grid in the northern part of Sweden; this was recognized as a mistake in the discussions of the WGE and it was agreed that this critical load should be ignored in the scenario calculations);
    - new data for France (containing some grids without critical loads, i.e., where no natural ecosystems exist).
- New information on emissions from ships derived from the Lloyds Register. More detailed investigations into the emissions from ships suggest SO_2 emissions from the Atlantic and the North Sea to be more than twice, and NO_x emissions by almost a factor of three, higher than assumed before (Table 8.1).

Table 8.1: Comparison of the old and new estimates of ship emissions

	SO_2		NO_x	
	before	now	before	now
Atlantic Ocean	316	640	349	910
Baltic Sea	72	72	80	80
North Sea	172	439	191	638
Sum	560	1151	620	1628

This new information resulting from more detailed analysis suggests that the analysis carried out in the first two Interim Reports underestimated to some extent the severity of the acidification problem. Keeping all other assumptions as before, the new data on critical loads and the higher emissions from ships make the 50 percent gap closure target for acidification much more difficult to achieve.

As explained above, a revision of the acidification-related scenario is outside the scope of this ozone-oriented Interim Report. For practical reasons, however, i.e., to examine the interaction of acidification and ozone strategies, a practical acidification scenario is required. For reasons of simplicity, a preliminary acidification scenario has been recalculated which is as close as possible to the B1 scenario used in the previous report taking into account the new information referred to above.

- A 50 percent (area-related) gap closure for acidification to be achieved for each grid (unchanged assumption from the earlier B1 scenario);
- 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 (if ships use high sulfur fuel, the 50 percent gap closure target is not achievable);
- Grid 14/13 in Ireland, where the gap closure for the new critical loads data is impossible to achieve, is excluded from the optimization. It was agreed with Ireland to further check the assumptions underlying the critical loads and emission estimates and to return to the problem at a later time.
- Grid 17/27 in northern Sweden is excluded from the optimization, since an error in the critical loads database was discovered.

- Grid 20/17 in Germany/Netherlands is excluded from the optimization. Already in the earlier Interim Reports this grid proved as difficult and expensive to protect (i.e., this grid was already the most ‘binding’ grid in the earlier analysis). It is important to note 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 percent gap closure approach in this grid is the 44 percentile; this means that even after successful gap closure, 43 percent 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. The reason why this illustrative scenario excluded grid 20/17 from the optimization is the fact that with the higher emissions from the sea (even if the sulfur content for ships is limited to 1.5 percent) the achievement of the gap closure target becomes virtually impossible and would require maximum feasible emission reductions in a number of countries at extremely high costs.

It must be stressed once more that all the assumptions made above need careful review and intensive discussions, and probably also revisions in order to arrive at acceptable solutions. Lack of time available for this ozone-oriented Interim Report did not allow for an in-depth analysis. Consequently, the resulting Scenario C11 should only be considered as illustrative, mainly useful for exploring the interaction of ozone- and acidification strategies.

The resulting emissions and costs for Scenario C11 are listed in Table 8.3 to Table 8.8. Figure 8.1 displays the binding grid cells for Scenario C11.

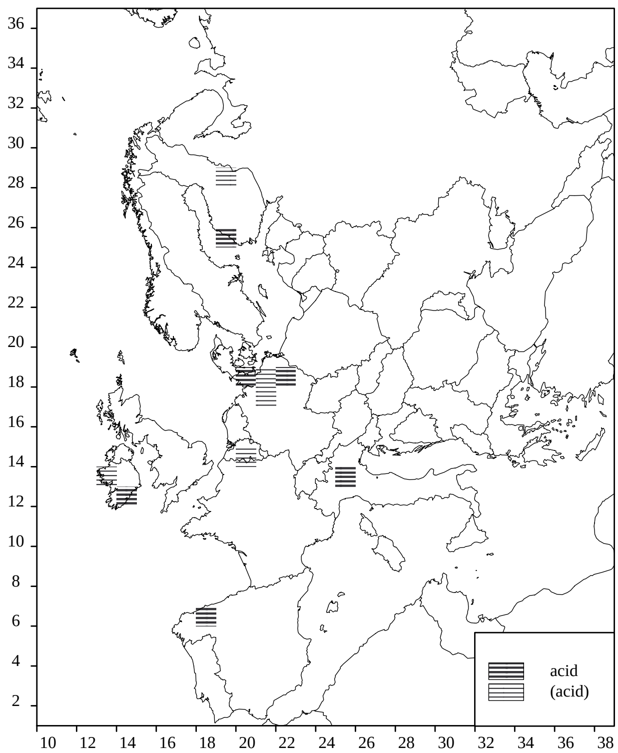

Figure 8.1: Binding grid cells for Scenario C11. The map indicates where after optimization acid deposition is at (indicated by 'acid') or closely below (indicated by '(acid)') the specified target. Note, however, that some grids where the 50 percent gap closure target is not achievable, are excluded from the optimization.

