Stefan Reis

Costs of Air Pollution Control

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Analyses
of Emission Control Options
for Ozone Abatement
Strategies

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With 94 Figures

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Abstract

This book describes the development and application of methods for the identification of cost-effective strategies for the abatement of ozone precursor substances (mainly nitrogen oxides, NO_x and non-methane volatile organic compounds, NMVOC) in Europe. To achieve this, a trend scenario for the development of NOx and NMVOC emissions has to be established. This scenario takes into account technological change as well as changes in activity rates in the relevant emission source sectors. In addition to that, the impacts of EU policies and legislation in place and in pipeline, for instance on road transport and on large combustion plants is reflected.

The development of such a trend scenario is of particular importance for the following assessment of emission control options beyond the business-as-usual development and their effects on ambient ozone levels. For this assessment, a model system had to be developed wich allows for an in-depth cost-effectiveness assessment of implemented measures. Furthermore, this model system makes it possible to identify emission targets to achieve compliance with EU thresholds, e.g. as set in the EC Daughter Directive on Ozone or as established by the World Health Organisation (WHO).

In an additional step, abatement costs for selected strategies are compared with avoided damage costs (i.e. benefits) due to reduced ambient ozone concentrations to conduct a comprehensive cost-benefit-assessment for a thorough evaluation of abatement strategies.

After the evaluation of different control scenarios, a set of conclusions can be drawn with respect to the future design of European air pollution control strategies. First, it is evident that even assuming full compliance with the EC National Emission Ceilings Directive (NECD) in the year 2010 and the thus resulting emission levels of NO_x and NMVOC, significant exceedances of air quality limit values for groundlevel ozone with regard to human health will occur all over Europe. In addition to that, the threshold set for the protection of agricultural crops, AOT40 (accumulated ozone over a threshold of 40 ppb, calculated for the growing season of April to June) cannot be achieved even by most stringent emission control options.

Based upon the model calculations conducted, an emission reduction of approx. 50% in the mid-term, and of about 80% on the long run below the trend scenario 2010 values would be needed to achieve compliance with ozone target values. As a comparison, the totel EU15 emission values for the NEC Directive are approx. 37% below the trend scenario emissions calculated here for NO_x and NMVOC. Finally, the potential contributions of emission control activities in Central and Eastern Eu-

rope in the frame of the accession process are evaluated on the example of Poland, the Czech Republic and Hungary. Here it is evident, that emission control in these countries will both positively affect ozone levels in EU15 countries, and lead to mutual benefits in terms of reduced damage costs.

In summary, a number of recommendations for the design of European air pollution control policies, in particular on groundlevel ozone, can be derived from the results of this work. From the perspective of cost-benefit analysis, it is strongly recommendable to move towards holistic, integrated evaluations of air pollution control, taking into account all relevant air pollutants and their effects. Only then it is possible to fully account for the partly significant synergy effects and hidden benefits from the reduction of air pollutants, without overestimating the costs versus the benefits. Furthermore, the established ozone thresholds and the mid- and long-term approaches for the development of emission limits in the frame of the Clean Air for Europe (CAFE) strategy should be reviewed.

Preface

During the summers of recent years, Germany – and other countries in Europe – experienced a considerable number of days, where limit values for ground level ozone set for the protection of human health were exceeded. This occurred in spite of reductions of ozone precursor emissions in Europe during the 1990s due to European and national environmental legislation. And with European air quality limit values having become more and more stringent over time, the question arises, to what extent emission control measures will have to be implemented to achieve compliance with short and long term targets for ozone and other air quality problems.

Emission control, however, is usually associated with considerable costs. Thus, air pollution control strategies do not only have to take into account compliance issues. Cost-effective approaches to achieve targets have to be identified. In addition to that, benefits arising from reduced levels of air pollution need to be accounted for in the frame of a cost-benefit assessment of different options to reduce air pollutant emissions, in order to find the most efficient pathway to improved air quality.

The research work described by this book tries to address all of these tasks, with the ultimate goal to improve the methodology and application of cost-effectiveness and cost-benefit analyses of air pollution control options. Its results aim to give answers to the most important questions associated with the reduction of ozone precursor emissions, their impacts on ground level ozone concentrations, and further options to achieve long-term air quality limit values set in the EC Ozone Daughter Directive, which has recently passed the final steps of the legislative process. The following chapters address key aspects of state-of-the-art research in the field of air pollution control, focusing on tropospheric ozone, as it brings together multiple disciplines, namely environmental sciences, engineering and economics to conduct a full scale assessment with the aim of providing tools and methods for policy development.

Acknowledgement

Any research conducted nowadays is marked by a high level of collaboration, even more so, when interdisciplinarity and integration of methods and tools are the focus of the scientific work. Hence, the work described in this book would have been impossible withouth the invaluable contributions, inspirations and comments of several colleagues. I would like to express my gratitude to the partners working in the

research project INFOS, funded by the European Commission, Directorate General for Reserarch for their excellent work which has formed the basis for the analysis conducted. In particular, I am greatly indebted to Dr. David Simpson, who never failed to ask the right questions and even more often helped to solve problems coming up with simply brilliant solutions. In addition to that, I would like to thank my supervisors, Prof. Dr.-Ing. Rainer Friedrich and Prof. Dr.-Ing. Günther Baumbach, as the work described here would have been simply impossible without their fair comments and experience.

Special thanks go to my colleagues at the Institute of Energy Economics and the Rational Use of Energy at the University of Stuttgart, Germany, in particular my coworkers in the Air Polluction Control Section, who did their share to support my work and offer helpful comments and support whenever needed.

Finally, without the inspiration and vision of my supervisor, Prof. Anthony Clayton, providing guidance while I was working on my diploma thesis at the University of Edinburgh back in 1996, I am not sure if I would have considered taking up scientific research at all. And last but - for sure - not least, there is no way to adequately express my gratitude for the never faltering support of my parents, Karl-Josef and Hildegard Reis, who encouraged me to pursue my goals and thus have a considerable share in the realisation of this book.

Contents

List of Acronyms and Abbreviations

AOTxx	Accumulated Ozone Exposure over a Threshold of xx ppb
BAT	Best Available Technology
BAU	Business As Usual
CAFE	Clean Air For Europe
CBA	Cost Benefit Analysis
CCC	Chemical Coordinating Centre
CEA	Cost Effectiveness Analysis
CIAM	Centre for Intetrated Assessment Modelling
CL	Critical Load/Level
CLRTAP	Convention on Longe Range Transboundary Air Pollution
CO	Carbon Monoxide
CORINAIR	Emission Inventory for Air Pollutants under CORINE
CORINE	Co-ordination d'Information Environmental
CRF	Common Reporting Format
CTM	Chemisty Transport Model
DG	Directorate General
EAP	Environmental Action Plan
EC	European Commission
ECE	*see* UNECE
EEA	European Environment Agency
EF	Emission Factor
EGTEI	Expert Group on Techno-Economic Issues
EMEP	European Monitoring and Evaluation Programme
ETCAQ	European Topic Centre Air Quality
EU(15)	European Union (15 Member States, *before the 2004 enlargement*)
EUDC	Extra Urban Driving Cycle
EUROPIA	European Petroleum Industry Association
EUROSTAT	Statistical Office of the European Communities
EUROTRAC	Project on the Transport and Chemical Transformation of Environmentally Relevant Trace Constituents in the Troposphere over Europe
EZM	European Zooming Model

FGR	Flue Gas Recirculation
GC	Gap Closure
GDP	Gross Domestic Product
GENEMIS	Generation of Emission Data for Episodes (EUROTRAC Subproject)
GHG	Greenhouse Gas
GIS	Geographical Information System
GNP	Gross National Product
HC	Hydrocarbons
HDV	Heavy Duty Vehicle
HM	Heavy Metal
HVLP	High Volume Low Pressure
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution Prevention and Control
LCP	Large Combustion Plant
LDV	Light Duty Vehicle
LEA	Low Excess Air
LNB	Low-NO_x Burner
MC	Motorcycle
MP	Moped
MSC-W	Meteorological Synthesizing Centre - West
MSC-E	Meteorological Synthesizing Centre - East
n.a.	not applicable
NEC(D)	National Emission Ceilings (Directive)
NEDC	New European Driving Cycle
NFR	Nomenclature for Reporting
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxide
O&M	Operation and Maintenance
OECD	Organisation for Economic Cooperation and Development
OFA	Over Fire Air
OFP	Ozone Forming Potential
OTC	Open-Top Chamber
p.a.	per annum
PC	Passenger Car
PM_{xx}	Particulate Matter *(with a diameter of less than xx μm)*
POPs	Persistent Organic Pollutants
POCP	Photochemical Ozone Creation Potential
ppm (ppb)	parts per million (billion)
SCR	Selective Catalytic Reduction

SEI	Stockholm Environment Institute
SNAP	Selected Nomenclature for Air Pollutants
SO_2	Sulphur Dioxide
SR-M	Source-Receptor Matrices
TFEIP	Task Force Emission Inventories and Projection
TFIAM	Task Force Integrated Assessment Modelling
UNECE	United Nations Economic Commission for Europe
US EPA	United States Environmental Protection Agency
WHO	World Health Organisation

1 Introduction

1.1 Scope

In the course of the last two or three decades, the concept and perception of air pollution control has undergone quite significant changes. Initially, policy action was driven by impacts alone, for instance severe forest damages and the public awareness which induced significant reductions of sulphur emissions by multilateral policies as well as stringent domestic emission control strategies. With increasing scientific understanding of the complex structure of environmental impacts and the development of more general, integrated approaches to address them, issues such as costs and effectiveness of strategies moved into the focus of policy design and decision making.

In the case of air pollution control, cost-effectiveness assessment became a modelling task which had increasing influence on the very design of policy implementation, e.g. the negotiations on individual protocols to the Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE). However, most of the early models did not address all relevant aspects and often were not transparent and flexible enough. Thus, the first task of this work here was the development and application of an advanced modelling framework which was capable of conducting cost-effectiveness analysis and even cost-benefit assessment of air pollution control strategies. This modelling framework was built around an optimisation model to find cost-effective solutions to achieve given air quality targets for tropospheric ozone, termed OMEGA-O_3 (Optimisation Model for Environmental Integrated Assessment - Ozone version), which was designed to avoid the aforementioned shortcomings of previous models. The problem of tropospheric ozone was deliberately chosen as it is marked by a non-linear relationship between the emissions of ozone precursor substances (mainly nitrogen oxides and non-methane volatile organic compounds) and hence a sophisticated modelling approach had to be established to properly relate emissions to resulting ambient ozone levels while applying a full-scale chemistry transport model (CTM) was not feasible for a vast number of optimisation runs. Furthermore, as the lack of transparency and flexibility was often a cause of major criticism of previously developed models, the model design had to act on the dictum of transparent and flexible design which shall facilitate the interpretation of model results and to contribute to quality control of the models' outcome.

While the model development and application form the core and main innovation

of the work described in this book, another major effort had to be made to establish the data basis on which the model is run. This task has proven to be significant as the quality of modelling results is extremely dependent on the quality of the data input (precursor emissions, abatement efficiencies, abatement costs etc.). In comparison to previous studies, which often only take a rather coarse and general approach (e.g. total number of road vehicles or total TWh produced in a country). By developing a detailed, bottom up sectoral structure of the main emission sources, a more comprehensive assessment of abatement options and potentials was feasible, which distinguishes the assessment conducted in this book significantly from previous research work.

An assessment model as it is described here needs to operate on a spatial and temporal aggregation level which makes it difficult, if possible at all, to directly evaluate model results versus real-world data from measurements, as it is the case for instance for meteorological or atmospheric dispersion models. As described in the final part of this work, model results have instead been evaluated for instance against the calculations of a full chemical transport model (CTM), which has been frequently validated itself versus measurements and within model intercomparisons.

The OMEGA-O_3 model and the whole modelling framework was applied in the frame of the European research project "Assessment of Policy Instruments for Efficient Ozone Abatement Strategies in Europe" (INFOS) funded by the Directorate General for Research (see *Friedrich and Reis, 2000*) and provided valuable results for the design of cost-effective ozone control strategies. Furthermore, the methodologies developed in the course of the design, testing and application of the OMEGA-O_3 model have significantly advanced the state-of-the-art of the general model development of integrated assessment models (IAMs), thus serving as a testbed for highly innovative further work. The lessons learned from OMEGA-O_3 provide direct guidance for the currently ongoing design and implementation of the OMEGA-2 integrated assessment model, which, as a logical step forward, addresses cost-effectiveness and cost-benefit assessment in a multi-pollutant multi-effect framework covering all relevant pollutants and incorporating as well greenhouse gases (see *Tarrason et al. 2001*, as well as *Reis et al. 2001*, *2002* and *2003*).

1.2 Aims

In summary, the aims of this book are to describe the development and application of an innovative optimisation model (OMEGA-O_3) for cost-effectiveness assessment (CEA), applying an iterative approach to find least-cost solutions to reduce tropospheric ozone concentrations. To operate this model, a vital preparatory step was the in-depth analysis and projection of input data for the calculation of cost-effective ozone abatement strategies for Europe, with particular focus on the assessment of the status-quo and the future development of emissions of ozone precursors (NO_x and NMVOCs in particular), abatement options and their related costs. Here

it was necessary to develop a much more detailed sectoral assessment of the relevant sources of ozone precursors, in particular road transport, energy production and solvent use than it was done in previous studies. Emission calculation and projection was conducted on the level of individual technologies, offering unique insight into potential abatement options and allowing for a comprehensive assessment. In addition to that, to conduct a detailed cost-benefit assessment (CBA), evaluating reduced damage costs due to reduced concentrations of ground level ozone versus the respective abatement costs, both in absolute terms and relative to countries' GDP to investigate the distributional effects of strategies and discuss issues of equity. Finally, with the accession process of countries from Central and Eastern Europe well under way, investigate, in how far the inclusion of selected Accession countries into emission control considerations would affect the results of the CEA and CBA analysis and derive recommendations for policy implementation.

Last, but not least, the work described in this book served as a means to conduct a proof of concept testing individual modules and scientific approaches, in particular for the modelling of non-linear air pollution problems, for a more general design of an integrated assessment modelling framework. In this respect its results - not just the numerical outcome of the assessment model, but the findings through model development and testing of different approaches and theories - have laid the foundations for the design of a project addressing the multi-pollutant multi-effect assessment of European air pollution control strategies, which are currently conducted in a further research project funded by the European Commission, the MERLIN project[1].

1.3 Structure

Following this introduction, air pollution in Europe is discussed with particular focus on tropospheric ozone (*Chap. 2*). There, the main driving forces for the development of a model framework are illustrated and put into perspective with current activities in environmental policy on different levels. After identifying the driving forces and defining the problem, the sources of emissions of ozone precursor substances are analysed as a basis for the subsequent development of a business-as-usual trend scenario (*Chap. 3*). Furthermore, options for emission control and the related costs are introduced and evaluated. In *Chap. 4*, the development of the assessment model for cost-effectiveness assessment is described in detail, addressing core model design as well as model evaluation and uncertainty treatment. The discussion and interpretation of modelling results is conducted in *Chap. 5*, focusing on cost-effectiveness and cost-benefit analysis, as well as the further analysis of additional reductions and aspects of EU enlargement and its influence on ozone abatement strategies. A further evaluation, with respect to the implications of the model

1. *http://www.merlin-project.info, 03.08.2004*

results for the design of efficient ozone control strategies, is conducted next (*Chap 6*). Finally, the conclusions summarise the findings of this work and an outlook is given on further research needs in *Chap. 7*.

2 Air Pollution in Europe

2.1 Introduction

2.1.1 Scope - Tropospheric Ozone put in Perspective

Table 2.1. Air pollutants and their effects *('+': medium impact, '++': major impact)*

Effects / **Pollutants**	**Tropospheric ozone**	**Acidification**	**Eutrophication**	**Urban air quality**	**Soil Contamination**	**Visibility**	**Formation of aerosols**	**Global Warming**
NH_3		++	++				++	
SO_2		++					++	
NO_x	++	++	++				++	
NMVOC	++						++	
CO	+			+				
Particulate Matter $PM_{2.5}$,				++		++	++	
CO_2								++
CH_4								+
N_2O								+
Heavy Metals (Pb, Cd, ...)				+	++			
Benzene				++			+	

The European Environment Agency (EEA) recently stated in their report *Environment in the European Union at the turn of the century* that *„Transboundary air pollution is a pan-European problem ...“*. This might seem trivial, but results of recent research indicates, that in spite of considerable emission reductions for the major air pollutants being projected until the year 2010, critical loads for acid and nitrogen deposition and limit values for tropospheric ozone will still be exceeded in most parts of Europe. *Table 2.1.* shows the main air pollutants and their related effects, bringing the problem of tropospheric ozone into perspective with other environmental pressures (cf. *Hov 1997* and *OECD 1990*). In addition to this trend, increasing scientific understanding of atmospheric processes on local, regional and even global level indicates, that air pollution and global warming show mutual influence to a far greater extent than anticipated. Tropospheric ozone, as an example, causes radiative forcing, while aerosols, partly caused by nitrogen oxides as well, can have both a cooling and warming effect. Thus, in the following sections, the focus will always be on tropospheric ozone, while trying to put it into perspective with other pollutants and effects1.

2.1.2 Emission Inventories and Monitoring in Europe

Among several activities to develop consistent and comprehensive emission inventories for Europe, the main projects are the CORINAIR inventory of air pollutant emissions and the EMEP programme. These two will now be described in detail:

2.1.2.1 The CORINAIR Emission Inventory

The CORINE (**co**-**or**dination d'**in**formation **e**nvironnementale) work programme was established by Council Decision 85/338/EEC (European Communities, 1985) and aiming at gathering consistent information about the environment and natural resources. A project to gather and organise information about relevant air pollutants (at that time related to acid deposition) was included and termed CORINAIR. The first CORINAIR emission inventory was compiled for the year 1985, containing information on SO_2, NO_x and VOC (as total volatile organic compounds) from the 12 Member States of the European Community. For the next inventory, CORINAIR 90, the system of previously 8 main source sectors was enhanced significantly, resulting in a SNAP sector structure covering all major sources of air pollutant emissions in about 260 different activities (*see Table 2.2.*).

The complete set of CORINAIR 90 SNAPs can be found in *ANNEX I.*In addition to this sectoral structure, data are collected for large point sources individually, covering power plants with a thermal input capacity of ≥ 300 MW, refineries, airports and other large installations. For area sources (all smaller sources emitting in a more diffuse manner) CORINAIR gathers emission data on an administrative boundary based level (county/department) called NUTS (level 3), CORINAIR 90 aims at providing a complete, consistent and transparent inventory for air pollutant emissions

in Europe for policy, research and other purposes. And in order to attain consistency, CORINAIR and EMEP have maintained close links and harmonised approach and methods throughout the project (*Eggleston 1996*).

Table 2.2. CORINAIR 90 sectoral structure

SNAP	Source Sector
1	Public power, cogeneration and district heating plants
2	Commercial, institutional and residential combustion plants
3	Industrial combustion
4	Production processes
5	Extraction and distribution of fossil fuels
6	Solvent use
7	Road transport
8	Other mobile sources and machinery
9	Waste treatment and disposal
10	Agriculture
11	Nature

After the inventory for 1990, a next dataset was prepared for the year 1994, with a slightly changed sectoral split accounting for a growing awareness that for some sectors, e.g. road transport, the initial sector definition was insufficient. The sectoral split was enhanced even more, leading to the current SNAP97 sectors, and additional pollutants were included- Besides the „classic" air pollutants, *heavy metals*, *persistent organic pollutants* (POPs) and *greenhouse gases* (GHGs) are taken into account today. In spring 2000, the 2nd edition of the joint EMEP/CORINAIR Emission Inventory Guidebook was published, which presents the by far most detailed and comprehensive description of methods and approaches used as the basis for the generating emissions for the CORINAIR emission inventory. The latest development in this field is the on-line-publication of the 3rd edition of the joint EMEP/CORINAIR Emission Inventory Guidebook in 2001[1]. Furthermore, harmonisation activities to bring together reporting requirements for different pollutants and to different supranational bodies are currently nearing completion. Even though a final layout has still to be defined, a synthesis of reporting requirements for air pollutants and greenhouse gases in one *common reporting format* (CRF) has been adopted in 2002.

1.*http://reports.eea.eu.int/technical_report_2001_3/en, 09.07.2004*

2.1.2.2 The EMEP Programme

In the frame of the Convention on Long Range Transboundary Air Pollution, the EMEP Programme (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe) has been set up to regularly provide Governments and subsidiary bodies under the Convention with qualified scientific information to support the development and further evaluation of the international protocols on emission reductions negotiated within the CLRTAP.

While focusing on assessing the transboundary transport of acidification and eutrophication initially, the scope of the EMEP programme has widened to address the formation of ground level ozone and, more recently, of persistent organic pollutants (POPs) and heavy metals.

The three main elements of EMEP are the collection of emission data, measurements of air and precipitation quality and finally, the modelling of atmospheric transport and deposition of air pollution. By combining these three elements, EMEP fulfils its required assessment and regularly reports on emissions, concentrations and/or depositions of air pollutants, the quantity and significance of transboundary fluxes and related exceedances to critical loads and threshold levels.

EMEP is set up in three different facilities:

- The Chemical Coordinating Centre (CCC), co-ordinating and inter calibrating chemical air quality and precipitation measurements,
- The Meteorological Synthesizing Centre-West (MSC-W) being responsible storage and distribution of reliable information on emissions and emissions projections, This centre is also responsible for the modelling assessment of sulphur, nitrogen and photo-oxidant pollutants,
- The modelling development for heavy metals and persistent organic pollutants (POPs) is within the responsibility of the Meteorological Synthesizing Centre-East (MSC-E).
- The recently formed Centre for Integrated Assessment Modelling (CIAM) supporting the work of the UNECE Task Force on Integrated Assessment Modelling (TFIAM)

Presently, about 100 monitoring stations in 24 countries participate in EMEP (*Fig. 2.1.*).

Fig. 2.1. EMEP Ozone monitoring stations in Europe

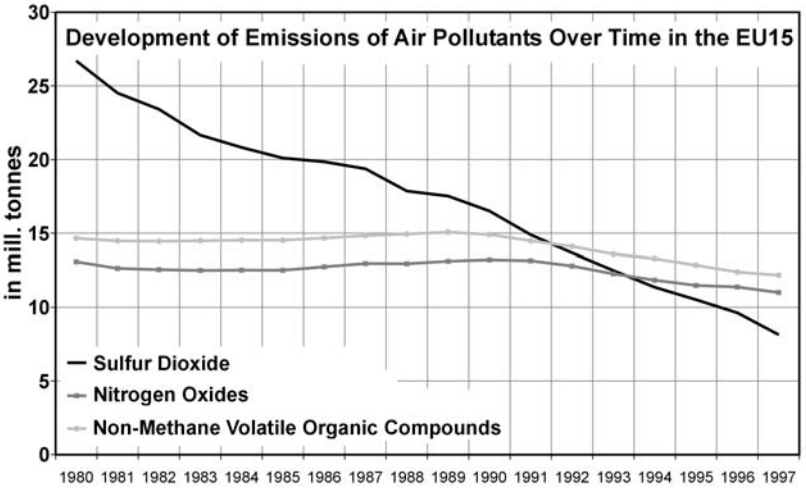

Fig. 2.2. Development of SO_2, NO_x and NMVOC Emissions in Europe (EU_{15}) over time (Source: EMEP WEBDAB, 2004)

2.1.3 Development of Air Pollutant Emissions over Time

Fig. 2.2. shows the development of emissions of three major air pollutants, NO_x, NMVOC and SO_2 over time. As can be seen, the emissions of SO_2 have been cut significantly during the last decade, mainly by introducing de-sulphurisation in large combustion plants, and reducing the sulphur content of liquid fuels. The beginning decrease of NO_x and NMVOC emissions in early 1990s falls in line with the introduction of three-way-catalysts (TWC) and the implementation of the EURO 1 emission standard for road transport vehicles. However, the increases in vehicle fleet and annual mileage consume a considerable share of the reduction. A further projection of how these emissions develop has to take into account all relevant activities and policies in place and in pipeline, which could affect the specific emissions of a source, as can be seen in *Chap. 3.*

2.2 Focus: Tropospheric Ozone

2.2.1 Ozone Formation in the Troposphere – The Tropospheric Cycle

Ozone is regarded to be the main photochemical oxidant present in the troposphere, originating from a formation process involving nitrogen oxides (NO_x), volatile organic compounds (VOC) and sunlight, VOCs are, according to the UNECE Gothenburg-Protocol of 1999, defined as follows:

"NMVOCs" comprise all organic compounds except methane which at 273.15 K show a vapour pressure of at least 0.01 kPa or which show a comparable volatility under the given application conditions.

They include pure hydrocarbons (containing only hydrogen and carbon) and organic compounds, containing further substances such as oxygen, nitrogen, chlorine or fluorine.[1]

This ozone formation process has been subject to thorough research for some time now, especially investigating the differing reactivities of the various hydrocarbons and their contribution to ozone production. Nitrogen oxides mainly originate from the combustion of fossil fuels, either in stationary sources (power and heat gen-

1. Other definitions are currently in use e.g. by the European Commission: The EC VOC-Directive (European Communities, 1999) defines VOCs as follows: *"An organic solvent is a volatile organic compound, which, without chemical transformation, by itself or in combination with other substances, dissolves raw materials, products or waste materials, or which is used as a detergent to dissolve residues, as a solvent, a dispersion substance or to increase viscosity or surface tension, as softener or conservation substance."*

eration) or mobile sources (road transport). Besides anthropogenic emissions of hydrocarbons, e.g. from road transport or the use of organic solvents, biogenic emissions from trees and other plants are of importance.

In the presence of NO_2 and sunlight, *Eqns. 2.1* and *2.2* describe how ozone is formed, In the absence of VOCs, ozone is reduced again according to *Eqn. 2.3*.

$$NO_2 + h \cdot \nu(\lambda < 410nm) \rightarrow NO + O(^3P) \qquad \text{E 2.1}$$

$$O_2 + O(^3P) \rightarrow O_3 \qquad \text{E 2.2}$$

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad \text{E 2.3}$$

Thus, NO, NO_2 and ozone concentrations form a stable equilibrium, which would not lead to such high ozone concentrations as they are currently observed, However, if VOCs are present, the following reactions (*Eqns. 2.4* and *2.5*) occur.

$$OH + RH + (O_2) \rightarrow RO_2 + H_2O \qquad \text{E 2.4}$$

$$RO_2 + NO \rightarrow NO_2 + RO \qquad \text{E 2.5}$$

RH is the representation of VOCs, in which H represents a hydrogen and R the rest of the molecule, e.g. CH_3, C_2H_5 or other alkyl radicals. As NO_x is oxidised according to *Eqn. 2.4*. it cannot reduce ozone (*Eqn. 2.3*), leading to an increase in ozone concentrations. The oxidation of NO to NO_2 by RO_2 or HO_2 molecules and subsequently the formation of O_3 from NO_2 and sunlight is described in more detail in *Fig. 2.3.*. Additional reactions of RO lead to further oxidation of NO.

2.2.1.1 Which thresholds should be targeted?

In general, there are two approaches to express limit values for tropospheric ozone, on the one hand, short term limit values such as hourly mean values of concentrations in ppb, ppm or $\mu g/m^3$, on the other hand thresholds for long term exposure, such as AOT. The concept of Accumulated Exposure Over a Threshold (AOT) expresses the exposure of crops, natural vegetation (e.g. forests) or population in ppm.h (see *Section 2.3.4*), counting the sum of differences between hourly ozone concentrations greater then the defined threshold of 40 or 60 ppb for each daylight hour ≥ 50 Wm^{-2}, resulting in a number of ppb.h (or ppm.h) for a receptor for a period of time. While limit values are mostly defined for the development of ozone legislation by the EC, AOT values are widely used in the scope of the UNECE and the EMEP programme (see *EMEP MSC-W, 1998*).

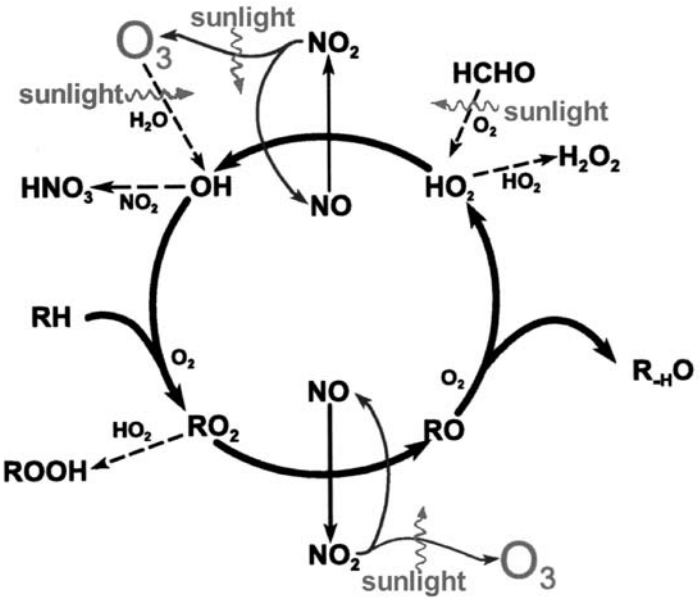

Fig. 2.3. Tropospheric cycles of catalysis (Source: PORG, 1997)

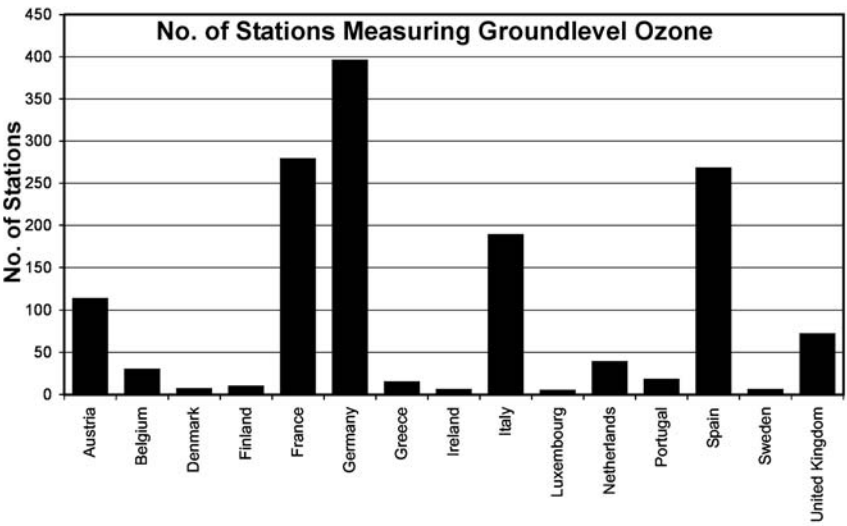

Fig. 2.4. The number of stations measuring groundlevel ozone by country

2.2.2 The Ozone Situation in 1999

The following section analyses the ozone situation as it has been monitored in the most recent year for which a complete dataset is available (i.e. 1999).

While *Fig. 2.4.* gives an overview on the number of monitoring stations for ground-level ozone in each EU member state, the seasonal development of occurrences of exceedances is displayed in *Fig. 2.5.*. The maximum observed concentrations remain on a considerably high level (above 300 µg/m³) from June to August, but the peak in ozone episodes was registered in July, regarding the duration of the exceedances as well as the number of stations concerned.

The number of days in exceedance of the alert threshold (180 µg/m³), set by the EC Ozone Directive in 1992 and kept by the new EC Daughter Directive on Ozone (European Communities 1997 and 2002) are given in *Fig. 2.6.*, showing, that ozone concentrations above 180 µg/m³ did not occur in Northern Europe, while especially Southern European countries faced a large number of exceedances in 1999. Finally, the maximum observed concentrations vary between 200 and 350 µg/m³, with the highest observed values in Italy and Spain (*Fig. 2.7.*). These measured ambient concentrations present the current state of the ozone problem to evaluate ozone abatement strategies against (cf. *Blanchard et. al., 1998* and *Möller, 2000*).

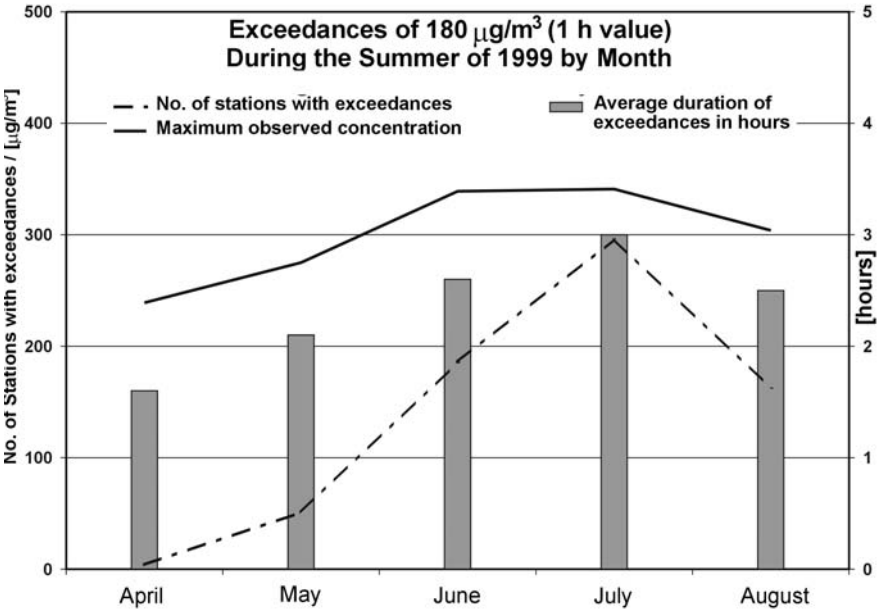

Fig. 2.5. Development of exceedances of 180 µg/m³ (threshold for the information of the public) during the summer of 1999 and average duration of the exceedances in hours in the 15 EU Member States (EU15, before the enlargement of 2004) (Source: *EEA 1999*)

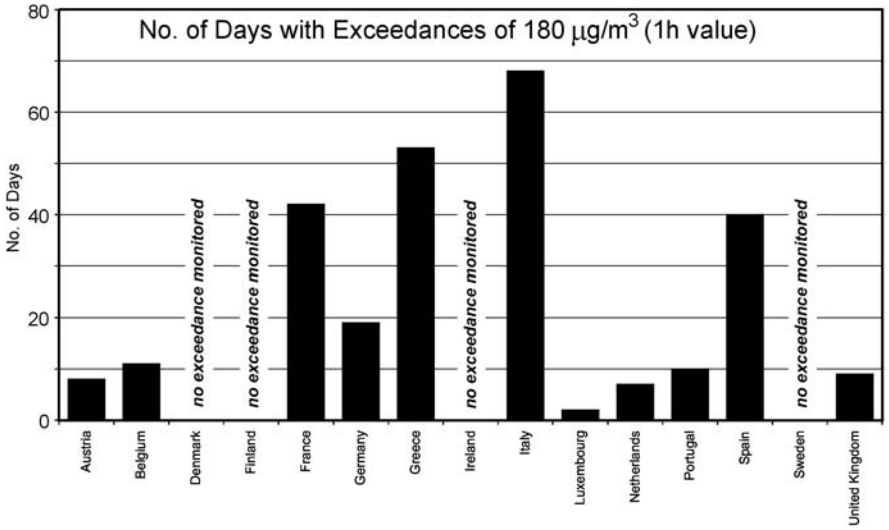

Fig. 2.6. Number of days with exceedances of 180 µg/m^3 in 1999 by country *(Source: EEA, 1999*)

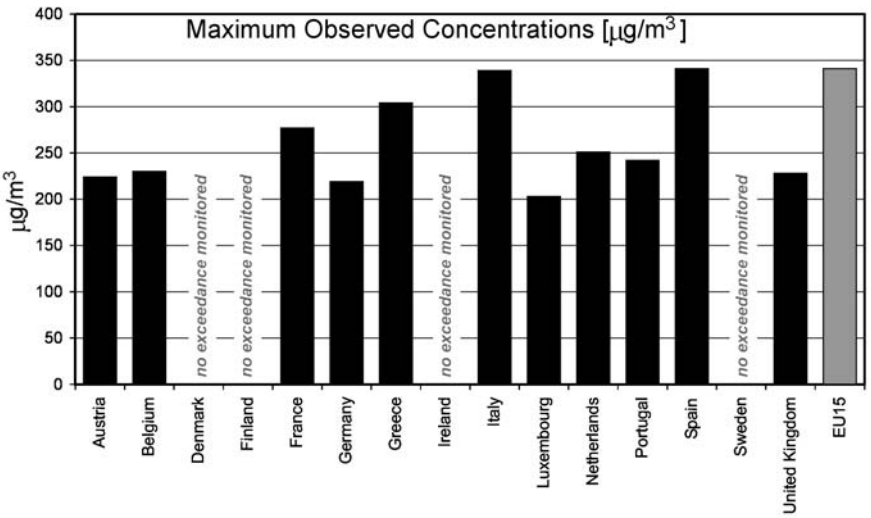

Fig. 2.7. Maximum observed ozone concentrations in countries, where exceedances of 180 µg/m^3 have occurred in 1999 (Source: EEA, 1999)

2.2.3 Specific Aspects of Ozone Formation

2.2.3.1 NO_x and VOC Limitation

NO_x limited and VOC limited regions can be distinguished, where ozone formation is limited by the respective lack or surplus of one of the components. In urban areas, where a large amount of NO is emitted, ozone levels are most often low because of the reaction described in *Eqn. 2.3.* In rural areas, some distance downwind of NO_x sources, the direct NO-sink becomes less important and a more balanced ratio between ozone precursors often leads to ozone generation and peak concentrations. For a more extensive discussion of ozone chemistry, including the important sink processes of HNO_3 and H_2O_2 formation, see, for example, *Seinfeld and Pandis* (1998).

2.2.3.2 Concepts to Assess the Reactivity of VOCs – Ozone Forming Potential (OFP) and Photochemical Ozone Creation Potential (POCP)

VOCs are no homogenous substance group, but a collection of a vast number of volatile organic compound species with different chemical properties and reactivities (*Hewitt 1999, Röll 1994*). A first distinction is usually made between Methane, which has a low reactivity with OH (*Eqn. 2.4*) and is thus less important for short term ozone formation, and the so-called NMVOCs. However, NMVOC still consists of a large number of species with highly different physical and chemical characteristics and different ozone forming potentials. Given such differences, which can be accounted for to some extent with atmospheric chemical models, it is clear that an assessment of the NMVOC speciation associated with each source is important to assessing the effects of control measures. For example, hydrocarbons, like toluene, ethene, butane and propene are mainly responsible for short-term ozone creation, while slower reacting alkanes play a more important role, when long-term (e.g. multi-day) formation is regarded (*Andersson-Sköld et al., 1992*).

Though, current emission inventories usually do not account for different species of NMVOC. For this study, the speciation was done in the stage of calculating spatial high resolution emission data for the dispersion models, using the speciation developed by *Middleton and Carter* (1999) and work conducted at IER (*Friedrich and Obermeier 1999*).

A widely used speciation of VOCs is documented in the chemical mechanism used in the *Regional Acid Deposition Model* - version 2, short RADM-2 (*Middleton, Stockwell and Carter 1990)*, which defines 15 different species of organic compounds based on the aggregation of 32 VOC substance classes distinguished by the emitting source, or the following definition of *Derwent and Jenkin* (1990) giving values for the POCP of substance *i* as follows:

$$POCP_i = \frac{\dfrac{\text{decrease in } O_3 \text{ without VOC at mid afternoon time point}}{\text{hydrocarbon emissions integrated to time point}}}{\dfrac{\text{decrease in } O_3 \text{ without ethylene at time point}}{\text{ethylene emissions integrated to time point}}}$$

Table 2.3. POCP values for selected compounds (Source: *Derwent and Jenkin, 1990*)

Methane	1	n-Butane	51
Ethane	11	Propane	52
Methanol	14	Toluene	61
Acetone	19	n-Octane	62
Acetylene	20	Acetaldehyde	64
Benzene	22	Ethylbenzene	67
i-Pentane	34	o-Xylene	71
Ethanol	35	**Ethylene**	**100**
i-Butane	35	p-Xylene	101
Formaldehyde	39	m-Xylene	106
n-Pentane	48	Propylene	113

The reactivities of VOC species have been investigated (*Middleton, Stockwell and Carter 1990*, *Carter 1994* and *Derwent and Jenkin 1990*) to assess the contribution of specific emission sources to the formation of tropospheric ozone in Europe and to determine control options which take this reactivity into account. And in order to devise an applicable method to use the reactivities in modelling work, two different approaches have been developed, the *photochemical ozone creation potential* (POCP, *Derwent and Jenkin 1990, Derwent et al. 1996* and *Jenkin and Hagman 1999*) and the *ozone-forming potential* (see above).

The ozone-forming potential (short: OFP) has been developed in the US and has been applied in several studies on photo-oxidants. Defining the ozone-forming potential as

$$OFP = KR \times MR$$

with *KR* being the number of molecules of a specific VOC that react with a given airshed and *MR* being the number of ozone molecules that are formed for each VOC molecule in the system that reacts. Based on this definition, *Carter and Atkinson* (1989) introduce the incremental reactivity (IR) to utilise the concept of OFP to be applied to investigations on ozone abatement strategies:

$$IR_i = \frac{\Delta[O_3]}{\Delta[VOC_i]}$$

The IR_i gives the incremental reactivity of species *i*, while $\Delta[O3]$ gives the change in the ozone concentration to assess the impact of VOCs on air quality (e.g. 8h mean concentration), and $\Delta[VOCi]$ represents the change in emissions of species *i*, gives some exemplary values calculated by *Carter 1997*.

Table 2.4. Ozone forming potentials (OFP) of selected organic compounds

Methane	0.016	n-Butane	1.18
Ethane	0.32	Ethanol	1.7
Acetone	0.49	Toluene	5.1
Propane	0.57	Acetaldehyde	6.3
Methanol	0.65	Formaldehyde	6.6
n-Octane	0.69	m-Xylene	14.2
Benzene	0.81		

Both concepts provide a valuable approach to account for the different reactivities of VOCs and thus to varying contribution to ozone formation. However, as *Carter* (1990) states, the relative reactivity of VOC species depends on environmental conditions, such as the availability of NO_x, and thus reactivity values could only be applied with sufficient reliability, if the environmental conditions of the investigated area are known precisely. Thus, in the case of modelling ozone formation and concentrations for whole regions, it is most often not possible to determine the POCP for all species precisely, which is the main reason why no differentiation according to the POCP has been conducted in the ozone modelling for this study. Still, the significant variation of POCPs shows, how important a detailed analysis of the emission sources and their VOC profiles can be to develop e.g. local ozone abatement strategies. The chemistry transport model (CTM) used to derive the source-receptor matrices for the optimisation (see *Chap. 4*) does account for different reactivities using a similar, yet more complex approach (*Andersson-Sköld and Simpson, 1999*).

Finally, OFP and POCP can both be used to analyse the impact on ozone formation that occurs from implementing abatement measures, as for example the VOC species emitted by an uncontrolled passenger car are significantly different than those emitted from a car equipped with a three way catalyst. A brief analysis of the different speciations and their respective ozone forming potentials will be conducted in *Chap 4.3*.

2.3 Air Pollution Impacts

2.3.1 Major Air Pollution Problems

As it has been briefly sketched in *Sect. 2.1*, air pollutants and their effects are widely interlinked and should, in general, be assessed in an integrated way. While the focus lies on tropospheric ozone, the methodology developed here can be easily extended towards an integrated approach, covering all relevant air pollutants and effects. And in order to put the problem of high concentrations of ground-level ozone into perspective, a short description of two related pressures arising from the emission of air pollutants in Europe is given here, to illustrate how emissions of ozone precursors are related to other environmental problems. This helps to explain for instance the difference in avoided damage costs when ozone related damages are compared to total benefits from the reduction of NO_x via acidification and eutrophication. The specific effects of high ozone concentrations is then discussed in the following sections as nitrogen oxides play a significant role in both acidification and eutrophication as well and have direct impacts on human health.

2.3.1.1 Acidification

Acid deposition is caused by the pollutants SO_x (SO_2 and sulphate), NO_y (NO_x, nitric acid and nitrate) and NH_x (NH_3 and NH_4). These compounds can be deposited to soils and waters by either precipitation (rain, snow or mist) or dry deposition. Highest deposition values have been measured in the industrialised and densely populated areas in Central Europe, sometimes exceeding the critical levels for the respective ecosystems by several hundred per cent. The major part of this deposition of acidifying substances originates from European emissions, with the main contributing activities being the combustion of fossil fuels (energy, transport) and agriculture. While NO_x emissions play the most important role in Western and Southern Europe, sulphur still dominates acid deposition in Central and Eastern European countries. Yet, there is no long term trend in total acid deposition available, as no historical data exist. A more detailed discussion of the sources and effects of acidification can be found in *Stanners and Bourdeau* (1995). The severity of the impact of acid deposition on vegetation is greatly dependent on the type of soil the plants grow in. Many soils have a natural buffering capacity and are able to neutralize acid inputs. In less buffered soils, vegetation is effected by acid deposition because:

- Increasing acidity results in the leaching of several important plant nutrients, including calcium, potassium, and magnesium. Reductions in the availability of these nutrients causes a decline in plant growth rates.
- The heavy metal aluminium becomes more mobile in acidified soils. Aluminium can damage roots and interfere with plant uptake of other nutrients such as magnesium and potassium.

- Reductions in soil pH can cause germination of seeds and the growth of young seedlings to be inhibited.
- Many important soil organisms cannot survive is soils below a pH of about 6.0. The death of these organism can inhibit decomposition and nutrient cycling.
- High concentrations of nitric acid can increase the availability of nitrogen and reduce the availability of other nutrients necessary for plant growth. As a result, the plants become over-fertilized by nitrogen (a condition known as nitrogen saturation).
- Acid precipitation can cause direct damage to the foliage on plants especially when the precipitation is in the form of fog or cloud water which is up to ten times more acidic than rainfall.
- Dry deposition of SO_2 and NO_x has been found to affect the ability of leaves to retain water when they are under water stress.
- Acidic deposition can leach nutrients from the plant tissues weakening their structure.

The combination of these effects can lead to plants that have reduced growth rates, flowering ability and yields. It also makes plants more vulnerable to diseases, insects, droughts and frosts.