8.2 Joint Optimization for Acidification, AOT40 and AOT60 (Scenario C12)

At the end of this report, Scenario C12 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 percent 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 percent gap closure target must be achieved in four out of five years (Scenario C1/C of this Report);
- An average 10 percent improvement of the gap closure achieved by the Reference (REF) scenario for the AOT40, but a 15 percent gap closure compared to 1990 as a minimum (Scenario C7);
- A 50 percent gap closure for acidification; however, the targets for three grids are excluded for the reasons discussed above (Scenario C11).

The following tables (Table 8.3 to Table 8.8) provide the detailed results for the joint optimization and compare them with the optimization outcomes for the three environmental problems. As to be expected from theory, the joint optimization is cheaper than the upper envelope of the individual problems. It is somehow surprising, however, that the cost saving is not dramatic (seven percent) and that relaxation of the most stringent reduction requirements is limited, although for individual countries the differences might be significant. 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 already be offered:

- 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 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 only prove cost-efficient if there are 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 reduction, which is 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 this lower NO_x emissions by further VOC reductions. It is interesting to note that (at least for this particular problem setting) the optimization tends more towards the second option. This can be explained (a) by the fact that the strong NO_x reductions required for acidification move the ozone system already close to the 'linear' behavior, where only little additional VOC is required any more to compensate the ozone increase, (b) the high NO_x reductions are expensive (if not impossible) to compensate 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 there the most expensive measures. For this particular example, the benefits to be made downwind for the ozone abatement lead even to slightly more NO_x and VOC reductions than it would result from the acidification interest alone.

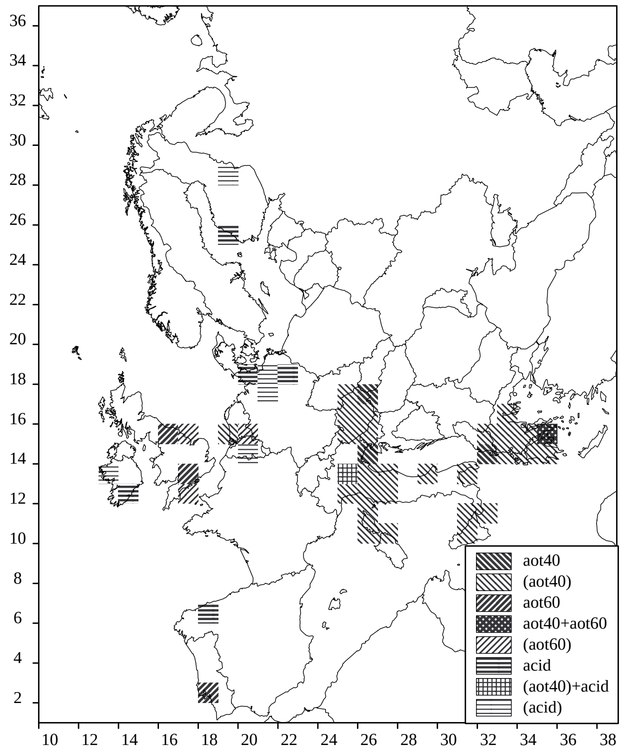

Figure 8.2: Binding grid cells for the combined ozone/acidification scenario C12. The map indicates where after optimization the exposures of AOT40, AOT60 and acidification, respectively, are at or slightly below (indicated with brackets) the targets.

Table 8.2: Area of ecosystems with deposition above their critical loads for acidification (in 1000 hectares)

	REF	C11	C12
Austria	935	733	724
Belgium	70	35	35
Denmark	16	7	7
Finland	1305	1237	1236
France	155	121	121
Germany	2653	1284	1273
Greece	0	0	0
Ireland	240	123	123
Italy	848	679	668
Luxembourg	32	12	12
Netherlands	127	53	53
Portugal	0	0	0
Spain	24	10	11
Sweden	1109	871	874
UK	1548	650	669
EU-15	9064	4532	4532

Table 8.3: NO_x emissions for the scenarios targeted at acidification and ground-level ozone