2.3.1.2 Eutrophication

When talking about eutrophication in the context of air pollution, it refers to the excess deposition of nitrogen (N) in soils and inland waters. The effect of this anthropogenic N deposition is in so far significant, as terrestrial ecosystems have, through evolution, adapted to an environment in which N limitation was the normal state. The increased deposition of N compounds changes the natural nutrient balance significantly, leading to eutrophication, where the total available N in an ecosystem exceeds the total N demand of all ongoing processes within the ecosystem. In some cases, the exceedance can be high enough to destabilise ecosystems in the long run, and affect the growth of different species depending on their tolerance to nitrogen availability.

2.3.2 The Concept of Critical Levels

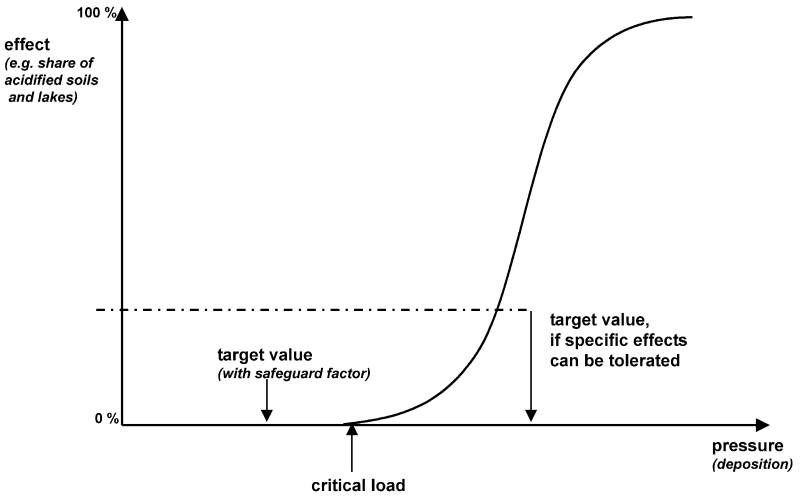

Fig. 2.8. The concept of critical loads illustrated

In most cases, ecosystems and living organisms are capable of coping with the intake or deposition of specific pollutants to some extent, or for a limited period of time, without showing any effects. But as a critical threshold is exceeded, adverse effects occur, such as reduced crop yields or respiratory problems in the case of groundlevel ozone.

A critical level is exceeded, as soon as effects can be monitored in the system, as it is sketched in *Fig. 2.8.*, while effects can show different dependencies on the amount of deposition. The concept of critical loads has been applied for instance in the frame of the UNECE 1st *Sulphur Protoco*l (see *2.4.3*) – in this case dealing with acidification – and detailed maps have been compiled, providing critical level data for ecosystems. The major benefit of this concept is, that it takes into account the different critical levels that apply to different ecosystems, thus enabling the design of a specific strategy for emission reduction and the development of target values.

2.3.3 Health Effects of Ozone

High concentrations of ground level ozone are known to have adverse effects on human health (cf. *Mücke 1991*, as well as *Schwartz 1997* and *UPI 1999*) and ecosystems and cause losses in crop yield of sensitive crops. The following sections describe these effects and approaches to assess impacts and derive thresholds and limit values for the protection of human health and crops and other vegetation.

The occurrence of adverse effects of increased concentrations of ground level ozone on human health has been widely accepted, even though it is difficult to define an overall level of impact for the whole population, as ozone peak may affect different groups of receptors, e.g. people with respiratory problems, elderly people, or children more than others. It has been noted, that people with asthmatic or similar respiratory diseases are especially sensitive to ozone concentration increases. *Table 2.5.* shows an overview of expected acute health impacts of different ambient concentrations. Within the European ExternE research project on *Externalities of Energy* (*ExternE 1998*), comprehensive studies of ozone impacts on human health have been assessed. While previous studies (cf. *ExternE 1995*) had focused on short term effects, as they were based on human experimental studies of short term exposures, the increasing knowledge about epidemiological impacts of air pollutants brought increased attention to long-term effects. ExternE derived a whole set of exposure-response functions based on various studies, some of these functions are shown in *Fig. 2.9.* for selected impact categories. It has to be noted, though, that these linear functions are calculated on population level, hence effects on individuals will most probably vary significantly, depending on the physical and health condition of the subject. As *Fig. 2.9.* indicates, the major effects are cases of restricted activity days (RAD) and symptom days (*cf. Table 2.5.*), while acute mortality or hospital admissions because of ozone exposure occur significantly less often and are thus not addressed.

Table 2.5. Health impacts of different ambient concentrations of ground level ozone (Source: *BMU 1995*)

Ozone concentration ($\mu g/m^3$)	Exposition	Health impact
40	30 minutes	smell noticeable
100	30 minutes	beginning irritation of the respiratory tract
160	6.6 hours	beginning impairment of lung function
240	30 minutes	reduced physical fitness
620	15 minutes	considerable irritation of the respiratory tract
1 000	1 hour	stinging eyes, claustrophobia
2 000	30 minutes	severe impairment of lung function

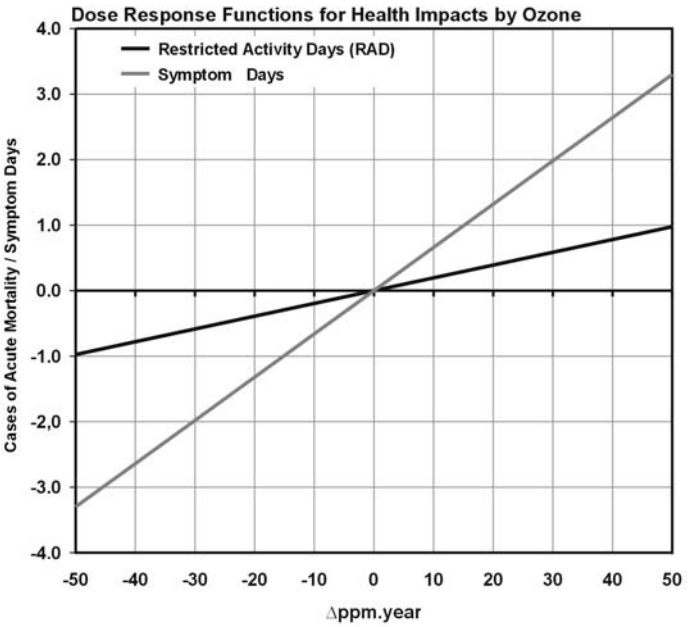

Fig. 2.9. Dose-Response functions for health impacts by Ozone (Source: *ExternE 1998*)

The World Health Organisation (WHO) states (*WHO 2000*), that the health problems of greatest concern are increased hospital admissions, exacerbation of asthma and inflammatory and structural changes in the lung, WHO thus favours a guideline value, which limits average daily exposure (i.e. inhaled dose and dose rates) rather than addressing the rare short term duration deterioration of air quality as it occurs during unusual meteorological conditions

2.3.4 Impacts on Natural Vegetation and Agricultural Crops

Besides the health effects described above, high concentrations of ground level ozone can seriously damage sensitive plants like agricultural crops or forest trees.

For agricultural plants, the damage can be observed as reduced crop yields, leading to an immediate monetary loss. After long-term investigations of impacts of air pollution on agricultural crops had been conducted first in the *US (National Crop Loss Assessment Network*, *Somerville et al.*, 1989), a European research programme was set up called the *European Open-Top Chamber (OTC) Programme* (*cf. Skärby et al. 1993, Fuhrer et al. 1997* and *Pleijl 1996*). As a result of this programme, yield curves were calculated depending on the ambient concentration of ground-level ozone, showing, that current ozone levels in Europe have a significant impact on

crop yield of wheat, while barley and oats were less sensitive to ozone exposure. Ozone effects on forest trees vary with different sensitivities of tree types. AOT40 for crops is calculated for daylight hours of a three month period (May to July), reflecting the specific sensitivity during the growing season of most agricultural crops in Europe. Within ExternE, results of several studies were assessed to derive exposure-response-functions (like in *Fig. 2.10.*) to calculate reduced crop yields from ozone exposure and hence monetary damages.

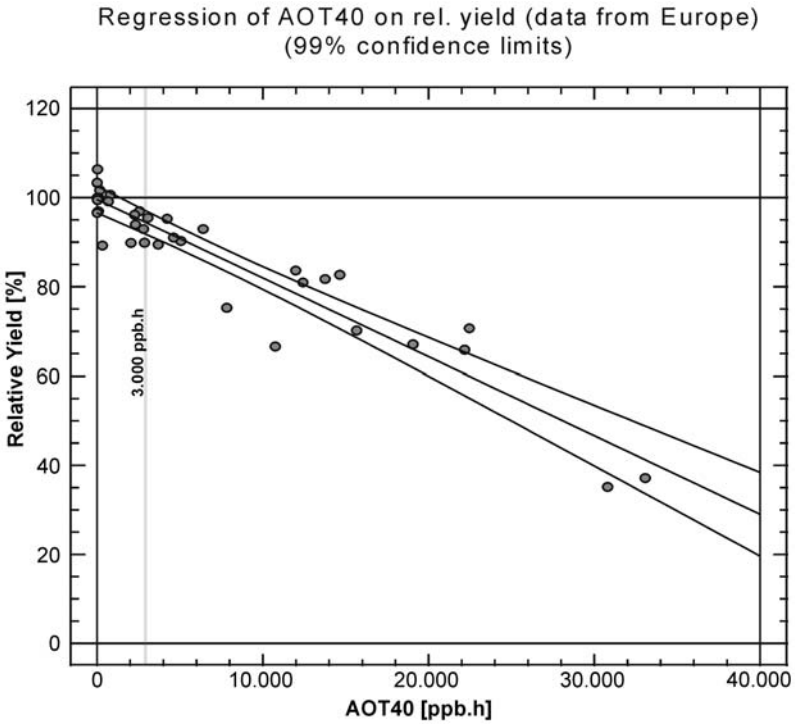

Fig. 2.10. Impacts of ozone concentrations on crop yield (Source: PORG 1997)

Table 2.6. shows the relative sensitivities for some selected agricultural crops. *Grünhage et al.,* (1999) have done a thorough investigation of the critical levels for ozone and conclude, that they should only be used to set levels for the protection of crops, i.e. to avoid damages, rather than to try to predict reliable grain losses. For forests, natural and semi-natural vegetation the data basis seems yet to be too small to set reliable source-receptor relationship, until a flux-oriented concept can be established to derive levels of critical absorbed doses. For the time being, AOT40 for forests provides an interim threshold to work with.

Table 2.6. Different levels of sensitivity to ozone for selected agricultural crops (Source: *ExternE 1998*)

Species	Tolerant[a]	Slightly sensitive[b]	Sensitive[c]	Very sensitive[d]
Wheat			X	
Barley	X		X	
Maize	X			
Soybean		X		
Potatoe			X	
Tobacco			X	
Sunflower			X	

a. no critical dose set
b. set dose at 10 ppm.h
c. set dose at 5.7 ppm.h
d. set dose at 2.9 ppm.h

2.3.5 Other Aspects of Tropospheric Ozone

While *Sects. 2.3.3* and *2.3.4*. address the most prominent and scientifically established impacts of high tropospheric ozone concentrations, one effect that is currently discussed is difficult to quantify. As *Finlayson-Pitts and Pitts (2000)* elaborately describe, tropospheric ozone can act as a greenhouse gas as well, in particular in the higher troposphere. The difficulty in quantifying its total effect lies, among other factors, in the dependency on the vertical distribution profile. It is beyond the scope of this book to fully take the Global Warming effect into account, but this aspect should certainly be addressed in future research integrating air pollution control and climate change.

In a similar way, carbon monoxide and methane contribute to long-term ozone formation and thus to the amount of background ozone, which is distributed over the northern hemisphere, contributing for instance to approximately 30 ppb of European background concentrations (*Mauzerall and Wang, 2002).* This background is of particular importance as the AOT threshold for agricultural crops set at 40 ppb is significantly sensitive to small changes in concentrations with the background levels so close to the threshold.

2.4 Activities on Air Pollution Control

2.4.1 Introduction

Tropospheric ozone, as described before, is formed from emissions of precursor substances under specific meteorological conditions, but it does often not occur immediately where those precursors are emitted. Peaks of ozone concentrations appear in quite a distance of the emission sources and this kind of transport leads to difficulties in particular where national action to reduce precursor emissions might be hampered (or supported) by activities across borders. Thus, reflecting the transboundary context of the problem, the focus when discussing legislative action to control and reduce emissions has to be supranational. In this section, European Union (EU) and UNECE policies, as two main players in dealing with transboundary effects of air pollution, in particular tropospheric ozone, are briefly evaluated.

2.4.2 The European Union

The European Union has recently introduced a new approach to tackling air quality issues, moving away from addressing each pollutant or problem independently towards an integrated air quality management strategy. The most important components of the EU air pollution control activities are described in the following section.

2.4.2.1 The Air Quality Framework Directive

With the development of the *Air Quality Framework Directive* (96/62/EC) on ambient air quality assessment and management, basic principles have been set to deal with air pollution on a European scale. The aims of this directive can be summarised as follows:

- defining and establishing ambient air quality objectives to avoid, prevent or reduce
  harmful effects on human health and the environment as a whole,
- assessing ambient air quality in Member States based on common methods and criteria,
- producing adequate publicly available information about ambient air quality, and
- maintaining ambient air quality where it complies with targets and improve, where it does not comply.

The European Commission has set out to establish optimal ambient air quality limit values, as well as assessment procedures and reporting requirements within ten to fifteen years through daughter directives covering specific individual pollutants

or groups of pollutants. Previous directives, e.g. concerning sulphur dioxide, particulate matter or nitrogen oxides are being replaced by these daughter directives.

Table 2.7. Summary of limit values for different air pollutants set by the Daughter Directives to the EC Air Quality Framework Directive (Source: EUR-Lex[a])

Pollutant	**Limit value** *(μg/m³)*	Reference period *(targeted at the protection of ...)*	**Target date to comply with limit value**
SO_2	350 (*24 exceedances)*	1 hour *(human health)*	January 01 2005
	125 *(3 exceedances)*	24 hours *(human health)*	January 01 2005
	20	year/winter period *(ecosystems)*	1 year *after implementation*
	500	3 consecutive hours *(warning threshold)*	–
NO_2	400	3 consecutive hours *(warning threshold)*	–
	200 *(18 exceedances)*	1 hour *(human health)*	January 01 2010
	40	1 year *(human health)*	January 01 2010
$NO + NO_2$	30	1 year *(ecosystems)*	1 year *after implementation*
PM_{10} (Stage 1)	50 *(35 exceedances)*	24 hour *(human health)*	January 01 2005
	40	1 year *(human health)*	
PM_{10} (Stage 2)	50 *(7 exceedances)*	24 hours *(human health)*	January 01 2010
	20	1 year *(human health)*	
Lead	0.5	1 year *(human health)*	January 01 2005
Benzene	5	1 year *(human health)*	January 01 2010
CO	10 mg/m³	8 hour mean *(human health)*	January 01 2005

a. *http://europa.eu.int/eur-lex/en/index.html, 03.08.2004*

For tropospheric ozone, the EC has issued the *Council Directive on Air Pollution by Ozone* in 1992 (92/72/EEC), which sets threshold concentrations (see *Table 2.7.*) and establishes monitoring and data exchange procedures for informing and, if necessary, warning the population. Member States have to report the results of continuous measurements of ozone concentrations to the European Commission, providing the following information:

- maximum, median and 98th percentile values of 1 hour and 8 hour mean concentrations,
- occurrence of exceedances of threshold levels (number, date and duration of the episode),
- peak concentration monitored in an episode of exceedance (*Beck et al, 1998*).

The population information threshold of 180 μg/m^3 was exceeded several times per year in most of the EC Member States, while the population warning threshold (360 μg/m^3, 1 hour mean) was exceeded on a few occasions only. The information that was issued when a threshold was exceeded received considerable attention from the media, and the increased public awareness has brought the ozone problem higher on the list of political priorities. As it has been described above, the limit and target values for respective air pollutants covered by the Air Quality Framework Directive are set by specific Daughter Directives, such as the *Daughter Directive on Air Pollution by Ozone*. Similar to the first *Daughter Directive* (99/30/EG), which covered emissions and concentrations of SO_2, PM_{10}, NO_2 and Lead in ambient air, this Daughter Directive defines long term objectives, target values and thresholds for different applications (see *Table 2.8.*).

Table 2.8. Ozone target values and objectives set by the Daughter Directive on Ozone (2002/3/EC)

Description	Averaging period	Value	Target year
long term objective: human health	yearly maximum 8 h mean (rolling average)	120 μg/m^3	–
long term objective: vegetation	AOT40, May to July between 8 and 20 CET	6 000 μg•h/m^3	–
target value: human health	daily maximum 8 h mean (rolling average)	120 μg/m^3 25 exceedances averaged over 3 years	2010
information threshold	1 hour	180 μg/m^3	–
alert threshold	1 hour	240 μg/m^3	–

The development of the Daughter Directives has to be seen in a context with the ongoing activities to harmonise different approaches to improve air quality, namely the *Directive on National Emission Ceilings* and the EC *Clean Air for Europe (CAFÉ) Strategy*. Furthermore, major reviews of the air quality targets under the AQ Framework Directive and its Daughter Directives are currently conducted, with the plan to amend the targets, where necessary.

2.4.2.2 The EC National Emission Ceilings (NEC) Directive

The proposal for this Directive was developed on the basis of knowledge acquired from several activities and research projects on air pollution and ambient air quality in Europe. Some programmes, such as, for example, Auto Oil I/II focused on a specific source sector, others were effect oriented, like the EC *Acidification Strategy*. In the course of these activities, it became obvious that even by implementing all Directives or strategies currently in place or in pipeline, air quality targets would still be significantly exceeded in the year 2010. Hence, the EU Member States decided to set emission ceilings for each country explicitly, by negotiation, covering all air pollutants related to the problems *acidification*, *eutrophication* and *ground-level ozone* (see *Table 2.9.*).

Table 2.9. National Emission Ceilings set by the NEC Directive *(Emissions in the year 2010 in kt) Source: European Communities (2001)*

	SO_2	NO_x	VOC	NH_3
Austria	39	103	159	66
Belgium	99	176	139	74
Denmark	55	127	85	69
Finland	110	170	130	31
France	375	810	1 050	780
Germany	520	1 051	995	550
Greece	523	344	261	74
Ireland	42	65	55	116
Italy	475	990	1 159	419
Luxembourg	4	11	9	7
Netherlands	50	260	185	128
Portugal	160	250	180	90
Spain	746	847	662	353
Sweden	67	148	241	57
United Kingdom	585	1 167	1 200	297
Total EU_{15}	**3 850**	**6 519**	**6 510**	**3 110**

The emission ceilings set by the NEC Directive correspond in most cases with those of the UNECE Multi-Effect Protocol (the so-called 'Gothenburg-Protocol') which gives emission ceilings as well and is currently being ratified by Parties to the Convention.

2.4.2.3 The Clean Air for Europe (CAFE) Strategy

Previous activities to improve air quality in Europe have usually been directed towards specific sources or source groups, respectively addressing individual pollutants or environmental effects. But in recent years, the need for a more integrated approach became more and more evident as the interdependencies between different environmental effects were better understood. Furthermore, the transboundary transport of air pollutants (cf. *2.4.3*) makes the need for a harmonized approach evident. In response to this, the DG Environment of the European Commission launched a work programme aiming at the development of a strategy called *Clean Air for Europe*, short: CAFE.

Table 2.10. Outline of the approach taken for the CAFE strategy (EC White Paper[a])

Review	Predict	Propose
(health) effects evidence (including risk assessment)	base case development for emissions (trend scenario/s)	revisions to air quality standards/ objectives
air quality standards/objectives	future air quality: - regional - local	cost effective strategy and measures to close the gap between forecast air quality and objectives, including evaluation of benefits
trend assessments of emissions and air quality	costs and effects of abatement options at - EU/European, - national and - local scale	implementation and monitoring arrangements
implementation of current directives, strategies, recommendations		future research needs

Source: EC DG Environment Discussion Paper, pers. comm.

a. The CAFÉ strategy is currently evolving and thus subject to changes and further development; up-to-date can be found at *http://europa.eu.int/comm/environment/air/cafe/index.htm, 03.08.2004* and in the *COM(2001)245* document

The full strategy is to be developed within the coming years and shall be implemented between 2003 and 2005. Key aspects of the development are to establish a framework for a longer term programme of research and analytical activity to support policy decisions to harmonise air quality research, emission forecast and the assessment of costs and effects of potential abatement measures. At the same time, best possible transparency and stakeholder involvement shall be granted, *Table 2.10.* summarises the key issues of the new approach taken.

2.4.3 United Nations Economic Commission for Europe (UNECE)

2.4.3.1 The UNECE Convention on Long-Range Transboundary Air Pollution

The UNECE designed its *Convention on Long-Range Transboundary Air Pollution* (CLRTAP) especially to account for the aspect of transport of air pollutants across country borders. With the roots of this convention dating back to the 1960s, the real development started with the United Nations *Conference on the Human Environment* in 1972. It was then acknowledged, that the problem of acidification originated from the transboundary transport of sulphur emissions and could thus only be solved by international co-operation. The convention was signed in 1979, being the first legally binding instrument to tackle air pollution on an international basis. While the early protocols to the CLRTAP aimed at uniform reductions of pollutants, e.g. setting targets of x% reduction of SO_2 for all parties to the Convention, later protocols, for instance the 2nd Sulphur Protocol, aimed at cost-efficient strategies with different targets set for different countries on the basis of model calculations

2.4.4 Integrated Pollution Prevention and Control (IPPC)

In addition to the directives that have been described above, the EU has a set of common rules on issuing permits for industrial installations, which are defined in the so-called IPPC Directive of 1996 (96/61/EC). IPPC stands for **I**ntegrated **P**ollution **P**revention and **C**ontrol. Basically, the IPPC Directive is about minimising pollution from various point sources throughout the European Union (cf. *OECD, 1996a*). All installations covered by *Annex I* of the Directive are required to obtain an authorisation (permit) from the authorities in the EU countries. Unless they have a permit, they are not allowed to operate. Permits have to be based on the concept of *Best Available Techniques* (or BAT), which is defined in *Article 2* of the Directive (see *below*). In many cases BAT means quite radical environmental improvements and sometimes it will be very costly for companies to adapt their plants to BAT.

Table 2.11. Protocols to the UNECE Convention on Long-Range Transboundary Air Pollution[a]

Protocol	Year	Emission target	Target year
1st Sulphur Protocol	1985	30% reduction of total sulfur emissions or their transboundary fluxes on the basis of 1980 emissions	1993
NO_x Protocol	**1988**	**1st step: stabilisation of 1987 (exception: USA 1978) emissions of NO_x** **2nd step: application of an effects-based approach to further reduce NO_x emissions or their transboundary fluxes**	**1987**
VOC Protocol	**1991**	**30% reduction in emissions of volatile organic compounds (VOCs) by 1999 using a year between 1984 and 1990 as a basis**	**1999**
2nd Sulphur Protocol	1994	An effects-based approach, the critical load concept, best available technology, energy savings, the application of economic instruments and other considerations was applied in the preparation of the Protocol, This has led to a differentiation of emission reduction obligations of Parties to the Protocol, The effects-based approach, which aims at gradually attaining critical loads, sets long-term targets for reductions in sulphur emissions, although it has been recognised that critical loads will not be reached in one single step	–
Heavy Metals Protocol	1998	reduce emissions for cadmium, lead and mercury below their levels in 1990 (or an alternative year between 1985 and 1995), targeting emissions from industrial sources (iron and steel industry, non-ferrous metal industry), combustion processes (power generation, road transport) and waste incineration	–
Protocol on Persistent Organic Pollutants (POPs)	1998	objective is to eliminate any discharges, emissions and losses of POPs, among others to reduce emissions of dioxins, furans, PAHs and HCB below their levels in 1990 (or an alternative year between 1985 and 1995) and laying down limit values for the incineration of municipal, hazardous and medical waste	–
Multi-Effect-Protocol	**1999**	**addressing ground-level ozone, acidification and eutrophication as the effects of emissions of several air pollutants, e.g. NO_x, NMVOCs, SO_2, NH_3 etc. and setting emission ceilings for countries**	–

a. *http://www.unece.org/env/lrtap/status/lrtap_s.htm, 03.08.2004*

To impose new and considerably tougher BAT rules on all existing installations in the European Union could jeopardise many European jobs, and therefore the Directive grants these installations an eleven year long transition period counting from the day that the Directive entered into force.

As from October 1999 the Directive applies to all new installations, as well as existing installations that intend to carry out changes that may have significant negative effects on human beings or the environment. As mentioned above, the Directive does not immediately apply to existing installations. These have been granted an additional 8 years of grace. However, some EU countries already have BAT based permitting systems also for this category. In addition to this, on the EU level, Directive 84/360 from 1984 also prescribes BAT based permitting, although it only regards emissions to air and is relevant to a more limited number of installations.

2.4.4.1 Definition of BAT

Best available techniques (see *Directive 96/61/EC*[1]) shall mean the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment:

- ***techniques*** shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned,
- ***available*** techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator,
- ***best*** shall mean most effective in achieving a high general level of protection of the environment as a whole.

2.4.5 World Health Organisation (WHO)

As the World Health Organisation defines (WHO), health is *„as state of complete physical, mental and social well-being and not merely the absence of disease and infirmity"*. Hence, the WHO is concerned in the case of air pollution not only in the assessment of health impacts, but as well in the setting of limit values and thresholds to protect human health. In this context, the WHO is working on all major health aspects of human development, and issues guidelines such as the Air Quality Guidelines of 1999 *(WHO 1999)*. For all key pollutants, short term and long term exposure

1.*http://europa.eu.int/scadplus/leg/en/lvb/l28045.htm, 29.07.2003*

effects have been assessed and limit values were derive for selected air pollutant as given in *Table 2.12.*

Table 2.12. WHO Guidelines for selected air pollutants (WHO 1999)

Compound	Annual ambient air concentration [μg/m^3]	Health endpoint	Observed effect level [μg/m^3]	Uncertainty factor	Guideline value [μg/m^3]	Averaging time
Carbon Monoxide	500 – 7 000	Critical level of COHb < 2.5%	n.a.[a]	n.a.	100 000 60 000 30 000 10 000	15 min 30 min 1 hour 8 hours
Lead	0.01 – 2	Critical Level of Pb in blood < 100 - 150 mg Pb/l	n.a.	n.a.	0.5	1 year
Nitrogen Dioxide	10 – 150	Slight changes in lung function in asthmatics	365 – 565	0.5	200 40	1 hour 1 year
Ozone	**10 – 100**	**Respiratory function responses**	**n.a.**	**n.a.**	**120**	**8 hours**
Sulphur Dioxide	5 – 400	Changes in lung function in asthmatics	1 000	2	500	10 min
		Exacerbations of respiratory symptoms	250	2	125	24 hours
		in sensitive individuals	100	2	50	1 year

a. n.a. = not applicable

3 Emissions, Sources and Abatement Costs

3.1 Introduction

As indicated before, the problem of ground level ozone is difficult to model. On the one hand, the formation of ozone from two different precursor substances and the implicit non-linearities require a sophisticated model approach to relate emissions to resulting ambient concentrations. This modelling approach will be discussed in depth in the next chapter.

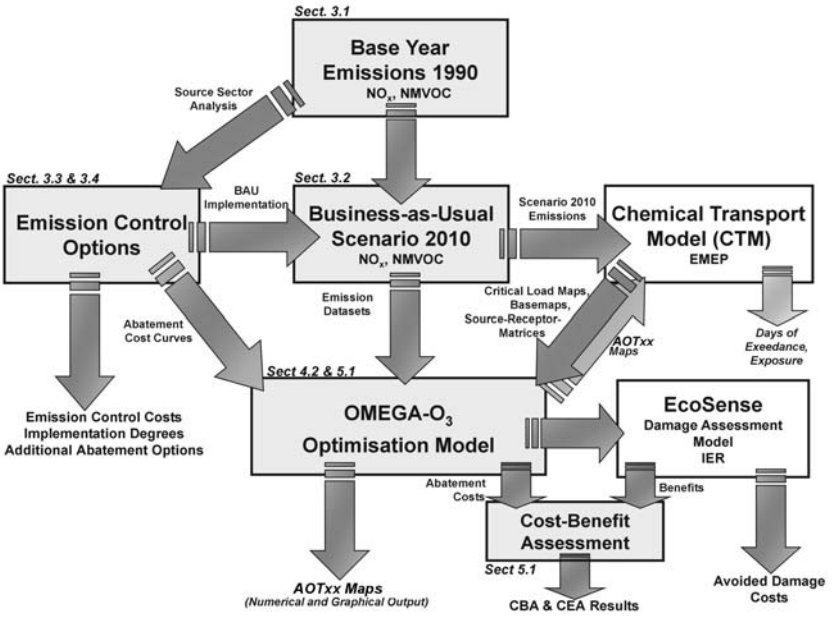

Fig. 3.1. Overview of the modelling framework (grey boxes: model development)

To run such a complex model, detailed sets of input data are needed, which provide, among others

- emission data (*Sect. 3.1* and *3.2*),
- information on emission control options and related costs (*Sect. 3.3* and *3.4*) and
- parameters for model operation and evaluation (e.g. source-receptor matrices).

Fig. 3.1 illustrates how the different data sets are linked and how data flows have to be organised to finally conduct the cost-effectiveness and cost-benefit assessment which is the core aim of the analysis here.

One of the critical issues is the assessment of emissions and the potential and applicability of emission control options. Even though there are various scenarios and analyses for specific sectors available (e.g. energy scenarios for the EU, projections of the development of vehicle fleets etc.), it has proven impossible to simply take one of these as direct input into the model. The reasons for this are mainly the general availability of numbers and scenario results, but typically no information on the methods and inputs that have been used are given. Thus, it is not feasible for instance to assess the reduction potential of abatement measures which go beyond the business-as-usual (BAU) development, since implementation degrees in the BAU case are not stated. The following sections describe in detail, how the analysis of the current and future emission situation as well as the portfolio of available emission control options have been assessed and a comprehensive data set was developed to operate the optimisation model.

3.2 Emission Analysis

3.2.1 Anthropogenic and Biogenic Emission Sources

Emissions of the ozone precursors NO_x and NMVOC mainly originate from anthropogenic sources, as the following sections will demonstrate. Other trace gases such as carbon monoxide and methane do contribute to ozone formation in the long term and thus contribute to the formation of background ozone concentrations. This has been excluded in this study, as the short term ozone formation which is in particular important for the assessment of peak ozone concentrations in summer is more or less driven by the availability of NO_x and NMVOC alone.

Biogenic emissions of NMVOCs from vegetation contribute a considerable share of total NMVOC. But as the focus of the emission analysis here was to identify abatement potentials, biogenic sources of emissions have also been excluded from the analysis. However, biogenic emissions have been implicitly included in the modelling of ozone concentrations by the Lagrangian EMEP Model.

A major problem for the analysis of emission sources was the availability of a consistent, correct and comprehensive emission data set, which at the same time provided a sufficient sectoral resolution to address important source groups directly. At the time being, only the CORINAIR emission inventory for the year 1990 complies with all these requirements. CORINAIR 94 still does not have emission data in all relevant sectors provided by countries, and CORINAIR 97 is even less complete yet. Thus, CORINAIR 90 was used as the basis for the sectoral analysis and hence as the basis for the calculation of the business-as-usual Trend Scenario for the year 2010.

Still, as 1990 is already more than 10 years past by now, CORINAIR 94 and the most recent complete emission data set from EMEP for the year 1998 and beyond was used in an ex-post analysis, to validate the analysis conducted on CORINAIR 90 data and on the other hand to check, whether the changes in emissions from 1990 to 1998 manage to support the development which has been projected until 2010.

Finally, it is important to state, that the emissions calculated for the trend scenario 2010 should not be evaluated as a *forecast* of future emissions levels, that will in any case be met. It is more a scenario which, assuming a specific development of implementing air pollution control legislation currently in place and in pipeline, gives a possible picture of ozone precursor emissions for the trend year. The path of this anticipated development can easily be changed, so will probably the National Emission Ceilings Directive itself, by setting more stringent emission limits per country than ever before, have a significant influence on the development in the next ten years. It has to be anticipated, that a number of additional – national and EC – activities will be taken by the member states to achieve their limits, and hence the expected trend scenario emissions will probably be undercut by reality. For this reason, the assessment of the future situation later on will always use the ozone situation resulting from an implemented NEC Directive in addition to that of the trend scenario and reduction scenarios, to give the full picture.

3.2.2 Sectoral Analysis

In order to develop strategies for ozone abatement, it is vital to know the structure and shares of all emission sources of ozone precursor substances, namely NO_x and NMVOC. In this case, the CORINAIR[1] emission inventory for Europe was taken as a basis.

This inventory provides a detailed collection of emission data, distinguishing the main sectors of activity relevant to air pollutant emissions. These SNAP[2] groups are

1. CORINAIR is a programme to establish an inventory of emissions of air pollutants in-Europe. It was initiated by the European Environment Agency Task Force and was part of the CORINE (Coordination of information on the environment) work programme set up by the European Council of Ministers in 1985
2. SNAP = Selected Nomenclature for Air Pollutants

usually subdivided down to activity level and present the best currently available information base for European emission data. *Fig. 3.2.* and *Fig. 3.3.* show the contribution of different source sectors (for the 15 European Union Member States) to total emissions of NO_x and NMVOCs for the EMEP 1998 data sets, the most recent inventory available. For a more detailed analysis of the emission sources, see below. For NO_x, three relevant source groups can be identified, stationary combustion, road transport and other mobile sources.

In the case of NMVOCs, the picture is somewhat different with road transport, solvent use and biogenic emissions being the main source categories. In addition to anthropogenic sources, biogenic emissions amount to approximately 15% of total EU15 NMVOC emissions according to *Simpson et al. 1999*. However, emission estimates for biogenic sources are still subject to vast uncertainties, since the data situation on emission potentials and biomass are still scarce, even though the quality and availability of land-use data has been improved in recent years. Finally, these emissions are not available for applying abatement measures, so remaining NO_x emissions could lead to ozone formation even if no anthropogenic NMVOC would be emitted.

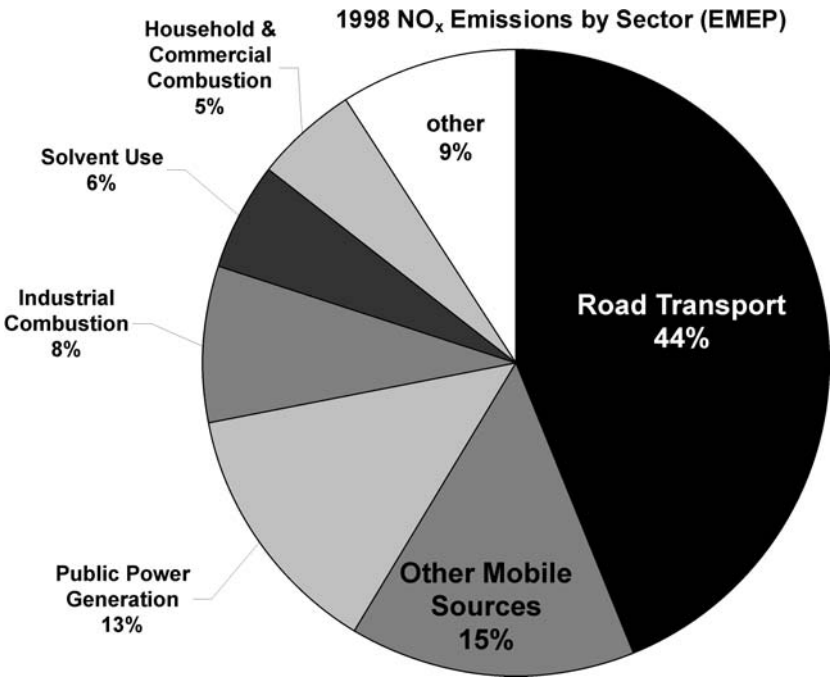

Fig. 3.2. Sectoral contribution to anthropogenic EU15 NO_x emissions according to EMEP in 1998

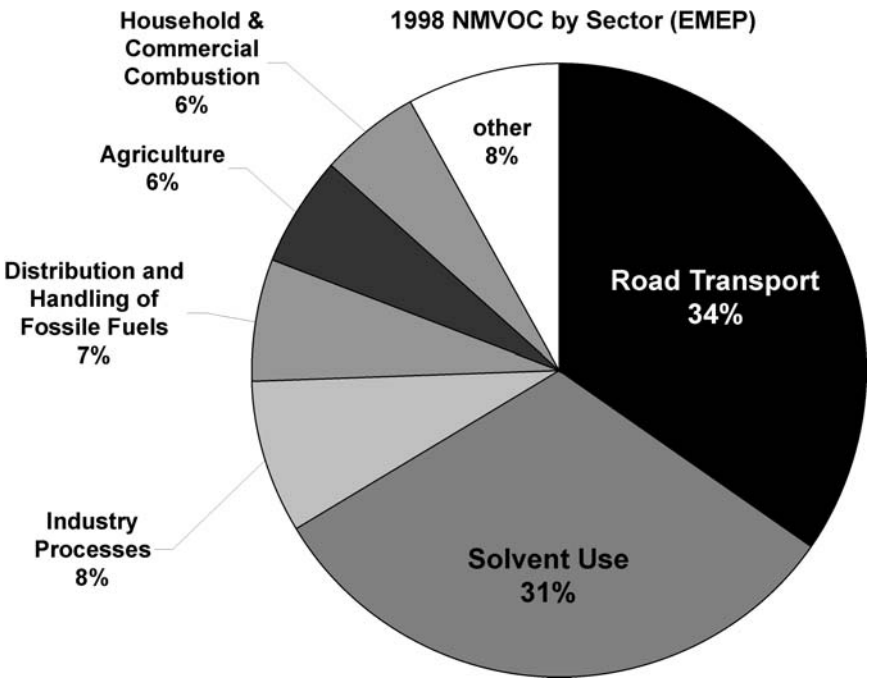

Fig. 3.3. Sectoral contribution to anthropogenic EU15 NMVOC emissions according to EMEP in 1998 (excluding biogenic NMCOV emissions, which account for approx. 15% of total NMVOC emissions in the 15 EU Member States)

Table 3.1. Shares of sectoral anthropogenic emissions of NO_x in the EU15 1998 (Source: *EMEP 1998*)

Source sector	Share
Road transport	44.0%
Other mobile sources and machinery	14.6%
Public Power, co-generation and district heating	13.4%
Industrial Combustion	7.9%
Solvent use	5.7%
Commercial, institutional and residential combustion	5.2%
Agriculture	4.0%
Production Processes	2.6%
Extraction and distribution of fossil fuels	1.3%
Waste treatment and disposal	1.3%

3.2.2.1 Sources of NO_x Emissions

NO_x emissions originate almost exclusively from combustion of fossil fuels. As well nitrogen from the air used for combustion (thermal and prompt NO) as nitrogen contained in the fuel (fuel NO) is oxidised. NO_x stands for the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The main product of combustion is NO, that is further oxidised to NO_2 in the atmosphere. The formation of NO_x in combustion processes is determined by the air-fuel-ratio, the temperature of combustion and the time spent in the combustion chamber. In addition to that, organic nitrogen compounds in fuels are partly oxidised to NO as well. The sectoral structures may vary considerably between the countries (see *Annex B*), reflecting differences in e.g. the vehicle fleets, the main fuels used for power generation, differing requirements to space heating due to average annual temperatures and so on (*Table 3.1.*).

In the following part the most important sectors are analysed in more detail:

- *road transport:* passenger cars cause 54% of the NO_x emissions of the transport sector, with the share coming from gasoline fuelled vehicles varying between 85% and 99% reflecting the different market shares of gasoline and diesel fuelled vehicles in EU countries. Heavy duty vehicles are responsible for 38% of transport emissions, being almost exclusively diesel operated. The contribution of light duty vehicles amounts to about 7%, while NO_x emissions of mopeds and motorcycles are negligible.
- *public power, co-generation and district heating:* the lion's share of sectoral NO_x emissions (91%) originates from large combustion plants with more than 300 MW thermal capacity. According to EUROPROG data for 1990 (EUROPROG 1996), solid fuels (hard coal and peat) were used in the bulk of the combustion plants, though natural gas shares were already increasing. Fuel oil only plays a minor role, with the exception of Italy and Portugal (see *Fig. 3.4.*). Power plants between 50 and 300 MW cause 4% of sectoral emissions only, the contribution of plants < 50 MW is insignificant in this sector.
- *other mobile sources or machinery:* about 50% of the emissions of this sector come from vehicles in agriculture, forestry, industry or the military. With a share of 34%, marine sources (i.e. ships and harbour activities) present the second largest source group, followed by railways (7%), airports (5%) and activities on inland waterways (4%).
- *industrial combustion:* this sector comprises industrial combustion plants for heat and power generation as well as process furnaces. Heat and power generation plants emit about 58% of the NO_x of this sector, but in contrast to the size distribution of plants in public power generation, most of the plants have a thermal power $\leq$ 50 MW. Process furnaces, where the processed good is in direct contact with the fuel, cause 33%, those without direct contact 9% of the NO_x emissions of this sector.

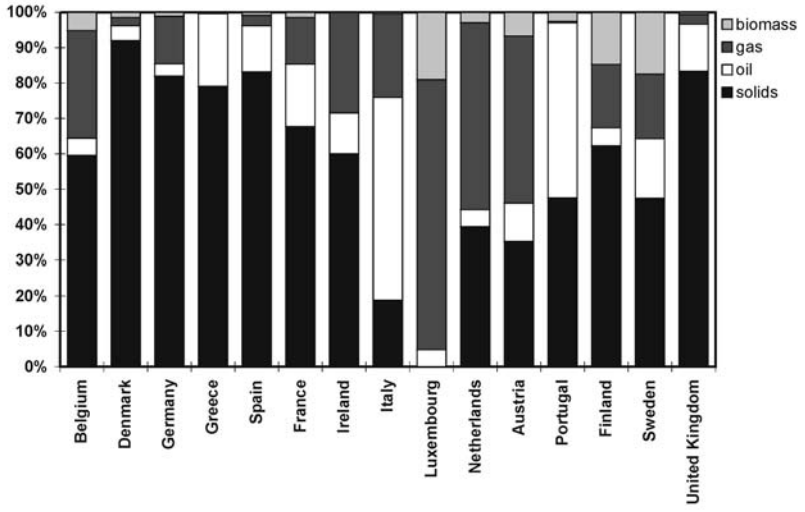

Fig. 3.4. Shares of fossil fuels for power generation in Europe 1990 (Source: IEA 1992)

- *residential and commercial combustion:* as can be expected for this sector, 99% of emissions come from plants ≤50 MW, representing the large number of household or commercial combustion systems, that mainly generate heat and warm water. Even though the share of this sector is not significant in comparison to the main source sectors, it is comparatively easy to reduce NO_x emissions from these plants, as will be described later.

3.2.2.2 Sources of NMVOC Emissions

Analysing NMVOC emissions, a vital difference to NO_x emission sources has to be noted. With an overall share of about 15% of total NMVOC emissions (*see Table 3.2.*) in the 15 EC Member States, biogenic emissions play a major role and should not be neglected. Again, the prominent role of road transport is evident, which contributes almost 41% of total anthropogenic NMVOC emissions, if emissions from the distribution of gasoline from SNAP 5 are taken into account and added to emissions from the operation of vehicles. The use of organic solvents for various applications is the source of about 32% of anthropogenic NMVOC emissions, followed by industrial production processes (8%).

The in depth analysis of the main source sectors provides the following results:

- *road transport:* as the most important difference to the analysis of NO_x emissions from this sector, NMVOC emissions almost exclusively originate from gasoline operated vehicles. In addition to that, emissions from the operation of the vehicles have to be distinguished from emissions due to gasoline evap-

oration from parked cars. Almost 52% of the transport NMVOC emissions come from the operation of passenger cars (between 95% and 99% from gasoline operated cars in individual countries), another 24% from the evaporation of gasoline from passenger cars, light duty vehicles and two-wheelers. Mopeds and motorcycles are responsible for 10% of the NMVOC emissions from transport, heavy duty vehicles for 9% and light duty vehicles for the remaining 5%solvent use: this sector is marked by a very diffuse source structure, covering industrial applications in almost all industry sectors and even the domestic use of solvent based products. The main sources of NMVOC emissions from solvent use are paint application (41 %), comprising the use of paints and varnishes in industry and car manufacturing as well as for construction and buildings and the domestic use. Manufacturing and processing of chemical products cause 13% of sectoral emissions, followed by solvent applications in degreasing and dry cleaning (10%). Domestic use of solvents (other than paint application) amounts to 13%, printing industry to 8% of the NMVOC emissions from solvent use.

- *production processes:* a vast number of individual processes are summed up in this sector, with the organic chemicals industry emitting the largest share of the emissions (31 %), followed by the petroleum industries (21%). The bulk of NMVOC emissions (34%) comes from a conglomeration of processes containing, among others, beverages and food production, paper pulp and chipboard production and road paving with asphalt.
- *extraction and distribution of fossil fuels:* as was already mentioned above, the major share of NMVOC emissions of this sector originates from gasoline distribution (50%), covering the whole process from refinery dispatch to refuelling operations at filling stations. The land and off-shore based extraction and first treatment of liquid fossil fuels causes 26%, that of gaseous fossil fuels another 13% of total NMVOC emissions of this sector. Finally, the gas distribution networks (pipelines, compressor stations and the final distribution to end-users) are responsible for 9%.
- *residential and commercial combustion:* as it has been already stated for NO_x emissions, almost all (98%) of the NMVOC emissions originate from plants $\leq$50 MW. These emissions are highly fuel dependent, with solid fuels (coal, lignite, wood) having between 50 to 200 times higher specific NMVOC emissions per TJ than natural gas or fuel oil.

Within the sector *other mobile sources*, off-road vehicles and machinery (60%) and marine sources (20%) emit the largest shares of sectoral NMVOC.

Table 3.2. Shares of emissions of NMVOC in the EU15 1998 (Source: EMEP)

Source sector	Anthropogenic emissions share	Share of total emissions[a]
Road transport	34.7%	29.6%
Solvent use	31.6%	26.9%
Natural sources	–	14.6%
Production Processes	7.9%	6.7%
Extraction and distribution of fossil fuels	6.6%	5.6%
Commercial/institutional/residential combustion	5.8%	5.0%
Agriculture	5.6%	4.7%
Other mobile sources and machinery	5.0%	4.2%
Waste treatment and disposal	1.9%	1.7%
Industrial combustion	0.6%	0.5%
Public power generation	0.5%	0.4%

a. including natural and biogenic sources

3.3 Country Analysis

3.3.1 Emissions per Country

Fig. 3.5. and *Fig. 3.6.* show that the five largest countries (France, Germany, Italy, Spain and the United Kingdom) cause 77% of NO_x and even 81% of NMVOC emissions in 1998. Relative shares of the most relevant source sectors are similar for all countries, major differences can be identified for the energy sector, reflecting the shares of fossil and other fuels in *power generation,* e.g. a larger than average share of nuclear power generation like in France.