	NO_x emissions (kilotons)						Change compared to 1990					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi- fication	*min.*	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi- fication	*max.*	Joint optim.
Scenario	REF	C1/C1	C7	C11		C12	REF	C1/C	C7	C11		C12
Austria	116	116	98	116	*98*	98	-52%	-52%	-60%	-52%	*-60%*	-60%
Belgium	199	175	199	175	*175*	178	-45%	-52%	-45%	-52%	*-52%*	-51%
Denmark	116	116	110	106	*106*	107	-57%	-57%	-59%	-61%	*-61%*	-61%
Finland	163	163	163	163	*163*	163	-42%	-42%	-42%	-42%	*-42%*	-42%
France	895	785	785	839	*785*	776	-45%	-52%	-52%	-48%	*-52%*	-52%
Germany	1289	1289	1185	1244	*1185*	1190	-57%	-57%	-60%	-58%	*-60%*	-60%
Greece	282	282	249	282	*249*	245	-28%	-28%	-36%	-28%	*-36%*	-38%
Ireland	74	74	74	33	*33*	35	-31%	-31%	-31%	-69%	*-69%*	-67%
Italy	1113	1113	945	1113	*945*	949	-45%	-45%	-53%	-45%	*-53%*	-53%
Luxembourg	10	10	10	10	*10*	10	-52%	-52%	-52%	-52%	*-52%*	-52%
Netherlands	218	218	218	215	*215*	203	-60%	-60%	-60%	-60%	*-60%*	-62%
Portugal	206	130	135	206	*130*	130	-1%	-38%	-35%	-1%	*-38%*	-38%
Spain	843	843	813	843	*813*	785	-28%	-28%	-31%	-28%	*-31%*	-33%
Sweden	205	205	205	205	*205*	205	-41%	-41%	-41%	-41%	*-41%*	-41%
UK	1186	1186	1186	918	*918*	893	-55%	-55%	-55%	-66%	*-66%*	-66%
EU-15	6915	6705	6375	6468	*6030*	5967	-48%	-49%	-52%	-51%	*-54%*	-55%

Table 8.4: VOC_x emissions for the scenarios targeted at acidification and ground-level ozone

	VOC emissions (kilotons)						Change compared to 1990					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*min.*	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*	Joint optim.
Scenario	REF	C1/C	C7	C11		C12	REF	C1/C	C7	C11		C12
Austria	305	305	256	305	*256*	269	-27%	-27%	-39%	-27%	*-39%*	-36%
Belgium	182	107	132	182	*107*	120	-46%	-68%	-61%	-46%	*-68%*	-65%
Denmark	89	89	78	89	*78*	89	-49%	-49%	-55%	-49%	*-55%*	-49%
Finland	108	108	108	108	*108*	108	-44%	-44%	-44%	-44%	*-44%*	-44%
France	1381	928	853	1381	*853*	917	-42%	-61%	-64%	-42%	*-64%*	-62%
Germany	1361	1010	944	1361	*944*	983	-56%	-67%	-70%	-56%	*-70%*	-68%
Greece	203	155	160	203	*155*	162	-31%	-47%	-46%	-31%	*-47%*	-45%
Ireland	42	42	42	42	*42*	42	-56%	-56%	-56%	-56%	*-56%*	-56%
Italy	1139	1139	862	1139	*862*	888	-38%	-38%	-53%	-38%	*-53%*	-52%
Luxembourg	8	8	8	8	*8*	8	-56%	-56%	-56%	-56%	*-56%*	-56%
Netherlands	258	144	137	258	*137*	145	-45%	-69%	-71%	-45%	*-71%*	-69%
Portugal	144	95	106	144	*95*	95	-27%	-52%	-46%	-27%	*-52%*	-52%
Spain	763	510	604	763	*510*	549	-26%	-51%	-42%	-26%	*-51%*	-47%
Sweden	287	287	287	287	*287*	287	-36%	-36%	-36%	-36%	*-36%*	-36%
UK	1276	849	1140	1276	*849*	830	-53%	-68%	-58%	-53%	*-68%*	-69%
EU-15	7546	5776	5717	7546	*5291*	5492	-43%	-56%	-57%	-43%	*-60%*	-58%

Table 8.5: SO_2 emissions for the scenarios targeted at acidification and ground-level ozone

	SO_2 emissions (kilotons)						Change compared to 1990					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*min.*	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*	Joint optim.
Scenario	REF	C1/C	C7	C11		C12	REF	C1/C	C7	C11		C12
Austria	57	57	57	57	*57*	57	-39%	-39%	-39%	-39%	*-39%*	-39%
Belgium	215	215	215	83	*83*	86	-32%	-32%	-32%	-74%	*-74%*	-73%
Denmark	71	71	71	22	*22*	22	-63%	-63%	-63%	-88%	*-88%*	-88%
Finland	116	116	116	108	*108*	108	-51%	-51%	-51%	-54%	*-54%*	-54%
France	691	691	691	270	*270*	278	-47%	-47%	-47%	-79%	*-79%*	-79%
Germany	740	740	740	464	*464*	476	-86%	-86%	-86%	-91%	*-91%*	-91%
Greece	361	361	361	361	*361*	361	-29%	-29%	-29%	-29%	*-29%*	-29%
Ireland	155	155	155	32	*32*	33	-14%	-14%	-14%	-82%	*-82%*	-82%
Italy	442	442	442	337	*337*	362	-74%	-74%	-74%	-80%	*-80%*	-79%
Luxembourg	4	4	4	4	*4*	4	-71%	-71%	-71%	-71%	*-71%*	-71%
Netherlands	56	56	56	39	*39*	39	-72%	-72%	-72%	-80%	*-80%*	-80%
Portugal	194	194	194	194	*194*	194	-32%	-32%	-32%	-32%	*-32%*	-32%
Spain	1003	1003	1003	615	*615*	622	-55%	-55%	-55%	-72%	*-72%*	-72%
Sweden	87	87	87	87	*87*	87	-24%	-24%	-24%	-24%	*-24%*	-24%
UK	980	980	980	351	*351*	375	-74%	-74%	-74%	-91%	*-91%*	-90%
EU-15	5172	5172	5172	3024	*3024*	3104	-61%	-61%	-61%	-77%	*-77%*	-77%

Table 8.6: NH_3 emissions for the scenarios targeted at acidification and ground-level ozone

	NH_3 emissions (kilotons)						Change compared to 1990					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi- fication	*min.*	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi- fication	*max..*	Joint optim.
Scenario	REF	C1/C	C7	C11		C12	REF	C1/C	C7	C11		C12
Austria	93	93	93	93	*93*	93	1%	1%	1%	1%	*1%*	1%
Belgium	96	96	96	96	*96*	96	1%	1%	1%	1%	*1%*	1%
Denmark	103	103	103	64	*64*	64	-26%	-26%	-26%	-54%	*-54%*	-54%
Finland	23	23	23	23	*23*	23	-44%	-44%	-44%	-44%	*-44%*	-44%
France	668	668	668	668	*668*	668	-3%	-3%	-3%	-3%	*-3%*	-3%
Germany	539	539	539	311	*311*	315	-27%	-27%	-27%	-58%	*-58%*	-57%
Greece	76	76	76	76	*76*	76	-3%	-3%	-3%	-3%	*-3%*	-3%
Ireland	126	126	126	118	*118*	118	2%	2%	2%	-5%	*-5%*	-5%
Italy	391	391	391	357	*357*	361	2%	2%	2%	-7%	*-7%*	-6%
Luxembourg	6	6	6	6	*6*	6	-14%	-14%	-14%	-14%	*-14%*	-14%
Netherlands	82	82	82	82	*82*	82	-64%	-64%	-64%	-64%	*-64%*	-64%
Portugal	84	84	84	84	*84*	84	-8%	-8%	-8%	-8%	*-8%*	-8%
Spain	345	345	345	345	*345*	345	-2%	-2%	-2%	-2%	*-2%*	-2%
Sweden	53	53	53	53	*53*	53	-15%	-15%	-15%	-15%	*-15%*	-15%
UK	270	270	270	238	*238*	242	-17%	-17%	-17%	-27%	*-27%*	-26%
EU-15	2955	2955	2955	2614	*2614*	2626	-78%	-78%	-78%	-80%	*-80%*	-80%

Table 8.7: Emission control costs for SO_2 and NH_3 (in million ECU/year)

	SO_2						NH_3					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*	Joint optim.
Scenario	REF	C1/C	C7	C11		C12	REF	C1/C	C7	C11		C12
	Total costs	Additional costs on top of REF					Total costs	Additional costs on top of REF				
Austria	245	0	0	0	*0*	0	4	0	0	0	*0*	0
Belgium	231	0	0	146	*146*	138	22	0	0	0	*0*	0
Denmark	103	0	0	121	*121*	120	41	0	0	225	*225*	222
Finland	152	0	0	10	*10*	10	34	0	0	0	*0*	0
France	1369	0	0	191	*191*	178	1	0	0	0	*0*	0
Germany	2624	0	0	352	*352*	284	0	0	0	1364	*1364*	1319
Greece	221	0	0	0	*0*	0	0	0	0	0	*0*	0
Ireland	79	0	0	198	*198*	174	206	0	0	244	*244*	244
Italy	1809	0	0	56	*56*	39	0	0	0	46	*46*	33
Luxembourg	10	0	0	0	*0*	0	12	0	0	0	*0*	0
Netherlands	208	0	0	36	*36*	35	797	0	0	0	*0*	0
Portugal	169	0	0	0	*0*	0	0	0	0	0	*0*	0
Spain	536	0	0	147	*147*	143	92	0	0	0	*0*	0
Sweden	320	0	0	0	*0*	0	16	0	0	0	*0*	0
UK	790	0	0	784	*784*	711	0	0	0	70	*70*	58
EU-15	8867	0	0	2041	*2041*	1832	1225	0	0	1949	*1949*	1876