3.3.2 Per Capita Emissions

The analysis of per capita emissions in each country for the year 1990 shows a split image and is used here to indicate the significant differences in relative emissions by country and hence potential starting points for the development of abatement strategies. Depending on several influencing factors, specific emissions vary between about 15 to almost 50 kilograms per capita, at an EU15 average of 30 kg/per capita.

France has a comparatively large share of nuclear power in electricity generation and thus less NO_x emissions from that sector compared to countries with a similar

economic performance. Portugals economy is still developing and energy demand as well as road transport do not yet cause as high emissions as in the more industrialised European countries.

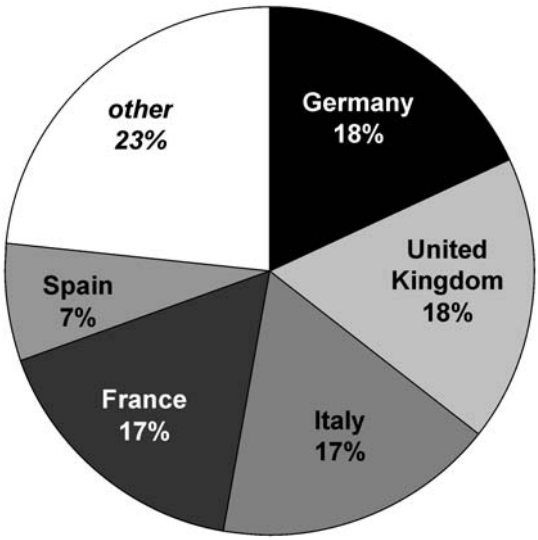

Fig. 3.5. NO_x emissions of EU15 countries 1998 (Source: EMEP WEBDAB 2004)

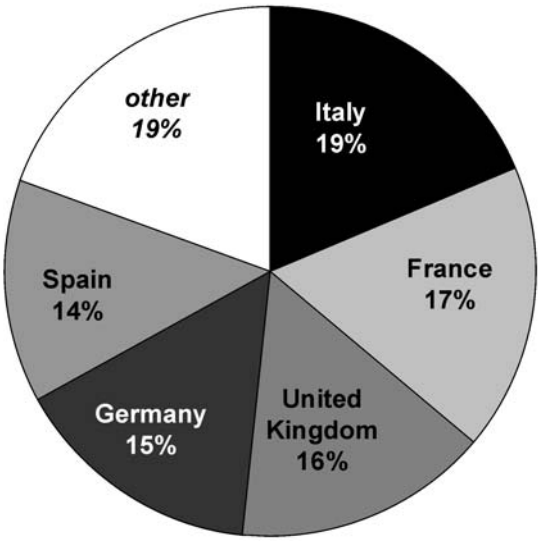

Fig. 3.6. NMVOC emissions of EU15 countries 1998 (Source: EMEP WEBDAB 2004)

Although Luxembourg has no major emission intensive industry and emissions from the energy sector are rather low as well, high specific emissions are caused by road transport, with Luxembourg having one of the highest rates of vehicles per inhabitant in Europe.Regarding NMVOC emissions the picture is similar to NO_x for Portugal and Luxembourg, while other countries show significant differences, e.g. Austria, Denmark and Finland. *Fig. 3.8.* only covers anthropogenic sources, the EU15 mean here is at about 34 kg per capita

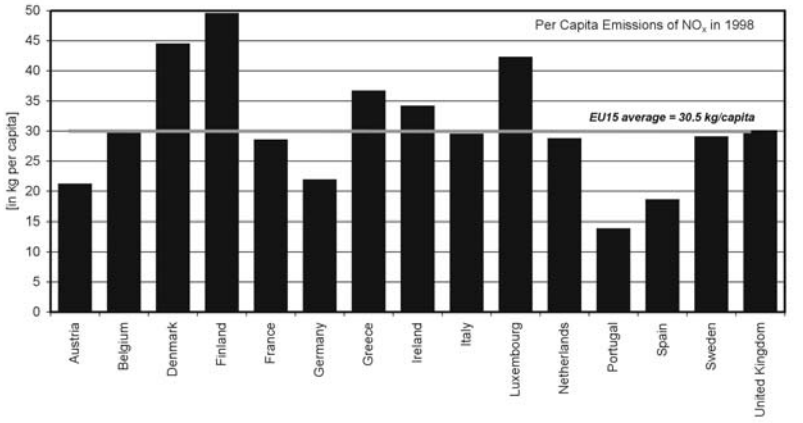

Fig. 3.7. Per capita emissions of NO_x in 1998 (Source: EMEP WEBDAB 2004)

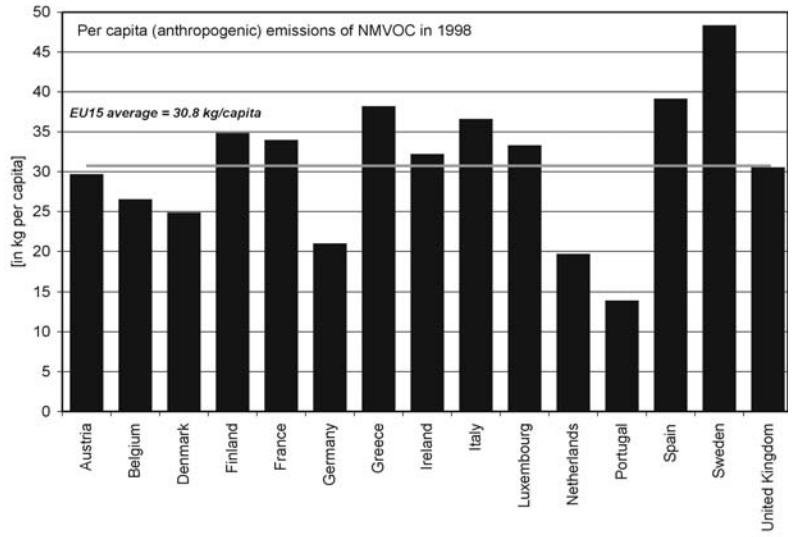

Fig. 3.8. Per capita emissions of anthropogenic NMVOC in 1998 (
Source: EMEP WEBDAB 2004)

3.3.3 Time Series Analysis

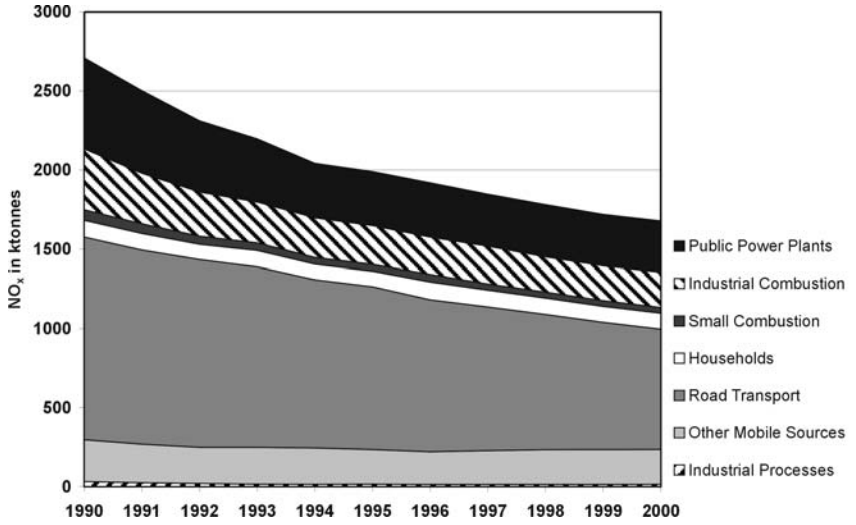

Fig. 3.9. Time series of NO_x emissions in Germany by sector (Source: *UBA 2004*)

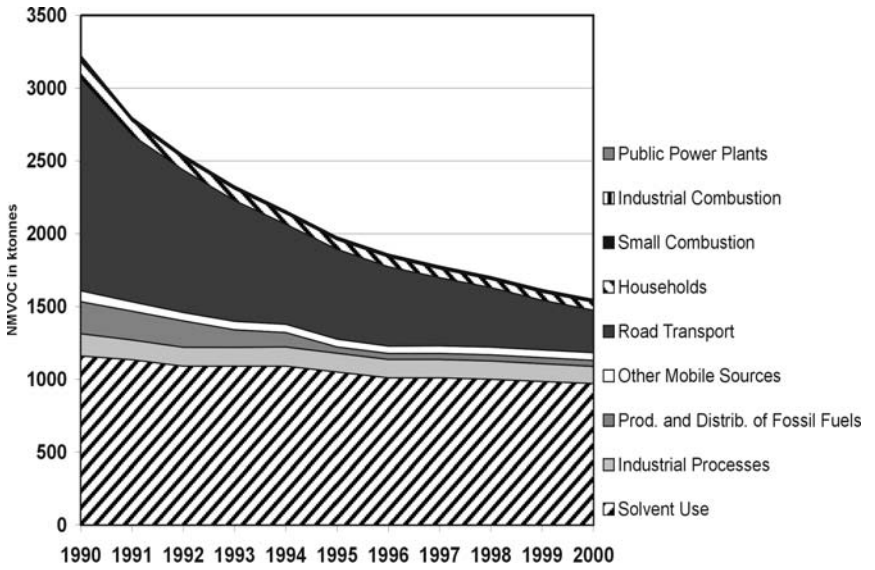

Fig. 3.10. Time series of NMVOC emissions in Germany by sector (Source: *UBA 2004*)

Besides the question, how emissions are distributed spatially and by sectors, it is important to analyse how emissions are changing over time.Thus, *Fig. 3.9.* and *Fig. 3.10.* display on the example of Germany the development of emissions by sector in the course of ten years, clearly indicating the impact emission control options have on different sectors, such as, for instance, the introduction of less emitting vehicles in road transport. As both the development of NO_x and NMVOC emissions indicate significant changes and thus gradually shifting relative contributions of individual source sectors, it becomes clear that for a detailed assessment of future reduction potentials, emission projections on the basis of policies and legislation in place or in pipeline – by country and sector – are essential.

3.4 Scenario Development

3.4.1 Methodology for Emission Projection: Approach

The prime objective for projecting the development of ozone precursor emissions for a future year was to assess the impacts of policies and legislation in place or in pipeline and to estimate the scope of the ozone problem under these conditions. The projection has to serve a number of purposes, mainly to

- provide the emission database to calculate ozone concentrations on regional and local scale in the trend year 2010,
- define a trend scenario, taking into account the legislative and technological framework and thus setting the options and limitations for further emission abatement activities,
- allow to assess efficiency of already implemented measures in terms of cost-effectiveness and ability to achieve the indicated targets, and finally
- to model the effects of structural and behavioural changes on the environmental problem under investigation.

Here, a hybrid approach was taken, accounting for both the need of a detailed assessment and the limitations due to lacking data on implementation degrees or sectoral structures, while covering all relevant sectors and the whole of the EU15 countries. This approach is described in detail in the following sections. Individual sectoral projections were conducted based upon Excel spread sheets, projecting emissions from a base case (1990) towards 2010 under the assumption of all policies and legislation currently in place and in pipeline as well as technology changes would occur.

3.4.2 Emission Projection for a *Business-as-usual* Trend Scenario for 2010

3.4.2.1 Basic Methodology

A major problem for the projection of future emission levels is that emission data is delivered to CORINAIR by all countries involved without providing the complete set of meta-data, which has been used for the calculation. Thus, it is very difficult to obtain information about e.g. fleet compositions, the age structure of power plants in the energy sector, or the amount of solvents used in a specific SNAP activity.

In general, two main approaches can be distinguished, one being based on socio-economic developments (top-down), the other technology based (bottom-up), but a combination of both approaches has to be used, if a harmonised projection of emissions from all sectors needs to be achieved. One crucial aspect of each projection is the selection of appropriate emission factors (EF), since these process or technology specific factors relating activity rates to emissions are subject to significant changes over time. Either technological development, or legislative requirements for abatement technologies heavily influence these emission factors and thus the specific emissions per activity rate. The basic formula of emission calculation, which can be applied to the projection of future levels as well, shows this dependency:

$$E = A \cdot EF$$

with	E	=	emission level	(t)
	A	=	activity rate	(activity units)
	EF	=	emission factor	(t / activity unit)

For the projection, it is vital to assess the future activity rates, such as energy demand, kilometers driven per vehicle, or amount of organic solvents used, as well as the emission factor for a future technology, which might differ considerably from that of the base year. In the CORINAIR/EMEP Emission Inventory Guidebook current emission factors are given for all sectors, but it has been necessary to use additional factors given by other information sources, e.g. the German Emission Factor Handbook to improve data quality by using state-of-the-art research findings.

Wherever possible, the guidelines provided by this handbook chapter have been used for the emission projection in this study, as it is described in the subsequent section.

3.4.2.2 Driving Forces of Emission Development

The approach used here for generating the projections of future emissions includes both, the assessment of future activity levels and the penetration of abatement technologies and their impact on specific emission factors. The penetration velocity of

these technologies is highly dependant on the legislative framework, as can be seen in the road transport sector, where vehicle fleets show growing implementation degrees of equipment according to the increasing stringency of the EURO emission standards for road vehicles. Future activity levels are determined by many different aspects, but for the projection, a set of indicators can be used that show sufficient correlation with the activity to be addressed. These proxies for projection are described in detail in the following sections.

3.4.2.3 Societal and Demographic Trends

The first proxy to be taken into account is that of the population development, since many environmental problems are directly related to urbanisation, individual or public transport demand, or energy demand. *Fig. 3.11.* shows the projected growth or decrease in population in 2010 compared to 1990 for all EU Member States and as an EU15 average.

This proxy was used to project activities such as the use of solvents from domestic use, or from paint application in construction and building.

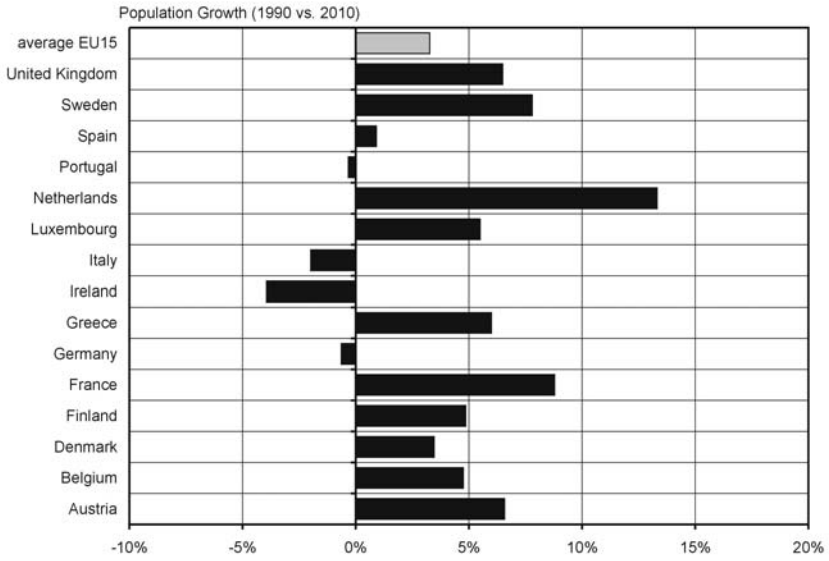

Fig. 3.11. Population growth in the EU15 – 1990 vs. 2010 (Source: EUROSTAT 1995)

3.4.2.4 Trends in Economic Development

In addition to the growth of population, economic activity levels have to be taken into account, having an impact on emissions from production processes, industrial energy demand and the demand for services. The development of the Gross Domestic Product (GDP) (*Fig. 3.12.*) was selected as a proxy, reflecting the different economic states in the base year and the anticipated growth rates to the trend year.

This proxy was used to project emissions from industrial energy demand, production processes and industrial applications of solvent use. As can be seen, Ireland and Portugal have comparatively high anticipated growth rates, catching up to the standards of the more industrialised EU countries. Since energy conversion and the use of fossil fuels in different sectors are responsible for a large share of ozone precursor emissions, it is important to thoroughly investigate trends in fuel demand and fuel shares. *Fig. 3.13.* shows that the shares of fossil fuel types used in electricity production vary considerably between individual countries

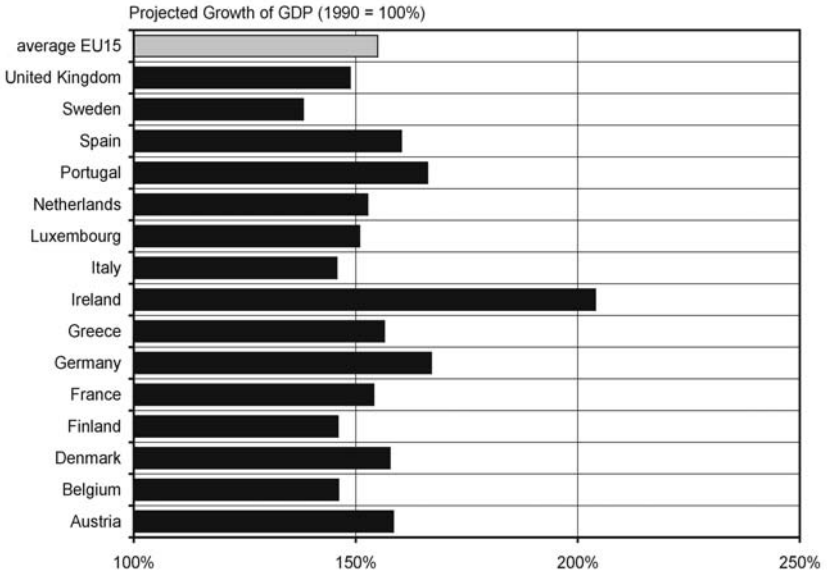

Fig. 3.12. Projected growth of GDP in the EU15 – 1990 vs. 2010 (Source: DG XVII 1996)

3.4.2.5 Energy Trends

There is a clear trend of a decreasing consumption of solid fossil fuels (mainly hard coal and lignite) in favour of an increase of natural gas use, while oil consumption

shows a slight increase. The combustion of natural gas is considered to be significantly cleaner than the use of hard coal or lignite and many new power plants being commissioned in the EU are natural gas fired.This change in fuels leads to a gradual reduction of NO_x emissions from energy production as natural gas bears less fuel-NO than solid fuels. In addition to that, other pollutants are reduced simultaneously, for instance SO_2 (Sulphur content of coal and oil) and particulate matter (dust from coal handling), while a slight increase of Methane and NMVOC emissions from a growth in natural gas demand (leakage from pipelines and storage) has to be anticipated (cf. *Annex B*).

This detailed projection of the fuel mix and the development of fuel shares is important, since the NO_x emission factors of solid fuels, oil and natural gas are significantly different. Furthermore, costs and reduction efficiencies of emission abatement measures for power plants are fuel-dependent as well (see *Chap. 4.3*)

3.4.2.6 Political and Legislative Framework for Projection

In addition to the anticipated changes in activity levels described in the previous section, political decision and legislative measures can have a major effect on emissions, namely the specific emission factors of processes or plants..

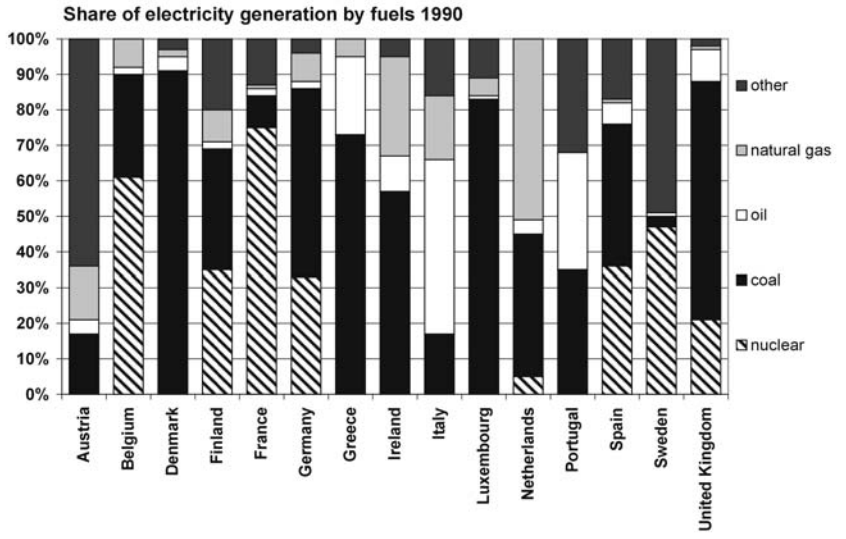

Fig. 3.13. Shares of fossil fuel use in electricity production in EU15 countries 1990 (Source: EC1996)

Three major areas of political and legislative action have been identified in this study and will be described in this section

- the EURO 1-5 emission standards for road transport vehicles[1] (based upon 91/441/EEC and following directives and regulations, European Communities 1991)
- the EC Large Combustion Plant Directive (88/609/EEC, European Communities 1988)
- the EC Solvent Use Directive (1999/13/EC, European Communities 1999)

These areas cover the most important sectors of ozone precursor emissions and have been adopted in recent years, they will develop their full impact either before the year 2010, or will at least have a significant effect until then. The individual directives and standards have to be seen in the context of the European Air Quality Framework Directive described in *Chap. 2*.

In addition to these most important legislative activities, a large number of regulations and limit values for specific substances, other sectors and groups of emitters have been taken into account as well.

3.4.3 Sectoral Air Pollution Control Policies

3.4.3.1 Road Transport

Annex B contains a comprehensive historical overview on legislation concerning air pollutant emissions from road transport vehicles, dating back to the year 1970. For NO_x and NMVOC emissions, the current EURO emission standards are the most important regulations, at full implementation reducing up to 96% of NO_x and 98% of NMVOC emissions from vehicles, depending on the fuel used (see *Table 3.3.*). According to the typical fleet renewal rates in each country, the EURO 3 and 4 standards will not yet have reached full implementation in the trend scenario for 2010, with average lifetimes of a passenger car varying between less than 10 and over 15 years in individual countries. A full implementation of the EURO 4 standard for all vehicle types will lead to a significant reduction of emissions from the road transport sector (about 80% of total sectoral NO_x and 88% of sectoral NMVOC emissions). Further legislation for this sector (cf. *Annex B*) includes quality standards for transport fuel and the related activities of the distribution of fuels, such as Stage I/II of the Directive for the distribution of gasoline, covering as well service stations (94/63/EC, Stage I/II) and includes further emission control for other pollutants, for instance Particulate Matter from diesel engines.

1. The EURO 5 standard for heavy duty vehicles was not yet integrated in the projection, as the legislative process had only just begun and the envisaged implementation in 2008 will not have a major impact on 2010 emissions

Table 3.3. Emission reductions achievable by EURO 1 – 5 standards related to pre-EURO levels[a]

standard *implementation year*	**EURO 1** *1990*	**EURO 2** *1996*	**EURO 3** *2001*	**EURO 4** *2005*	**EURO 5**[b] *2008*
	NO_x				
PC *gasoline*	-81.2	-94.0	-94.8	-96.4	
PC *diesel*	-46.3	-39.8	-57.0	-74.2	
LDV *gasoline*	-82.7	-89.6	-94.8	-96.3	
LDV *diesel*	-4.4	-11.9	-70.4	-73.1	
HDV	-11.8	-21.6	-56.5	-76.5	*-50 (rel.)*
	NMVOC				
PC *gasoline*	-87.6	-92.4	-94.9	-98.5	
PC *diesel*	-54.8	-66.7	-78.6	-84.8	
LDV *gasoline*	-87.6	-89.5	-94.7	-96.3	
LDV *diesel*	-69.7	-76.2	-88.0	-97.7	
HDV	-70.3	-82.0	-95.6	-92.6	

a. Source: Institute for Prospective Technology Studies (IPTS) Analysis (see *Friedrich and Reis 2000*)

b. The EURO 5 standard is currently in preparation with the aim to halve specific HDV NO_x emissions and is anticipated to come into force in 2008. However, recent findings indicate that emission factors for NO_x from HDV may have been significantly underestimated in current analyses and thus the abatement efficiency may need to be revised accordingly.

The amount of directives and regulations reflects the importance of this sector for air quality control, especially since transport demand is projected to grow significantly in the near future. Thus, the reductions shown in Table 5.2 are offset to some extent by the growth in vehicle fleets, while annual mileage per vehicle is regarded to remain more or less constant, as it has been assumed as well by other studies, e.g. by SHELL. In the case of NO_x emissions from heavy duty vehicles, even an overall increase of emissions is projected for the trend scenario, reflecting a major growth in freight transport in most of the EC Member States, which outweighs the reductions achieved by the penetration of EURO 4 compliant HDVs until then.

It has to be noted that these directives and regulations usually set an emission standard, not requiring specific equipment or technologies for compliance. The current state-of-the-art of technology options being used to achieve these standards are described in detail in *Sect. 3.4*.

3.4.3.2 Energy Sector

The Large Combustion Plants (LCP) Directive was introduced mainly to reduce the emissions of sulphur (SO_2) and nitrogen oxides from large combustion plants, which contribute by far the largest share of any individual source group to the emissions of these pollutants (about 68% of SO_2 and 27% of NO_x emissions, *Radunsky and Ritter 1996*). The Directive uses the approach of *Best Available Technology* (BAT) to install emission limits for new large combustion plants to be commissioned as well as for existing plants to comply with by a target year. The development of this Directive was related to the UNECE Convention on Long Range Transboundary Air Pollution protocols (see *Chap. 2*) and to other European Commission Directives, e.g. regarding the sulphur content of fuels (72/116/EEC) and the Framework Directive on *Integrated Pollution Prevention and Control* (IPPC), that was adopted in 1996. In terms of environmental targets, the LCP Directive is expected to aid in accomplishing the targets of the Commissions' Community Strategy to Combat Acidification.

For this study, it was assumed that all countries would follow the requirements of the LCP Directive and that new plants would use BAT (mainly primary measures or SCR for the reduction of NO_x emissions) to meet the limit values. For the commissioning of new plants, the projected future energy demand was used in addition to EURPROG data to assess the share of existing 1990 plants in 2010. This distinction was necessary to assess the costs for different abatement options. The high investment costs and long lifetimes (between 30 and 40 years for a typical LCP) make retrofitting feasible, other than in the transport sector, where a retrofit of older cars in use is not regarded to be an efficient option for advanced emission control technology.

An investigation carried out by *ERM* (*1996a*) assumed a reduction of NO_x by 54% relative to 1990 for the EU15, while the projection of this study amounted to a reduction of 47%, having taken into account a higher implementation degree of emission abatement equipment in operation in Germany in the base year 1990.

3.4.3.3 Legislation on Specific Substances

The European Community directly addressed emissions from the use of organic solvents with the EC Solvent Directive (1999/13/EC, *European Communities 1999*).

Aimed at setting emission ceilings and reduction targets for individual sectors of solvent use (see *Annex B*), the Annex to this Directive names each sector to be regulated and set specific targets to be met by a specified target year. EU Member States have to install legislation to comply with the Directive by the end of 1999. New installations are required to comply with the Directive from the start, whereas for existing installations compliance is required by October 30, 2007. EC assessment assumed a possible reduction of 57% (relative to 1990) by 2007.

Since the projection was made for the year 2010, the Directive should have full impact on the emissions by then, affecting all installations operating in the trend

year. The assessment of emission reduction potentials, however, is immensely difficult due to the scarce date available on the solvent using sector. Expertise from previous studies at IER (cf. *Obermeier at al. 1997*, *Berner et al. 1996*) were used along with feedback from the IPTS Expert Survey on the Solvent Sector to determine the potential emission reduction for all EU 15 Member States. It has been assumed that only few countries, e.g. Germany, Austria, the Netherlands, Denmark and Sweden have already started to implement emission control equipment in this sector yet, according to national legislation, thus the main activities will be taken in the coming years. Projected reduction of NMVOC emissions from the solvent use sector (SNAP 6) ranges between 18% and 44%, reflecting the differing shares of source activities within the EU countries, with 61% of total emissions from this sector being covered by the Solvent Directive

The Solvent Directive is implemented by the means of emission limits being set for each sector, either a combination of process and fugitive emission limits or a total emission limit. Process emission limits describe concentration limits applying to VOC emissions from contained sources (between 20 and 150 $\mu g/m^3$ depending on the sector and specific solvent consumption). Fugitive emission limits target uncaptured VOC emissions and are expressed as a percentage of the solvent input. Between 5% to 45% (depending on the sector and the solvent consumption) may be emitted. Finally, total emission limits apply to industry sectors, setting a fixed emission limit per unit of production (e.g. for several coating sectors, dry cleaning, wood impregnation and vegetable oil extraction).

3.4.4 Detailed Sectoral Projection

In this section, the assumptions that have gone into the emission projection for a business-as-usual trend scenario for the year 2010 will be described. For those sectors, which contribute major shares of ozone precursor emissions, this projection has been conducted rather detailed and on a disaggregated level. For the remaining sectors, which have been assessed to be of minor importance for the development of NO_x and NMVOC emissions, a trend development was assumed that goes along with other projections found in literature.

3.4.4.1 Emissions from the Energy Sector

Future energy demand was taken from the conventional wisdom scenario of DG Transport and Energy, using the projection of the growing input of fossil fuels into power generation (instead of growing final energy demand to take into account NO_x-neutral sources like nuclear or hydro power, as nuclear power has diminishing acceptance in Europe and hydro power only limited further potential).

For the all power plants in this sector, the requirements of the Large Combustion Plant Directive of the EC have been taken into account. Data for each country was harmonised similar to the approach taken by the International Institute for Applied

Systems Analysis (IIASA) (*Amann et al. 1996*), selecting the use of air pollution control equipment for each plant type by country. To comply with the LCP Directive, countries are required to equip the large combustion plants with primary measures (PM). In addition to that, some EU member states' national regulations make the use of Selective Catalytic Reduction-installations (SCR) mandatory.

The projection has focused on activities with installed capacities >300 MW, which contribute more than 97% of total NO_x emissions in SNAP 1 (CORINAIR 90). The sectoral contribution to NMVOC emissions is very low and has not been subject to investigations, but the increasing use of natural gas in energy production will probably lead to a slight decrease in fuel related NMVOC emissions. According to the trend scenario for 2010, total EU15 NO_x emissions from SNAP 1 will be reduced by 47% relative to CORINAIR 90 emissions.

3.4.4.2 Emissions from Residential and Commercial Combustion

This sector is marked by a highly diffuse structure, containing emission sources from small household heating systems towards medium sized plants for commercial and institutional utilisation. Being used mainly for space heating and process heat (water etc.) purposes, no major change in activity levels per capita can be expected, while improved insulation and increasing energy efficiency in small boilers will even lead to a slight decrease in emissions.

Above all, technological improvements such as increasing efficiency in boilers, improved insulation of buildings and the application of low-NO_x-burners and other primary measures will have some impact on emissions in 2010. The trend scenario assumes a slight reduction of NO_x (5.1%), but an even more significant reduction of NMVOC (9.3%), which is primarily caused by the fuel switch from solid fuels and oil towards natural gas.

3.4.4.3 Emissions from Industrial Combustion

Industrial combustion plants emit the second largest share of NO_x emissions from stationary sources. For the projection of future activity levels, the growth in energy demand within the energy sector was taken from the conventional wisdom scenario of *Energy in Europe to 2020*. While combustion plants contribute about 53% of total sectoral NO_x emissions, various industrial processes (SNAP 3.3) have been identified as a major source as well. For these processes it is assumed that an increase in emissions due to a growth in industrial production is offset by improved efficiency on a process level, keeping emissions constant on the CORINAIR 90 level. Thus, only a slight reduction is projected, reducing NO_x emissions from this sector by 16%, mainly from the LCP Directive leading to the installation of emission control measures in industrial LPCs.

For the identified combustion plants in the industry sector, the same regulations apply as for large combustion plants (LCP Directive, *European Communities 1988*).The implementation degree of emission control equipment has been calculat-

ed accordingly, leading to an overall sectoral emission reduction (see above). On the process level, no major emission reduction was assumed for the trend scenario. However, selected processes with significant NO_x emissions will be subject to the implementation of further reduction measures beyond the trend, e.g. cement production and iron and steel production.

3.4.4.4 Emissions from Fuel Handling

The fuel handling sector is a major contributor to NMVOC emissions (7.3% of total EU15 emissions according to CORINAIR 90). Within this sector, the handling of liquid fuels was identified to be the most significant source, concentrating on the distribution path of gasoline from refineries to service stations. As a proxy to assess the future development of this source, the growth in demand for fossil fuels was used (*Energy in Europe to 2020*, DG XVII). Specific growth factors have been identified for solid fuels, oil, natural gas and gasoline (see *Figs. 3.13*. to *3.15.*).

Following directive 94/63/EC, activities to reduce NMVOC emissions have been taken into account at the refinery and depot level (*Stage IA*) and for service stations (*Stage IB*). Furthermore, Stage II controls have been assumed to be implemented for the largest share of service stations, resulting in an overall reduction of 45% within gasoline distribution (57% for large service stations, 15% – 1% for medium and small service stations with/without derogation). Due to the projected increase in fuel demand, total sectoral emissions of NMVOC only show a reduction of 26.3% compared to CORINAIR 90.

3.4.4.5 Emissions from Solvent Use

With a share of 28.7% of total EU15 NMVOC emissions, solvent use was identified as the second largest contributor. And since the bulk of activities covered by this sector is related to industrial activity, growth assumptions for the countries' Gross Domestic Product (GDP) have been used as proxies to project future activity levels. For the domestic use of solvents or paints, population development was used instead. The EC Directive on VOC emissions from solvent use (1999/13/EC, *European Communities 1999*) and the UNECE VOC protocol to the Convention on Long Range Transboundary Air Pollution (CLRTAP) have been taken into account to reflect current reduction plans in this sector. For all countries of the EU15, significant reductions of emissions from solvent use have been assumed, leading to an overall decrease of NMVOC emissions from SNAP 6 by 31% compared with CORINAIR 90. For all countries, compliance with the VOC protocol is foreseen. Although for Greece, Portugal and Ireland the relatively high growth rate of industrial production (reflected through GDP) will prove to offset abatement activities to a large extent.

3.4.4.6 Emissions from Road Transport

For emissions from Road Transport, several variable have been investigated to assess the development of emissions. On the one hand, emission factors determine the amount of a pollutant emitted related to a specific activity (e.g. g/km driven), on the other hand, the size and technological composition of the vehicle fleet and a change in activity rates and patterns have are of interest. Data on size and composition of EU15 vehicle fleets was obtained from Deliverable 16 of the MEET project (*MEET* 1997b). To be used for the generation of the trend scenario for the year 2010, this data had to be adapted to meet the sectoral aggregation level of CORINAIR 90 and to improve transparency. Thus, vehicles have been attributed to technology groups such as pre-EURO, EURO 1, EURO 2 EURO 3 and EURO 4 for Passenger Cars (PCs), Light Duty Vehicles (LDVs) and Heavy Duty Vehicles (HDVs). For Two-Wheelers (TWs), 2-stroke and 4-stroke engines were distinguished into Stage I and Stage II controls for Mopeds (< 50 ccm) and uncontrolled and controlled (> 50 ccm).

Given activity rates have also been adapted to comply with this aggregated data, providing information on km driven per vehicle and year. The change from 1990 to 2010 levels was calculated using only modifications in emission factors and fleet composition (vehicle types and technology levels); annual mileage per vehicle was kept constant, assuming that a single vehicle would not be operated in a way much different from 1990, regarding the shares of urban, rural and highway driving patterns as well. This approach involves an error since with increasing vehicle density (vehicles per inhabitant), the specific annual mileage per vehicle is bound to decrease. However, projected activity levels have not been available and as the time horizon until 2010 is not too far into the future, a constant annual mileage was assumed as a simplification.

For PCs and LDVs a trend exists towards an increasing share of diesel operated vehicles, while for HDVs the share of gasoline fuelled vehicles was assumed to be zero. Liquified Petrol Gas (LPG) does play a minor role, being only used to some extent in Belgium, The Netherlands and Italy and was thus not being taken into account. Projected emission levels show considerable reductions in this sector, amounting to a decrease by 39% for NO_x and even 67.5% for NMVOC.

Together with data on technical emission abatement measures (see *Chap. 4*), IPTS provided mean emission factors for NO_x and NMVOC for each vehicle type and EURO emission standard. The emission factors used for the projection reflect the development of European legislation on emission standards for road vehicles. Table 5.1 presents all regulations taken into account. The implementation degree of each standard was provided by MEET (*MEET 1997a, b, c* and *1998*), assuming the timely coming into force of EURO 3 and EURO 4 standards. Since a normal turnover of vehicle fleets was projected, there will still be only relatively few vehicles complying to EURO 4 in the 2010 trend case. And since a retrofitting of vehicles with –mainly built-in– emission abatement technologies is not feasible, only activities to promote a faster turnover of the vehicle fleet can lead to a further significant reduction of emissions from road transport beyond the trend.

3.4.4.7 Emissions from Other Mobile Sources

This sector proves to be rather difficult to handle, because it comprises a collection of sources, which do not have much in common. For emissions from Airports (SNAP 8.5), a significant increase can be assumed due to growing demand for air transport. However, contributing only 4.7% of total sectoral NO_x emissions, this has not been taken into account for the trend scenario. The main source group within this sector is that of off-road vehicles and machines (SNAP 8.1) with a share of 50% of total sectoral NO_x and even 60% of total sectoral NMVOC emissions. Activity levels for this source group have been assumed to remain constant, too.

While other mobile sources emit a significant share of total EU15 NO_x emissions (12.4%), their contribution to total EU15 NMVOC emissions is considerably lower (3.8%). For the trend scenario, no major emission reduction activities have been taken into account, assuming that technological improvements and abatement technologies applied especially in the field of off-road vehicles and machines as required by Directive 2001/63/EC on the reduction of emissions of gaseous pollutants by non-road mobile machinery will be offset by increasing activities.

3.4.5 Trend Scenario Emissions

Compiling the detailed sectoral projections, the trend scenario for 2010 shows an overall reduction of NO_x by 30%, for NMVOC the reduction is 36% (*Fig. 3.14.* and *Fig. 3.15.*), with respect to growing economies and e.g. increases in road transport a considerable decrease in emissions. However, to achieve a significant reduction of tropospheric ozone concentrations, it will not be sufficient, thus making it necessary to identify additional measures and strategies for reduction.

As *Fig. 3.14.* and *Fig. 3.15.* (see *Table 3.4.* and *Table 3.5.* as well) indicate, the relative reduction of emissions is far from homogeneous among EU15 countries, changes ranging from +1.7 to –42.4% for NO_x and –13.1% to 48.2% for NMVOC. But it can be seen that the major emitters (Germany, France, Italy and the United Kingdom) are able to cut their emissions considerably. However, it has to be stated that even the latest available emission data (i.e. *EMEP 2000*) are prone to considerable uncertainties and inconsistencies in reporting of individual countries are known.

The following *Table 3.6.* shows that above all the reductions in road transport and power generation (NO_x), respectively road transport and solvent use (NMVOC) dominate the future emission levels. But it becomes obvious, though, that with these emissions being reduced, other sectors, such as *industry processes* or *other mobile sources* become more important.

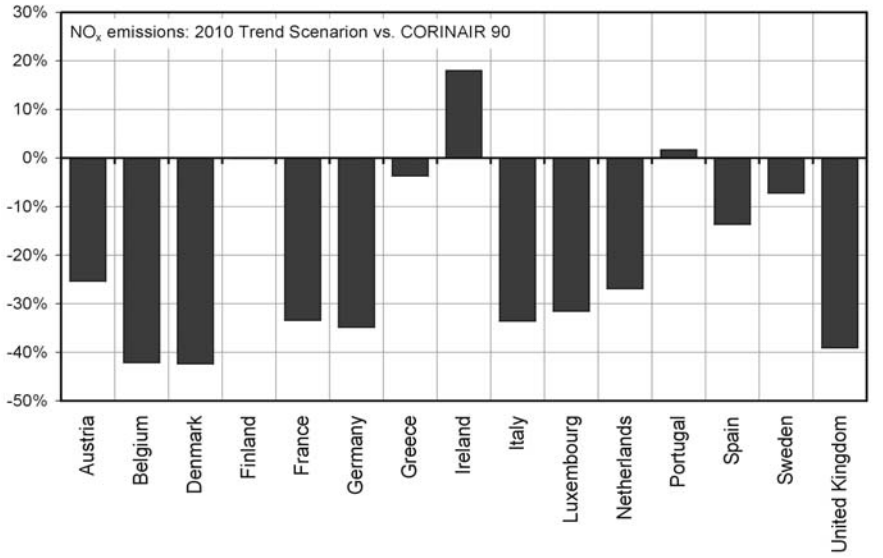

Fig. 3.14. 2010 NO_x trend emissions vs. CORINAIR 90 emissions by country

Table 3.4. NO_x emissions in the trend scenario for 2010 compared with CORINAIR emission inventory data (ktonnes)

NO_x Emissions	**CORINAIR 1990**	**EMEP 2000**	**TREND 2010**
Austria	226.6	183.6	169.2
Belgium	343.2	288.9	198.5
Denmark	273.3	207.2	157.5
Finland	268.5	235.8	268.3
France	1 584.6	1 432.0	1 054.8
Germany	2 979.7	1 637.0	1 941.2
Greece	542.7	340.0	522.7
Ireland	115.7	125.1	136.6
Italy	2 041.3	1 485.0	1 356.0
Luxembourg	23.1	17.0	16.0
Netherlands	561.0	420.0	410.0
Portugal	215.3	369.3	219.1
Spain	1 247.4	1 419.0	1 077.2
Sweden	345.1	246.6	320.2
United Kingdom	2 773.2	1 512.0	1 688.9
Total EU15	**13 541.0**	**9 919.6**	**9 531.2**
change relative to CORINAIR 90		*- 26.7%*	*- 30%*

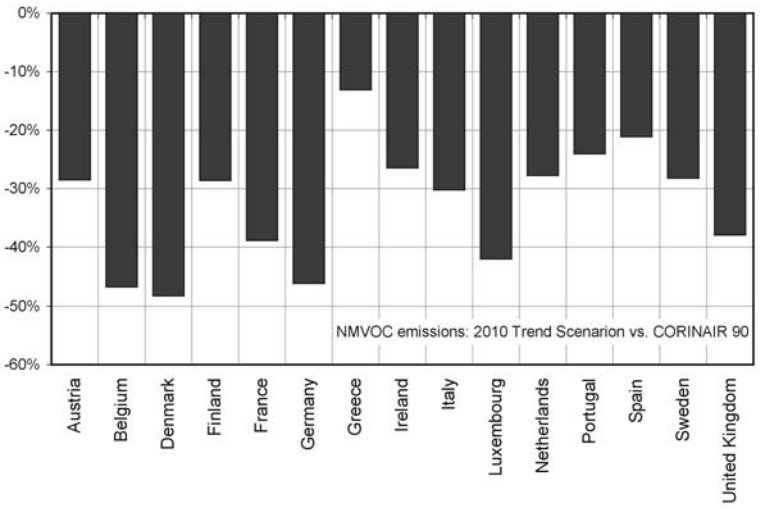

Fig. 3.15. 2010 NMVOC trend emissions vs. CORINAIR 90 emissions by country

Table 3.5. Anthropogenic NMVOC emissions in the trend scenario for 2010 compared with CORINAIR emission inventory data

NMVOC EU15	CORINAIR 1990	EMEP 2000[a]	Trend 2010
Austria	418.9	238.7	299.5
Belgium	364.9	248.0	194.4
Denmark	169.1	131.9	87.5
Finland	165.3	159.9	118.0
France	2 403.7	1 659.0	1 469.1
Germany	2 936.6	1 653.0	1 582.1
Greece	324.9	350.0	282.3
Ireland	180.4	90.3	132.7
Italy	2 395.8	1 671.0	1 671.3
Luxembourg	18.7	14.9	10.9
Netherlands	456.7	280.7	329.9
Portugal	205.8	483.7	156.3
Spain	1 118.8	1 548.0	882.3
Sweden	451.3	417.8	324.0
United Kingdom	2 602.0	1 498.0	1 614.6
Total EU15	**14 213.2**	**10 480.0**	**9 154.9**
change relative to CORINAIR 90		*- 26.3%*	*- 36%*

a. after CORINAIR 94, the methodology for calculating biogenic emissions from forests (SNAP 11) and agriculture (SNAP 10) has been changed; these figures have been corrected to be comparable to CORINAIR 90 and the trend scenario for 2010

Table 3.6. Overview on sectoral changes comparing CORINAIR 90 to the year 2010 trend scenario

Sector	NO_x reduction	NMVOC reduction
Road Transport	-39%	-67%
Power Generation	-47%	+9%
Other Mobile Sources	a.c[a]	a.c.
Industrial Combustion	-16%	a.c.
Residential & Commercial Combustion	-5%	-9%
Industrial Processes	+55%	+53%
Waste Treatment & Disposal	+3%	+2%
Fossil Fuel Production & Handling	+4%	-26%
Solvent Use	a.c.	-31%
Agriculture	a.c.	a.c.
Total	**-30%**	**-36%**

a. a.c. = assumed constant

3.5 Assessing Abatement Costs

3.5.1 General Approach and Methodology

In the early stages of air pollution control, the main focus was on the significant reduction of impacts on health and vegetation, e.g. the reduction of particulate emissions from large combustion plants, or combating acid rain. And since these first steps towards cleaner air have been mainly taken by command and control mechanisms, setting emission limits for large combustion plants or road vehicles, efficiency was only measured in terms of achieving air quality targets. Costs, or even cost-effectiveness have never been discussed then.

But in recent years, along with the introduction of economic instruments into the field of environmental protection and air pollution control, more thought was given to the cost aspects, especially when a portfolio of measures could reach the same air quality target and it was necessary to determine the best option. Another strong motivation for the investigation and calculation of abatement costs and thus the efficiency of measures was the introduction of the concept of external costs, since the knowledge about marginal damage costs and marginal abatement costs is essential to determine the optimal pollution level. And while quite some work has already been conducted on the assessment of impacts of air pollution and furthermore the quantification and monetarisation of benefits of air pollution control, only few approaches and models are yet available which include the calculation of abatement costs as well.