Table 8.8: Emission control costs for NO_x and VOC and the sum for all pollutants (in million ECU/year)

	NO_x and VOC						Total for all pollutants					
		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*[1])	Joint optim.		AOT60 50% GC	AOT40 REF+ 10%avg	Acidi-fication	*max.*	Joint optim.
Scenario	REF	C1/C	C7	C11		C12	REF	C1/C	C7	C11		C12
	Total costs	Additional costs on top of REF					Total costs	Additional costs on top of REF				
Austria	702	0	308	0	308	223	951	0	308	0	308	223
Belgium	808	198	54	31	198	119	1062	198	54	177	344	257
Denmark	331	0	13	12	20	11	475	0	13	358	366	353
Finland	487	0	0	0	0	0	672	0	0	10	10	10
France	5207	496	605	38	621	534	6577	496	605	229	812	712
Germany	8001	578	1098	62	1098	886	10625	578	1098	1778	2814	2489
Greece	461	36	62	0	75	68	683	36	62	0	75	68
Ireland	200	0	0	53	53	45	485	0	0	495	495	463
Italy	5571	0	565	0	565	509	7380	0	565	102	667	581
Luxembourg	53	0	0	0	0	0	74	0	0	0	0	0
Netherlands	1006	189	226	6	231	229	2011	189	226	42	267	264
Portugal	863	372	248	0	372	372	1032	372	248	0	372	372
Spain	3486	191	113	0	202	174	4115	191	113	147	349	317
Sweden	920	0	0	0	0	0	1257	0	0	0	0	0
UK	4964	1345	256	291	1637	1820	5754	1345	256	1145	2491	2589
EU-15	33061	3405	3548	493	5380	4990	43152	3405	3548	4483	9370	8698

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.