In this respect, it is necessary to define the use of *efficiency* and (cost-) *effectiveness* in this work, as these keywords are sometimes used in different contexts. Cost-*effectiveness*, as it is used here, describes the best (optimal) way to reach a predefined (air quality) target with least possible costs. Hence, *efficiency* will be used to describe the performance of a specific measure, i.e. its *cost-benefit-ratio*, where the *benefit* is the physical improvement of air quality and the costs are the total abatement costs associated with the implementation of the measure. Great care has to be taken in the use of the keyword benefit, since it can refer to the physical improvement of air quality (= reduced ambient concentration of air pollutants) as well as the quantified reduction of damage costs (i.e. monetary benefit) of implementing air pollution control measures. As both benefit concepts are applied within this study, the relevant definition will be clarified when it is used.

Finally, with this knowledge, the efficiency of any air pollution control measure (this applies for bundles of measures as well) can be defined as total costs for the implementation of this measure relative to the amount of emissions abated. For a more extensive discussion of efficiency issues *see Sect. 3.2*.

3.5.2 Guidelines for Cost Data Collection

When trying to calculate the costs of abatement of environmental pollutants, four main factors can be identified which determine these costs: the type of pollutant, the diversity of emission sources, the scale of abatement and the pollutant concentration in the waste stream (cf. *Hartman et al., 1994*). For any abatement measure, a core set of information has to be collected to address and quantify these factors. A measure in this context is defined as a device to be applied in order to reduce the emissions of a specific activity. To specify this rather general definition for this study, only technical measures will be taken into account. This exclusion of non-technical measures is mainly based on the non-availability of cost and efficiency data on an operational level. Available studies on non-technical measures usually feature sector- or economy-wide applications of economic instruments. In addition to that, most often non-technical measures investigated incorporate technical measures on the implementation level. Hence, to keep the analysis transparent, only technical measures have been included.

A recent study by the EEA has resulted in a base set of information to be collected for any type of environmental protection measure (*EEA 1999*):

- detailed description of the pollution source
- detailed (technical) description of the measure itself (e.g. performance, operating parameters, applicability to sources, availability)
- cost components (and how they have been calculated)
- reference year
- data source

For this study, *emission sources* were defined according to CORINAIR SNAP 90 nomenclature (see *Annex I*), for the most relevant source groups, as detailed as down to activity level (SNAP level 3). This presents a major difference to most other modelling approaches, where costs and emission reductions are usually calculated on a far more aggregated level. And as each abatement measure and its effect on the emission parameters of a source has to be described in as much detail as possible, these activities have in some cases even been split further, e.g. to distinguish emissions originating from diesel or gasoline fuelled vehicles. The main categories of abatement measures can be defined as follows:

- primary measures
  - *good housekeeping (e.g. improved maintenance)*
  - *process modifications (e.g. closed-chamber processes)*
  - *process-integrated measures (e.g. low-NO_x burners)*
  - *product reformulation (e.g. low solvent-content paints)*
- secondary measures
  - *end-of-pipe technologies (e.g. catalysts in the exhaust gas stream)*
- non-technical measures
  - *organisational and/or lifestyle changes (e.g. modal switches to public transport)*
  - *taxes and permits (e.g. on fuels or emissions)*

As stated above, non-technical measures will not be addressed within this study. Data on abatement measures have been collected by the *Institute for Prospective Technology Studies* in the frame of the European research project INFOS (F*riedrich and Reis, 2000*). The cost categories will be discussed in detail in *Sect. 3.5.3*. To make sure that only costs, which are directly related to air pollution control measures are accounted for, measures have to be assessed to their main purpose. This is difficult in some cases, as the environmental effect (i.e. reduced emissions of air pollutants) and other effects (e.g. reduced production costs through increased efficiency of the process) might be in the same scope. Thus, for this study, only measures will be taken into account, which are applied with the sole purpose of reducing the emission of NO_x and NMVOCs from a source, not accounting for other benefits, such as, for example, the reduction of other pollutants at the same time. Finally, the part of the total cost of a measure, that is attributed to air pollution control has to be defined. Here, the approach of additional costs provides the best option, referring to the excess costs of an equipment including an abatement measure X in comparison to the same equipment without this measure.

3.5.3 Generating Abatement Cost Curves

The basic design of an abatement cost curve is comparatively easy, giving information about the abatement potential of a respective measure and the related abatement costs (most often marginal abatement costs in [*monetary units/physical units*] of pollutant abated). However, in the case of tropospheric ozone, some critical issues have to be investigated to generate a cost curve to be of use in an optimisation approach.

These critical issues are

- non-linearity of ozone production,
- inhomogeneous sectoral contribution of NMVOC species,
- measures that reduce both pollutants (i.e. the allocation of abatement costs to each pollutant abated).

Varying levels of tropospheric ozone precursors (NO_x and NMVOC) in different regions lead to a situation, where ozone production may be either NO_x-limited, or NMVOC-limited. Thus, the emission of one unit of NO_x or NMVOC (and its atmospheric transport) in one place leads to different ozone effects in each receptor area. By generating source-receptor-matrices, this situation can at least be statically mapped, leading to blame matrices, where the emission of one unit of NO_x (or NMVOC) from a specified place is related to the generation of a corresponding amount of tropospheric ozone in each affected area. Especially in the case of NO_x emissions, this generation of ozone can be negative, reflecting the potential of NO_x (in this case NO) excess to reduce ozone.

These aspects lead to the conclusion that in order to reduce tropospheric ozone, a reduction of NO_x has to be accompanied by a reduction of NMVOC as well, if an increase of ozone levels in some areas shall be avoided.

- On the other hand, available technical measures to reduce emissions of ozone precursors can be structured in the following way:
- NO_x abatement measures (e.g. energy sector: SCR, SNCR, primary measures)
- NMVOC abatement measures (e.g. solvent use sector: low solvent paints)
- NO_x & NMVOC abatement measures (e.g. transport sector: 3-way-catalyst)

While either NO_x or NMVOC abatement measures are relatively easy to handle, measures which reduce both precursors at the same time are more difficult. Whenever such a measure is implemented, the simultaneous reduction of both pollutants makes it necessary to re-calculate the resulting ozone concentration for all affected areas. And due to the non-linear relationship between emissions and ozone formation, a possible increase in at least some areas cannot be excluded.

As to the sectoral contributions of ozone precursors, it is basically not satisfactory to investigate NMVOCs as one homogeneous pollutant. But even though some

research has been directed to the speciation of VOCs for modelling purposes (cf. *Middleton 1990* and *Carter 1994*), virtually no information is available as to the reduction of specific VOC species by abatement measures. Thus it is – for the time being – impossible to improve technical cost curves for NMVOC abatement by including information on relevant VOC species' reduction potential. However, within the EMEP chemical transport and dispersion model (CTM) applied in the context of this work, different VOC profiles are taken into account, especially in the transport sector, and a detailed investigation of the specific contribution of each vehicle class in terms of VOC species is conducted.

3.6 Emission Abatement Options

3.6.1 Abatement Options Analysed

3.6.1.1 Large Combustion Plants

In this section, the measures taken into account for the development of the trend scenario and which are technically available for additional emission reductions beyond the trend will be discussed. In the energy sector, the large combustion plants are usually marked by considerable lifetimes and hence there is always the option to either retrofit an existing plant with air pollution control equipment, or, in case a new plant is built, include the equipment in the initial setup already (cf. *Rentz and Ribeiro, 1995*).

And as the costs of these two options can vary considerably, they have been distinguished in the assessment of measures and costs (see *Fig. 3.16.* and *Fig. 3.17.*) as follows:

- **Retrofitting existing plants (for each fuel: coal, gas, oil)**

  Primary Measures [PM] (combustion modifications such as: low-NO_x burner LNB, low excess air LEA, over fire air OFA, flue gas recirculation FGR)

  Secondary Measures (Selective Catalytic Reduction SCR)

  Combined Primary and Secondary Measures (PM + SCR)

- **Installation at new plants (for each fuel type: coal, gas, oil)**

  Primary Measures [PM] (combustion modifications such as: low-NO_x burner LNB, low excess air LEA, over fire air OFA, flue gas recirculation FGR)

  *Secondary Measures (*Selective Catalytic Reduction, SCR)

  Combined Measures (PM + SCR)

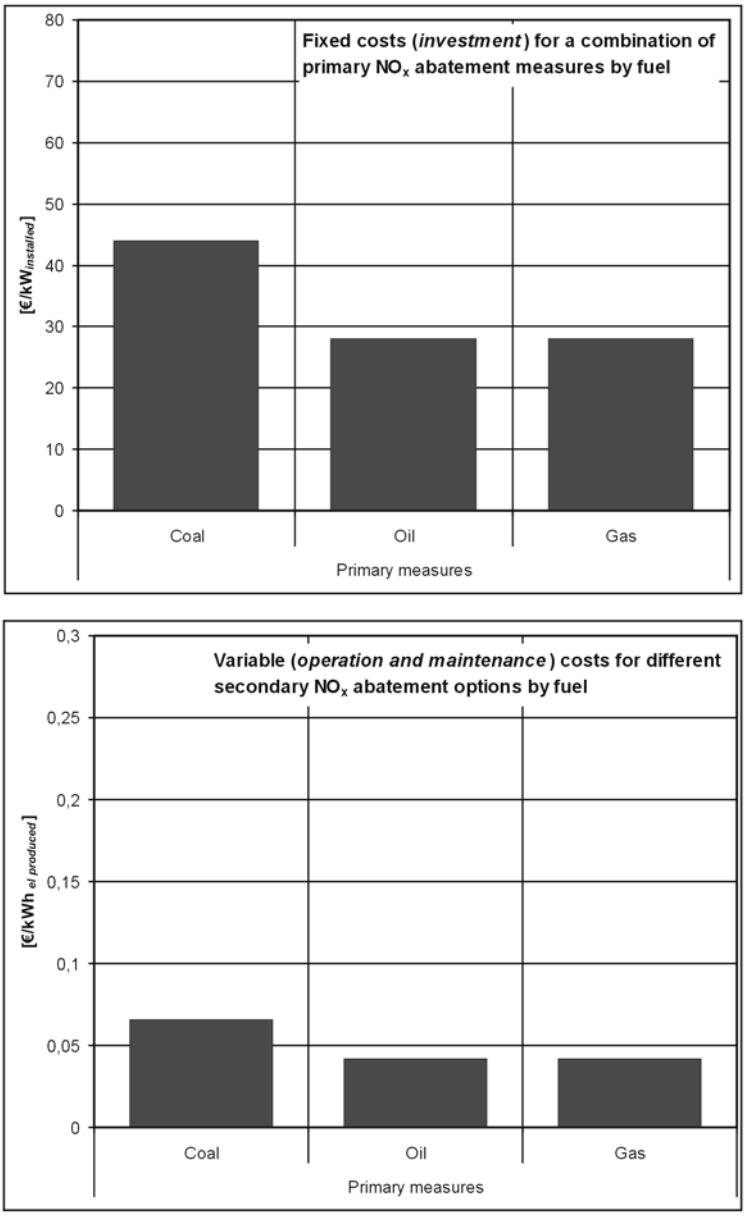

Fig. 3.16. Comparison of fixed and variable costs per kW (resp. kWh_{el}) for different primary NO_x abatement measures for retrofit by fuel

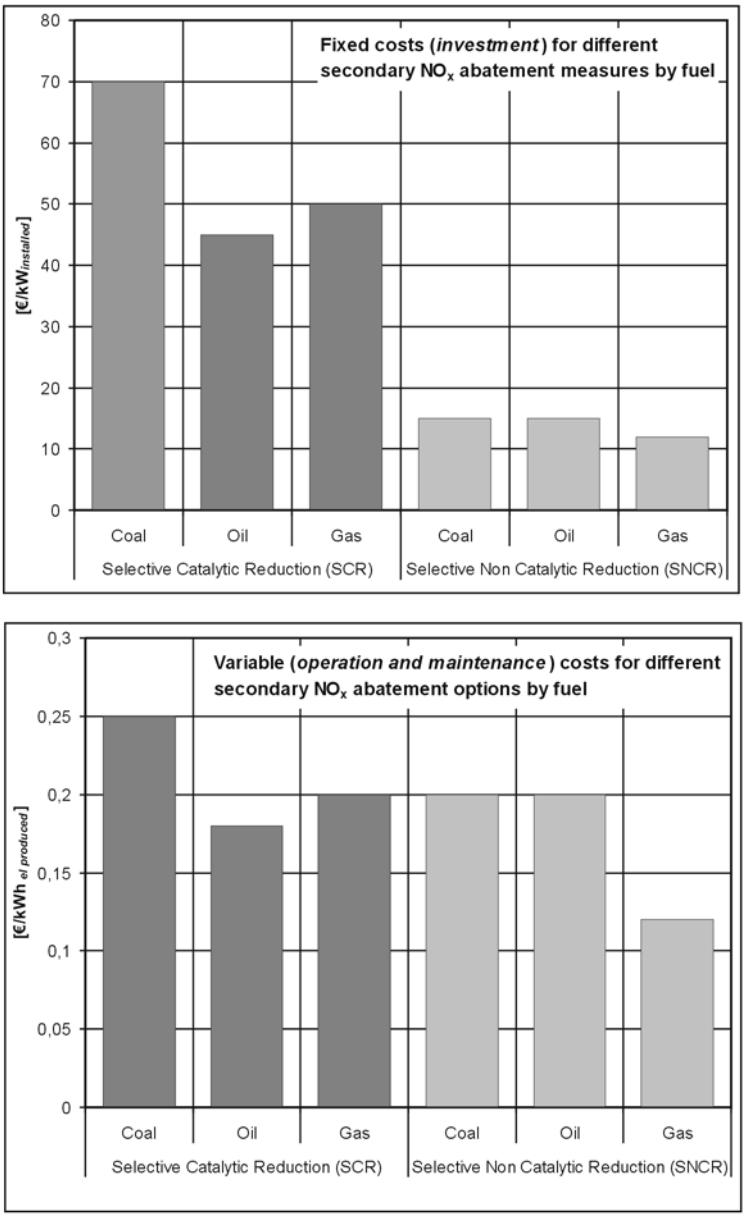

Fig. 3.17. Comparison of fixed and variable costs per kW (resp. kWh_{el}) for different secondary NO_x abatement measures for retrofit by fuel

3.6.1.2 Residential Combustion Plants

In residential combustion, boiler size restrictions and small installed capacities in households and commercial buildings do usually not allow for the installation of secondary measures, and commercially available, modern burners for residential combustion plants can have one or more of the primary measures built in:

- **Primary Measures** (mostly LNB and other combustion modifications)

3.6.1.3 Solvent Use

Emissions from solvent use can occur at the production level, or when a product is applied later on in the products' life cycle. For solvent emissions from domestic application of solvent containing products (i.e. domestic paint application) only measures such as substitution by no- or low-solvent containing products are feasible, as it is more or less impossible to contain solvent emissions while applying solvent-containing paint to a building, for example. At production level and for industrial and other professional application, though, various measures can be applied to reduce the amount of solvents being emitted into ambient air, and in some cases processes can even be modified in a way that a large proportion of the solvent can be recycled. The following list contains the most important sectors where solvents are used and gives some exemplary options for their reduction:

- *Furniture Coating* (good housekeeping, process modification, substitution, thermal oxidation & adsorption)
- *Coil & Film Coating* (good housekeeping, thermal oxidation)
- *Surface Cleaning* (good housekeeping, improved design, new enclosed system, double lidded system -DLS, single sealed chamber, DLS with carbon adsorption)
- *Vehicle Refinishing* (good housekeeping, high volume low pressure - HVLP, enclosed gunwash, HVLP + high solids, HVLP + water borne)
- *Vehicle manufacture* (good housekeeping, substitution medium solids, substitution (water based), thermal oxidation)
- *Rubber Production* (good housekeeping, process modification, thermal oxidation, carbon adsorption, substitution)
- *Printing* (good housekeeping, thermal oxidation)
- *Adhesive and Sealand Use* (process modification, good housekeeping, thermal oxidation, process modification – high solids)
- *Domestic Solvent Use* and *Paint Application in Construction and Building* (good housekeeping, low solvent containing paints, substitution)

In most cases, primary measures such as good housekeeping or substitution are comparatively cheaper than secondary measures, which often involve the applica-

tion of expensive equipment (e.g. enclosed systems, thermal oxidation) to contain the solvent vapours and for fluegas after treatment. Other studies have conducted quite thorough reviews of VOC abatement options in the UK, results from these studies are included here (*Berner et al. 1997, ERM 1996a, b* and *Klimont et al. 1997*). And in addition to the direct cost differences, most secondary measures need quite a significant amount of energy which, if supplied through the use of fossil fuels, reduces NMVOCs at the cost of generating CO_2 emissions.

3.6.1.4 Fuel Distribution

Following the EU Petrol Vapour Recovery Directive (Stage I/II) for small, medium and large service stations and depots (EC 94/63/EC), technical measures to reduce the emissions of VOCs during the whole process-chain from refineries to service stations will be implemented in the trend scenario. With the current timetable, even small and medium service stations, which have to comply with less stringent emission limits for a transition period, will be adapted by the year 2010.

3.6.1.5 Road Transport

For the road transport sector, technical measures achieving compliance with EURO 1 to 4 standards have been taken into account. As most vehicles' average lifetimes are in the range of 10 to 15 years, the option for retrofitting them with more advanced emission controls does not make sense economically. In addition to that, state-of-the art emission control such as it is necessary to achieve the stringent emission limits of EURO 3 and 4 in particular requires engine design and motor management working in a way, that it is simply impossible to retrofit a vehicle with an outdated engine at all. Hence, the replacement of older vehicles with lower-emission vehicles is being regarded as the option of choice here. For the trend scenario, fleet composition and technology splits for each country have been taken from data collected within the MEET Project *(MEET 1998*). For the control of evaporative emissions, a small carbon canister was included as a requirement with the introduction of the EURO standards already. The following list indicates exemplary technology packages that have been identified for different vehicle types, and which are currently available to the market, or in a pre-market stage of development at least:

- **Passenger Cars and Light Duty vehicles, gasoline operated:**
  EURO 1 compliance
  Three-way catalyst underfloor positioned, initial injection improvements
  EURO 2 compliance
  Three-way catalyst underfloor positioned, injection optimisation (dual-point, sequential point or multi-point injection)
  EURO 3 compliance
  Three-way catalyst close coupled positioned (or advanced formulation Pt/Pd/Rh, Pd/Rh underfloor mounted), injection optimisation, exhaust gas recirculation, secondary air injection, engine management systems

EURO 4 compliance
Three-way catalyst (Pt/Pd/Rh, Pd/Rh plus close coupled starter catalyst (Pd-only, Pd/Pd/Rh) or electrically heated catalyst), advanced engine management systems, on-board diagnostics, secondary air injection

- **Passenger Cars and Light Duty vehicles, diesel operated:**
  EURO 1 compliance
  direct/indirect injection, turbocharged injection
  EURO 2 compliance
  highspeed direct/indirect injection, turbocharger and intercooler, diesel oxidation catalyst (Pt/Pd), exhaust gas recirculation, engine management system
  EURO 3 compliance
  high speed direct/indirect injection, electronically controlled turbocharger/ intercooler and exhaust gas recirculation, advanced engine management systems, diesel oxidation catalyst, de-NOx catalyst (V/Ti/W, urea, Pt zeolite), Particulate traps
  EURO 4 compliance
  further improvement of the above mentioned technologies
- **Heavy Duty Vehicles**
  EURO 1 compliance
  turbocharger, air-to-air or air-to-water intercooler, redesigned injectors, higher injection pressures, variable injection timing
  EURO 2 compliance
  turbocharger, intercooler, electrically controlled injection, variable injection timing, engine management systems, exhaust gas recirculation
  EURO 3 compliance
  advanced electronically controlled turbocharger and intercooler, electronically controlled exhaust gas recirculation, engine management system, diesel oxidation catalyst, catalytic trap oxidiser, advanced injection systems
  EURO 4 & 5 compliance
  further improvement of the above mentioned technologies plus de-NO_x, mobile SCR, particulate traps
- **Mopeds** (< 50 ccm, 2-stroke)
  oxidation catalyst, advanced catalyst technology
- **Motorcycles** (> 50 ccm, 2-stroke & 4-stroke)
  three-way catalyst, engine modifications
- **Evaporative Emissions**
  small carbon canister, large carbon canister for gasoline operated vehicles

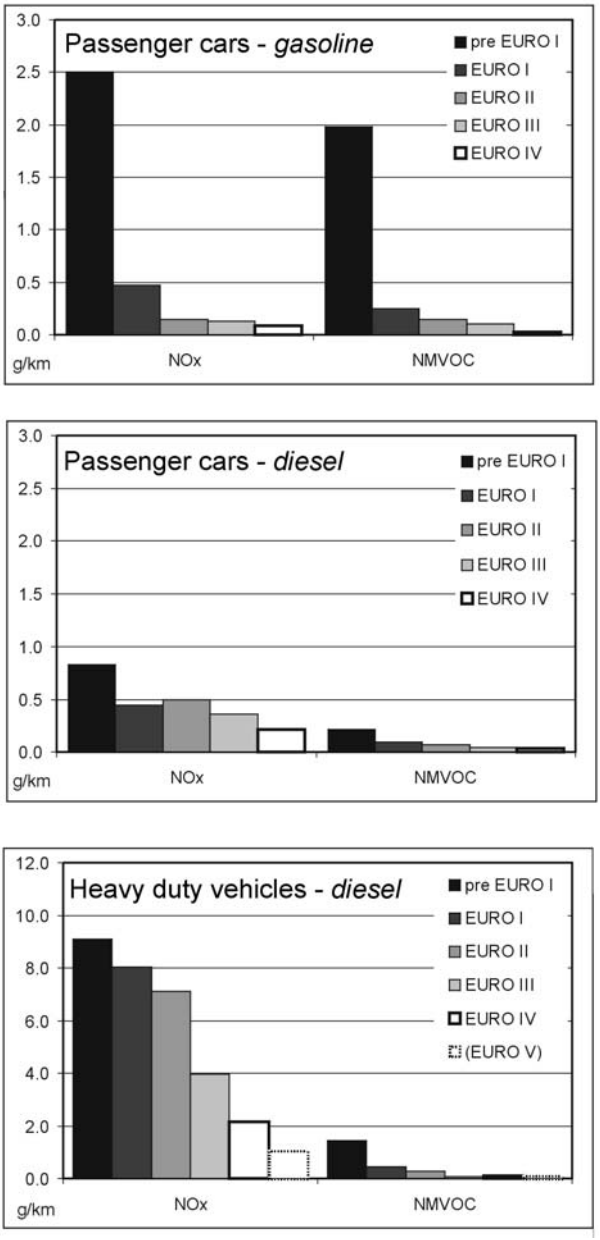

Fig. 3.18. Comparison of NO_x and NMVOC emission factors by technology standards for passenger cars and heavy duty vehicles

Fig. 3.18. displays the development in average emission factors (in g/km) exemplary for passenger cars (gasoline, diesel) and heavy duty vehicles, for the latter, the currently proposed EURO V standards has been included to show the latest development. Further options for air pollution control beyond the trend scenario measures will be discussed in *Chapt. 6*.