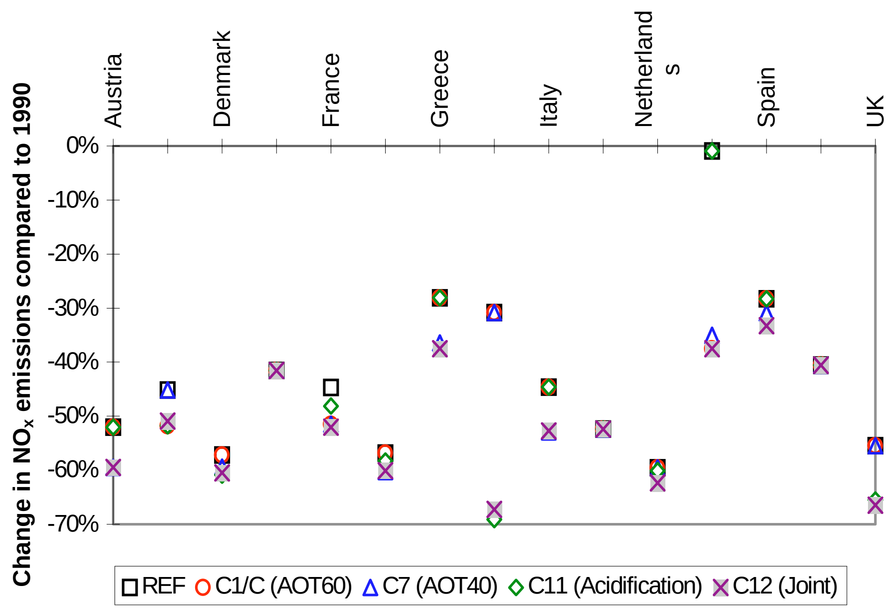

Figure 8.3: Change in NO_x emissions for the combined scenarios

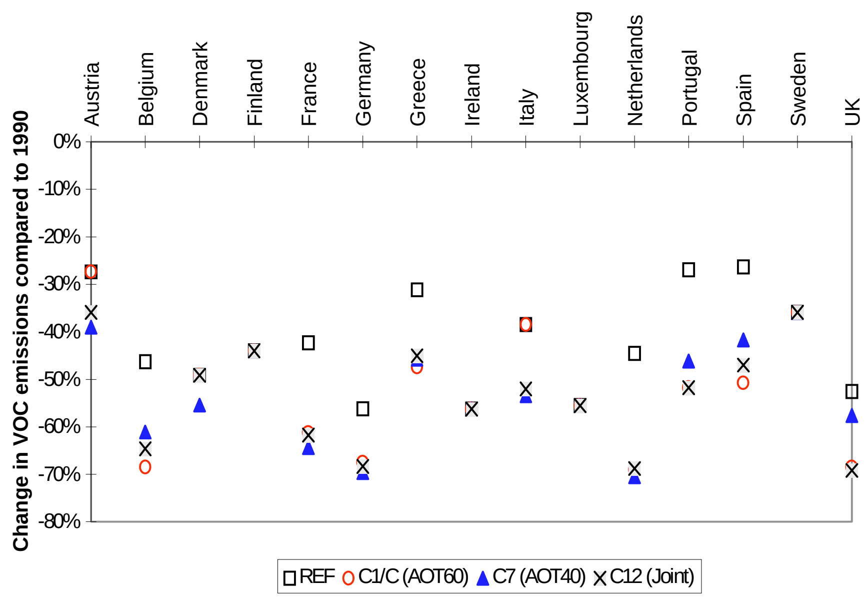

Figure 8.4: Change in VOC emissions for the combined scenarios

8.3 Comparison of the Exposure Indices

Table 8.9 to Table 8.11 compare the cumulative exposure indices for vegetation, human health and acid deposition. It is interesting to note that the optimization does not always yield the minimum cumulative exposure index for the target environmental problem. For instance, in case of the cumulative population exposure index, the AOT4-optimization achieves (at similar costs) for the EU-15 a lower cumulative exposure index 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 for the cost-effectiveness of scenarios. For instance, the wider scope of the ‘ten percent improvement over the REF gap closure’ target as used for the AOT40-optimizations yields for the EU-15 a higher overall protection than the ‘peak-shaving’ implied with the uniform minimum gap closure targets of the illustrative AOT60 optimizations. Further work will be necessary to explore this aspect in more detail and to maximize the possible benefits.

Figure 8.5 to Figure 8.7 graphically display the cost-effectiveness of the scenarios in relation to the different environmental problems. Although the combined solutions always show in these graphs higher total abatement costs than the optimizations focused on individual problems, alone, they are still the most cost-effective way of achieving the various targets simultaneously.

Table 8.9: Comparison of the AOT40 cumulative vegetation exposure indices (million hectares.excess.ppm.hours)

	REF	C1/C (AOT60)	C7 (AOT40)	C9 (AOT40+ AOT60)	C11 (acid)	C12 (O3+acid)
Austria	27	25	22	22	27	22
Belgium	15	12	12	12	15	12
Denmark	5	4	4	4	5	3
Finland	0	0	0	0	0	0
France	252	200	200	195	246	196
Germany	132	107	101	99	130	101
Greece	15	15	13	13	15	13
Ireland	1	0	0	0	1	0
Italy	122	115	102	102	121	103
Luxembourg	1	1	1	1	1	1
Netherlands	9	6	6	6	9	6
Portugal	29	22	23	22	28	21
Spain	134	109	110	108	133	104
Sweden	2	1	1	1	2	1
UK	20	12	15	12	21	13
EU-15	632	523	510	499	624	498

Table 8.10: Comparison of the AOT60 cumulative population exposure indices (million persons.excess.ppm.hours)

	REF	C1/C (AOT60)	C7 (AOT40)	C9 (AOT40+ AOT60)	C11 (acid)	C12 (O3+acid)
Austria	5	4	3	3	5	3
Belgium	37	26	26	25	37	26
Denmark	3	2	2	2	3	2
Finland	0	0	0	0	0	0
France	108	69	69	65	103	67
Germany	140	102	97	95	137	97
Greece	4	3	3	3	4	3
Ireland	2	1	1	1	1	1
Italy	62	55	39	39	61	40
Luxembourg	1	1	1	1	1	1
Netherlands	43	30	30	29	42	29
Portugal	9	5	6	5	9	5
Spain	13	7	7	7	13	7
Sweden	2	1	1	1	2	1
UK	80	45	56	45	80	45
EU-15	367	249	245	226	360	229

Table 8.11: Ecosystems with acid deposition above their critical loads for acidification (1000 hectares)

	REF	C1/C (AOT60)	C7 (AOT40)	C9 (AOT40+ AOT60)	C11 (acid)	C12 (O3+acid)
Austria	935	929	899	915	733	724
Belgium	70	70	70	70	35	35
Denmark	16	16	16	16	7	7
Finland	1305	1304	1302	1302	1237	1236
France	155	154	154	154	121	121
Germany	2653	2611	2561	2573	1284	1273
Greece	0	0	0	0	0	0
Ireland	240	240	240	240	123	123
Italy	848	832	784	802	679	668
Luxembourg	32	31	31	31	12	12
Netherlands	127	126	126	126	53	53
Portugal	0	0	0	0	0	0
Spain	24	24	24	24	10	11
Sweden	1109	1108	1106	1107	871	874
UK	1548	1541	1539	1540	650	669
EU-15	9064	6374	6292	6327	4532	4532

Table 8.12: Emission control costs for the different scenarios (in million ECU/year)

	Total costs REF	Additional costs on top of REF C1/C (AOT60)	C7 (AOT40)	C9 (AOT40+ AOT60)	C11 (acid)	C12 (O3+acid)
Austria	951	0	308	262	0	223
Belgium	1062	198	54	106	177	257
Denmark	475	0	13	0	358	353
Finland	672	0	0	0	10	10
France	6577	496	605	605	229	712
Germany	10625	578	1098	954	1778	2489
Greece	683	36	62	66	0	68
Ireland	485	0	0	0	495	463
Italy	7380	0	565	506	102	581
Luxembourg	74	0	0	0	0	0
Netherlands	2011	189	226	200	42	264
Portugal	1032	372	248	372	0	372
Spain	4115	191	113	167	147	317
Sweden	1257	0	0	0	0	0
UK	5754	1345	256	1244	1145	2589
EU-15	43152	3405	3548	4482	4483	8698

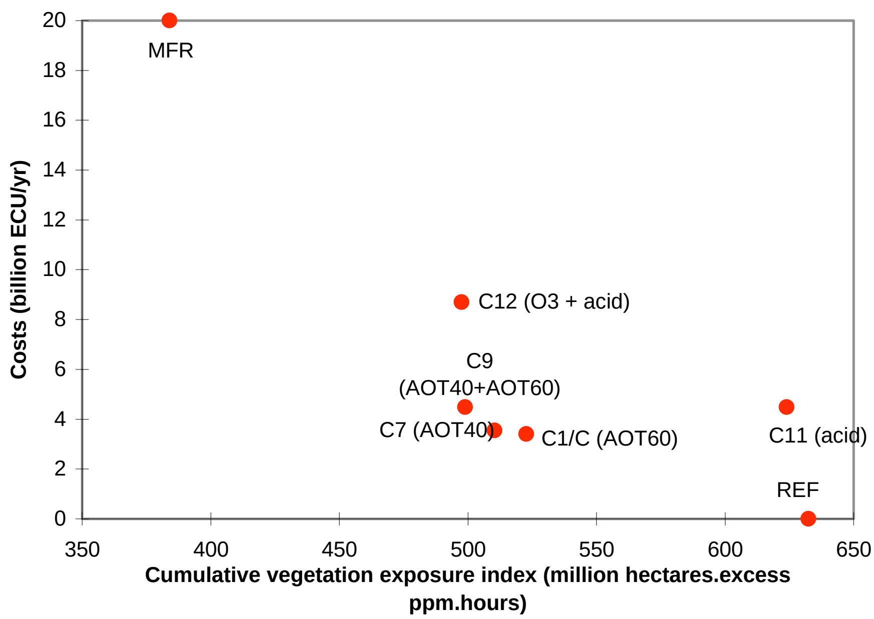

Figure 8.5: Cost-effectiveness of the scenarios for the AOT40 cumulative vegetation exposure index

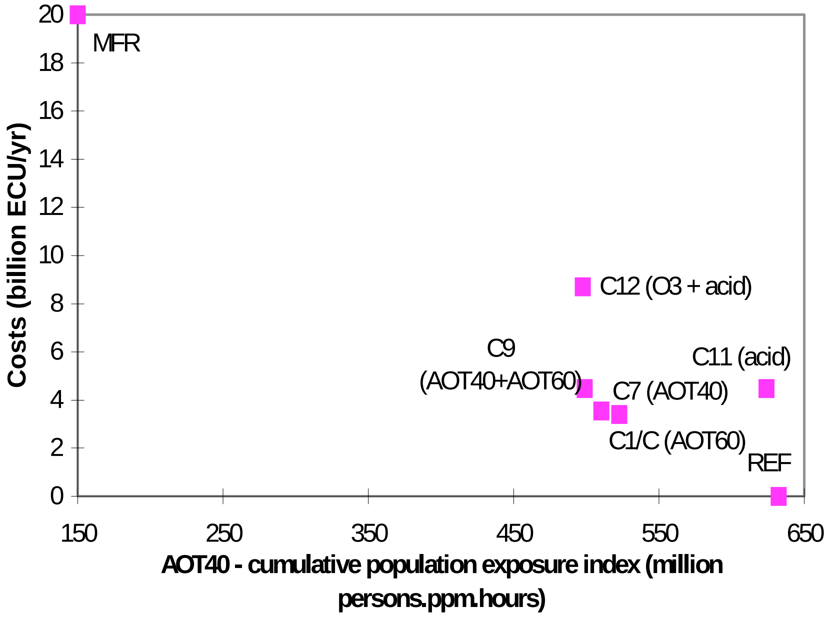

Figure 8.6: Cost-effectiveness of the scenarios for the AOT40 cumulative vegetation exposure index

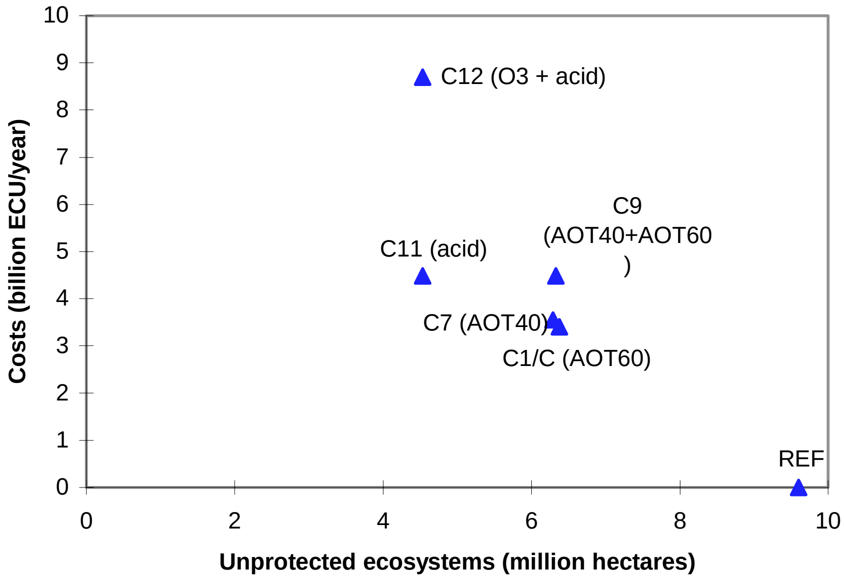

Figure 8.7: Cost-effectiveness of the scenarios for the protection of ecosystems against acidification

9. Summary of the Scenarios and Conclusions

9.1 Summary of the Scenarios

The scenarios presented in this report provide a first 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 until now.

The currently available models support the theory that at the moment there are two fundamentally 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 disappears and 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 everywhere the environmental long-term targets discussed for the ozone strategy. 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 as 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 has 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. Using the mean meteorological conditions, there is a clear downwards trend of the AOT60 resulting from the current policy. A cumulative populatoin exposure index (which combines the population densities with the actual ozone levels) is expected to decrease by 55 percent compared to 1990, and could be brought down further by implementing the maximum control (-82 percent 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 for the EU-15 countries, the cumulative exposure index shows a variation of ±40 percent in relation to that of the mean meteorology.

It is essential to decide about the protection target, i.e., whether a certain protection level must be achieved also under the worst condition, or whether a certain (frequency of an) excess is acceptable. If no violations are allowed at all, 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 bringing the large-scale excess exposure down.

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 almost 60 percent.

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 to satisfy the environmental constraints also 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 15 percent lower than those of the simple approach, where the most stringent emission reductions from five individual solutions are combined .

To explore some practical emission control strategies, scenarios have been calculated for health-related gap closures of 45 percent, 50 percent and 55 percent. Due 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 set of scenarios 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 36 percent compared to 1990, and the maximum feasible emission reductions could bring it down by 60 percent. 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 Reference 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 10 percent 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.

9.2 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 has been shown via sensitivity analysis that the potential for additional emission reductions from mobile sources may significantly change the requirements for stationary sources. It is planned to address this issue in one of the next reports in more detail.

A further shortcoming of this report is the exclusion of possible emission controls in the non-EU countries. This decision was purely motivated by time considerations, and it is firmly planned to extend the analysis to the non-EU countries in the future.

Finally, also the restriction to a single energy- and transport-scenario has to be seen as a serious deficiency of this report. It is foreseen to revisit this issue in the near future, taking into account, i.a., the decisions made at the Kyoto conference on future emissions of greenhouse gas emissions.

9.3 Conclusions

Despite the preliminary character of some the modelling tools and databases, some robust conclusions can already 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 currently discussed for the EU Ozone Strategy 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 clearly specify the accepted extent of exceedences of the target levels. Preparing for the most unfavorable conditions might prove expensive and might not yield the optimal reduction for the average conditions.

- Starting from the currently planned emission control measures, the further reduction of health-related ozone exposure tends in most countries mainly towards additional VOC control, while approaching vegetation-related protection criteria will activate also further NO_x control.

- 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 will be possible. There is concrete planning to address the most important issues in the near future.

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