3.6.2 Calculating Costs of Abatement Measures

3.6.2.1 Cost Components

The main cost components to be collected are the total investment expenditure and the annual operating and maintenance (O&M) costs. While the former describes a fixed cash flow at the beginning of the lifetime of an abatement measure, the latter covers all recurring costs resulting from the operation of the equipment. While these two cost components set the minimum requirements for cost data collection, a more detailed split of the total investment expenditure into costs for equipment and the costs for installing the equipment would be favourable. Furthermore, annual O&M costs should be collected split into energy costs, materials and services, labour and fixed O&M costs (e.g. for a service contract). In addition to that, potential savings, for example due to reduced energy consumption, or recovered solvents etc. should be quantified and included into the cost figures.

3.6.2.2 Annual costs

As stated above, the total investment expenditure and the annual O&M costs give two different types of costs, and in order to relate the emission reduction to its specific costs, they have to be harmonised. And as emission reduction is usually calculated per year, cost figures should be calculated accordingly. The *Guidelines for Defining and Documenting Data on Costs of Possible Environmental Protection Measures* (*EEA 1999*) distinguishes between two major approaches for the annualisation of total costs of a measure:

- Discounted Cash Flow Approach

  Total annual costs = the present value (PVC) of the *total cost stream* (i.e. investment expenditure plus net operating and maintenance costs) × *capital recovery factor*

- Present Value of Total Costs

  Total annual costs = annual capital costs (i.e. yearly depreciation charge plus average interest cost per year) + *net annual operating and maintenance costs*

The latter has been used to calculate annual cost in this work as the representation of fixed costs (investment in period $t = 0$) and annual recurring operating costs is

consistent with available cost data and is defined as follows:

$$A_t = C_0 \cdot \underbrace{\left[\frac{r \cdot (1+r)^n}{(1+r)^n - 1}\right]}_{\text{capital recovery factor}} + OC$$

where

C_t = total investment expenditure on the abatement equipment in period t (usually 1 year)
OC_t = total operating and maintenance costs in period t
r = the discount (interest) rate per period (cf. *Rabl 1996*)
n = the estimated lifetime of the equipment in years

3.6.2.3 Retrofit cost

In some cases, it is possible to retrofit an existing installation with equipment to reduce its emissions of a specific pollutant, or even several pollutants. Due to space restrictions, necessary changes or reconfigurations in the process etc., it is, in general, more costly to retrofit an existing installation, than having the emission control measure included in the design of the installation from the start. In addition to that, the removal efficiency of a retrofit-measure can be lower, than that of comparable built-in measures. In this study, retrofitting has only been taken into account for stationary sources (energy sector, household combustion and solvent use). It has been assumed that the technology that has to be installed to comply with emission standards such as EURO 3 or EURO 4 for road transport vehicles is rather difficult to be retrofitted to existing, older vehicles. Features like electronic motor management or advanced engine design cannot just be added to a vehicle, as it has been possible with early catalysts in the early 1990s.

3.6.2.4 Regional differences

For all abatement technologies taken into account a general availability in all EU15 countries has been assumed. Differences in price indices have not been accounted for, as these technologies should be available on the common market in the European Union without major differences. This applies to all cost categories as they have been distinguished above. However, the costs per unit of pollutant abated can vary significantly between countries, reflecting, for example, variations in activity levels such as annual mileage of a passenger car. Hence, by combining country specific data on emissions sources with general cost information, the final cost figures take into account regional differences to some extent.

3.6.2.5 Apportioning costs to specific pollutants

The issue of apportioning costs to specific pollutants occurs, whenever a measure

reduces more than one pollutant simultaneously, and the importance of finding a practicable solution for cost apportioning becomes evident, when efficiency issues are discussed, i.e. the need to find out, if measure A is „better“ than measure B arises. If only measures are assessed, that remove a single pollutant, they can be ranked by their marginal costs or unit costs and used to construct a single abatement cost curve rather easily.In the case of ozone precursors, measures concerning stationary combustion sources (NO_x) and for the solvent use sector (NMVOC) fall in this category. But if a measure reduces two (or more) pollutants simultaneously, as it is the case for most measures applied to road transport sources, a mechanism to allocate a specific fraction of the total costs to each pollutant abated needs to be developed.

Possible approaches for this allocation mechanism could be

- cost-splitting by abatement efficiency (i.e. splitting costs by relative % removal),
- cost-splitting using proxies (e.g. toxicity or suchlike),
- problem-oriented cost allocation, or the
- recalculation of costs according to the share in the optimum case.

If abatement costs are allocated by using the specific abatement efficiency for each pollutant, this reflects a purely source-based approach. The relative contribution to the environmental pressure under investigation is not taken into account. This approach is usually rather easy to use, since information on the technical efficiency of a measure is easy to obtain and the accuracy of measure data is rather high. The underlying idea is to attribute a share of total costs to each pollutant abated, which reflects the relative ranking of removal efficiency, i.e. if pollutant X is reduced by a measure by *y*% and pollutant W by *z*%, the cost share for pollutant X would be equal to *(y/(y+z))*. This approach leads to a cost splitting which attributes the largest cost share to those pollutants, which are mainly removed by a measure, leading to unit costs that are comparatively moderate as the bulk of costs is attributed to the pollutant with the highest removal rate for each measure. However, this way of cost splitting does not reflect in any way the contribution of each pollutant to the problem under investigation.

Another approach is to take a proxy or a direct link to the problem, i.e. an indicator which reflects, in an easily comparable way, a relationship between the pollutants and the environmental problem investigated. A fairly good example for a proxy in this context is the Global Warming Potential, short GWP, which normalises the contribution of a number of greenhouse gases (GHGs) to global warming to the effect of Carbon Dioxide, thus giving factors to scale emissions of these other GHGs and make emission reductions directly comparable. In a similar way, the acidification potential (giving the potential of a substance to form H^+ ions) and the eutrophication potential (phosphates as a reference substance for the release of bio-available Nitrogen or Phosphorus) are used as a means of standardising the varying contribution of different substances to one specific problem. However, as the formation of ground level ozone shows significant non-linearities due to variations depending on

meteorological conditions and the ratio of NO_x and NMVOC available both on a temporal and a spatial scale, it is not feasible to determine one proxy or even a function giving a means to assess cost splits based upon NO_x/NMVOC contribution to ozone formation on a sound scientific basis. Finally, a recursive approach was tested, which was based on the relative costs of abatement of NO_x and NMVOCs in the optimal solution for a given target. Costs were allocated to either pollutant first proportional to its relative share in the optimal case, then inversely proportional, to investigate the resulting changes in subsequent model runs (with the now adapted cost allocation). In this case, no real conclusive impacts of this recalculation could be identified, mostly because of the quite small changes in unit costs and thus no major change in position on the cost curves.

Having identified the potential problems with these approaches, a sensitivity analysis was carried out to assess, if, and to what extent, a variation in unit costs due to changes in cost attribution would have a significant impact on the position of individual measures in cost curves and hence on the outcome of the optimisation. The results of this analysis indicated no significant changes, which can be explained with the rather distinct relative cost differences between the main sectors for which abatement measures have been investigated. Since cost apportionment would only be of importance for road transport, where measures reduce the emission of both precursor substances simultaneously, the composition of cost curves overall did not change much, if at all. On the basis that, for the purpose of the work presented here, different approaches have been tested and either found to be infeasible (e.g. splitting by contribution to ozone formation, see above) or did not have any significant effects on the optimisation results, an equal apportionment of costs to both pollutant was set. However, the general problem needs further investigation and in particular for optimisation problems with even more individual pollutants taken into account, a solution has to be found (see as well *Reis et al. 2002* and *2003*).

3.6.3 Detailed Calculation of Costs per Sector

In this section, the calculation of abatements costs from the cost data collected by the Institute for Prospective Technology Studies (see *Friedrich and Reis, 2000*) is described for the main source groups. The applicability of measures to a specific source are defined as the maximum share of total sources where implementation is technically feasible.

3.6.3.1 Calculation of Abatement Costs for Road Transport Sources

The calculation of emission reductions from road transport vehicles is based on the emission factor, i.e. the rate per activity unit for each pollutant, which is emitted under standard operation conditions, the activity rate itself and the abatement technology applied:

$$\Delta E_{i,j} = \frac{\alpha_j \cdot A_j \cdot (EF_{i,\,before} - EF_{i,\,after})}{10^6 \frac{g}{t}}$$

$\Delta E_{i,j}$	= emission reduction of measure *i* applied to sector *j* [t]	
α_j	= applicability to source *j*	[%]
A_j	= activity rate of source *j*	(km driven in [km/yr])
$EF_{i,before}$	= emission factor *before* application of measure *i*	[g/km]
$EF_{i,after}$	= emission factor *after* application of measure *i*	[g/km]

In addition to that, the calculation of annualised abatement costs is conducted as described in *Sect. 3.6.2*, leading to the addition of the annualised fixed costs and the operating costs for the respective year, depending on the average mileage of the vehicle:

$$C_i = (V \cdot c_{annual}) + (A_j \cdot c_{operating})$$

C_i	= total annual costs of implementation	[€]
V	= source units	(number of vehicles)
A_j	= activity rate of source j: kilometers driven	[km]
$c_{annnual}$	= annualised investment (fixed costs) of measure *i*	[€/vehicle*yr]
$c_{operating}$	= operating (variable) costs of measure *i*	[€/vehicle*year]

Finally, calculating the unit costs of one tonne of pollutant abated:

$$c_i = \frac{C_i}{\Delta E_i}$$

c_i	= unit costs	[€/tonne pollutant abated]
C_i	= total costs	[€]
ΔE_i	= total costs	[t]

3.6.3.2 Calculation of Abatement Costs for Solvent Use Sources

The calculation of abatement costs from solvent use is conducted similar to that of road transport sources, with some differences:

$$\Delta E_{i,j} = \alpha_j \cdot A_j \cdot R_{i,j}$$

$\Delta E_{i,j}$	= emission reduction of measure i applied to sector j	[t]
α_j	= applicability to source	[%]
A_j	= activity rate of source *j* (solvents emitted)	[t/yr]
$R_{i,j}$	= emission reduction achieved by measure i applied to source *j*	[%]

In contrast to road transport, where the number of vehicles and their average mileage can be, thanks to thorough research and statistics, determined rather accurately, the vast number of sources and the lack of a homogeneous structure makes it necessary to base the calculation of emission reductions on the amount of solvents applied and emitted. The uncertainties involved in this approach can be considerable, but at the time being, it is the only possible solution to address emissions from the solvent use sector on a European scale.

The way to calculate annual total abatement costs is the same as described above for road transport:

$$C_i = (V \cdot c_{annual}) + (A_j \cdot c_{operating})$$

C_i	= total annual costs of implementation	[€]
V	= source units (tonnes of NMVOC treated, if applicable)	[t]
A_j	= activity rate of source *j* (solvents emitted)	[t]
$c_{annnual}$	= investment (fixed costs) of measure *i*	[€/unit*yr]
$c_{operating}$	= operating (variable) costs of measure *i*	[€/unit*year]

Calculating the unit costs of one tonne of pollutant abated:

$$c_i = \frac{C_i}{\Delta E_i}$$

c_i	= unit costs	[€/tonne pollutant abated]
C_i	= total costs	[€]
ΔE_i	= total costs	[t]

3.6.3.3 Calculation of Abatement Costs for Power Plants

In the case of power plants, detailed information on vital parameters such as operating hours, fuel inputs and the state of application of emission control equipment could be gathered from various studies (*EUROPROG, DGXVII*). Hence, it was possible to conduct the calculation of abatement costs in a rather detailed way. The calculation of the emission reduction is straightforward again:

$$\Delta E_{i,j} = \frac{\alpha_j \cdot A_j \cdot (EF_{i,\,before} - EF_{i,\,after})}{10^6 \frac{g}{t}}$$

$\Delta E_{i,j}$	= emission reduction	[t]
α_j	= applicability to source	[%]
A_j	= activity rate of source j (electricity generated)	[GJ]
$EF_{i,before}$	= emission factor *before* application of measure *i*	[g/GJ]
$EF_{i,after}$	= emission factor *after* application of measure *i*	[g/GJ]

For power plants, the implementation of emission control equipment is considerably influenced by the EC *Large Combustion Plant Directive* (88/609/EEC). Thus, the following levels of emission control have been defined for power plants, to define the applicability for primary and secondary measures:

Existing power plants according to trend scenario for the year 2010 can have either one of the following states:

- uncontrolled (UC)
- equipped with primary measures (PRIM)
- equipped with secondary measures (SECM)
- equipped with primary AND secondary measures (P&SM)

Hence, the following options to enhance the emission control technology of a power plants (each for COAL, GAS and OIL fired plants) can be selected:

- *Option 1a:* uncontrolled → primary measures
- *Option 1b:* uncontrolled → secondary measures
- *Option 1c:* uncontrolled → primary & secondary measures combined
- *Option 2:* primary measures → primary & secondary measures combined
- *Option 3:* secondary measures → primary & secondary measures combined

The calculation of total abatement costs is based upon the fixed (annualised) costs which occur at the installation of the measure and depending on the installed capacity of the power plant:

$$C_i = (V \cdot c_{annual}) + (A_j \cdot c_{operating})$$

C_i	= total annual costs of implementation	[€]
V	= source units: installed capacity	[MW_{el}]
A	= activity rate: electricity generated	[GJ]
c_{annual}	= investment (fixed costs) of measure *i*	[€/MW_{el}]
$c_{operating}$	= operating (variable) costs of measure *i*	[€/GJ]

Finally, calculating the unit costs of one tonne of pollutant abated:

$$c_i = \frac{C_i}{\Delta E_i}$$

c_i	= unit costs	[€/tonne pollutant abated]
C_i	= total costs	[€]
ΔE_i	= total costs	[t]

A comprehensive list of all abatement measures taken into account can be found in *ANNEX C*.

4 Optimising Ozone Abatement Strategies

4.1 Introduction

4.1.1 Aim: Optimisation of Air Pollution Control Strategies

Country-specific emission control options to identify cost-effective ways to reduce transboundary air pollution have been investigated for some years now. Indeed, recent UNECE and EU emission control strategies have specified sets of country-specific emission reductions which are calculated to meet agreed environmental targets at least cost. Furthermore, these environmental targets are spatially variable, for instance for acidification problems, being based upon so-called critical levels (cf. *Chap.2*), which represent levels of deposition or concentration above which environmental damage is believed to occur. The UN ECE *2nd Sulphur Protocol* represented the first move towards this more complex but cost-effective approach. Optimisation techniques (ASAM - *ApSimon et al. 1994*; CASM - *Bailex, 1996*; RAINS - *Alcamo et al.,1990*) were applied together with information on the cost of emission reductions in each country (abatement cost curves), EMEP calculations of country-to-grid depositions, and maps of critical loads for sulphur (*Posch et al., 1995*). This approach towards *integrated assessment modelling* resulted in a set of target emissions which varied from country to country. Similar techniques have recently been developed for ozone (*Schöpp et al., 1999*), using a parameterisation of EMEP MSC-W modelling results as the basis and which were used as part of the EU *Acidification and Ozone Strategy* to set EU national emissions ceilings (*Amann et al., 1999*). In general, costs and effectiveness can be determined on different levels, such as for whole economies, or at sectoral, company or individual level.

One of the basic questions that each optimisation study has to answer is, if the approach taken will find *the* one optimal solution to the problem under investigation. As *Simpson and Eliassen* (1999) state in their description of the basic methodology of the iterative approach taken here, there is no guarantee that the iteration model will find the absolute minimum rather than a local minimum in cost-space. However, as can be read in the publications around the RAINS model, even applying a complex solver-based approach, has to cope with the fact, that this global optimum in itself is often not the answer that needs to be found. For example, *Makowski et al.* (1998) describe the use of additional restraints for the RAINS model to prevent results being found, which would, e.g. require one country to reduce emissions to zero, while others would be completely unaffected. Even though this

would be the (mathematically) global optimal solution, it is obvious, that its implementation would not be (politically and technically) feasible, hence the introduction of restraints to guide the solver towards 'sensible' results.

Apart from that, as it will be described in *Sect. 4.2.1.*, the problem of ozone formation and its non-linearity does create a problem in itself for a solver based approach, because in trying to find a global optimum, a reduction path might be chosen that leads to adverse effects, i.e. a significant increase in ozone in the short run. While this is mathematically acceptable, no real-world air pollution control strategy could be implemented, which would accept an increase in air pollution for some years to reach a more favourable target in the long run.

Finally, to find the optimal solution, there would have to be one single clearly definable target to be achieved, which is difficult, if not impossible in the case of a complex problem like air pollution control. Even for tropospheric ozone, where local and regional impacts and different areas with domination of NO_x or NMVOC control can be identified, and only two precursors have to be taken into account, the definition of *the* one target to be achieved is a matter of choice and preference. Is a reduction of ozone levels over all grid cells under investigation favourable, or a reduction of maximum exceedances in a limited number of grid cells? Does a strategy have to be optimised for the protection of agricultural crops, for forests, or human health?

For the iteration approach on which OMEGA-O_3 is based upon, *Simpson and Eliassen* (1999) have discussed the aspect of optimality in detail. As to the question, in what respect the OMEGA model applied in this study finds an optimal solution, it can be stated, that it provides a cost-effective solution for a given ozone target by a step-wise selection of cost-effective abatement options over all countries, that will improve the ozone situation at least costs.

4.1.2 Aspects of Cost-Effectiveness and Cost-Benefit Assessment

In order to evaluate abatement measures and options as to their ability to achieve air quality targets at an optimal allocation of resources, tools to assess not only the costs of abatement, but as well the benefits arising from reduced levels of pollution have to be applied (cf. *Argent et al., 1999, Hanley and Spash, 1993, Luken 1990*, *Munda 1996* and *Nas 1996*). The tools used within this study are basically *cost effectiveness assessment* (CEA) and *cost benefit assessment* (CBA), which shall be briefly described here.

Both tools are used in different settings to assess the impacts across society arising from e.g. the introduction of new environmental regulations, or the implementation of environmental or other policies (e.g. *EC 1995, Manne and Richels, 1997* and *Mishan 1973*). While qualitative approaches try to describe these impacts rather than trying to determine the magnitude of such effects, cost-benefit analysis and cost-effectiveness analysis are applied to provide more detailed information about the magnitude or significance of potential impacts.

RPA 1998 define the two approaches as follows:

- **cost-benefit analysis** examines the trade-offs in terms of the costs and benefits of a policy; and
- **cost-effectiveness analysis** determines the least-cost option of attaining a pre-defined target.

Basically, the benefits assessed are the reductions of damages caused by air pollution and the costs are those needed to implement a reduction strategy by means of technical and/or non technical measures (cf. *Friedrich and Krewitt, 1997*). Typical relationships – from the viewpoint of an economy – between costs and benefits can be expressed as shown in *Fig. 4.1.*, for either total costs/benefits (above), and for marginal values (below). Both costs and benefits increase as the percentage of emissions reduced rises, but the net benefits are diminishing as the slope for total costs increases at an increasing rate. The net benefits are equal to the difference between the curves ($\overline{AB}$) where L^* marks the optimal degree of control, maximising the net benefit. Another option to determine the optimal degree of control is displayed below, where the marginal benefits/costs are given, i.e. the increment of total benefits/costs when emission control increases by one unit. Here, the optimal degree of pollution marked by L^* is determined by the point, where marginal benefits equal marginal costs.

CBA and CEA are used as appraisal tools (cf. *RPA 1998*) among other tools such as compliance cost analysis (CCA), environmental impact assessment (EIA) or applications of multi-criteria analysis (MCA). *Table 4.1.* gives an overview on the use of CBA and/or CEA in different countries.

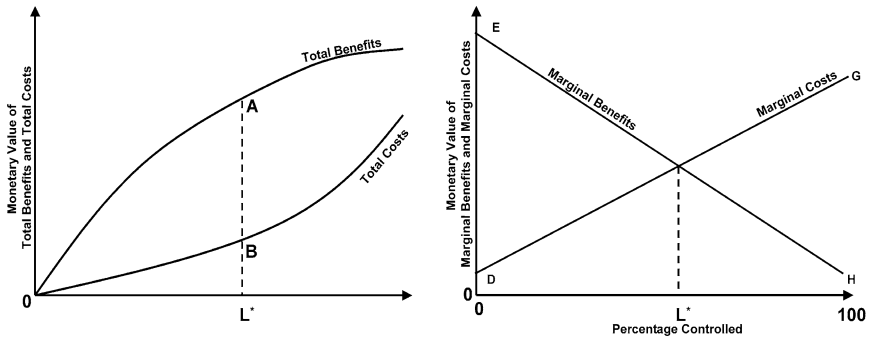

Fig. 4.1. Graphical display of costs and benefits to determine optimal degrees of air pollution control

Table 4.1. Policy areas analysed using Cost-Benefit Assessment and/or Cost-Effectiveness Assessment (Source: *RPA 1998, p. 17*)

Country	Policy area
Australia	all physical development and regulatory proposals
Austria	national parks, traffic planning
Canada	health protection policies, risk management, tobacco regulations, air pollution control, water pollution abatement, contaminated site remediation, multi-media standard setting, workplace health and safety, chemical risk management
Denmark	all policy areas
Finland	sulphur emissions trading programme
France	public investment, climate change
Netherlands	air, noise, soil, safety and waste policies, chemical substances, road pricing, congestion toll, health care
United Kingdom	environmental issue, project appraisal, transport schemes
United States	assessment of hazard levels, policy appraisal

4.1.3 State of the Art: Selected Assessment Models

There are a number of models being used in similar applications of cost-effectiveness assessments in Europe, among which three shall be described a bit more detailed and compared with the OMEGA-O_3 model in terms of performance and applicability.

4.1.3.1 RAINS

The RAINS Model (*Regional Air Pollution Information and Simulation*) was initially developed by IIASA, Laxenburg (see *Amann et al. 1996, 1999*) as a tool for the integrated assessment of strategies to reduce acid deposition in Europe and Asia (*Alcamo et al. 1990*). In its current state of development, RAINS addresses emissions of SO_2, NO_x, NH_3 and NMVOC and calculates acid deposition, eutrophication and ozone concentrations for different scenarios and abatement strategies. The optimi-

sation is conducted using a solver (Linear Programming, LP) and provides results such as optimal emission reductions, total costs and marginal costs for each country, as well as depositions for each grid cell after the optimisation. RAINS has been extensively used in the process of the negotiations around the CLRTAP protocols (see *Chap. 3*) and is currently extended to deal with particulate matter emissions as well.

4.1.3.2 ASAM

The Abatement Strategies Assessment Model (ASAM) was developed at Imperial College, London (*ApSimon et al.* 1994, *ApSimon and Warren,* 1996 and *Warren and ApSimon*, 1999, 2000) to calculate cost-effective abatement strategies designed to reach different environmental targets, addressing acidification and eutrophication in Europe. The optimisation process in ASAM is conducted step-wise, enabling it to display results at any predefined expenditure level, providing information on deposition levels, exceedances of critical loads and marginal costs. ASAM was used in the preparation of the UNECE CLRTAP 2nd Sulphur Protocol (see *Chap. 3*).

4.1.3.3 CASM

The Stockholm Environment Institute (SEI) at York has developed an integrated assessment model as well, the Co-ordinated Abatement Strategy Model (CASM), which links emissions of sulphur and nitrogen oxides with atmospheric transfer, a map of sensitivity to acidic deposition for Europe, and costs of abatement option application in each European country. It has been applied in the preparation of the UNECE NO_x Protocol. CASM is also being applied in the assessment of air pollution from the transport sector. Initially focusing on sulphur and nitrogen oxides, current work is including the impact troposphere ozone on crops and forests (*Bailey 1996* and *Bailey et al. 1996*).

4.1.3.4 Comparison

When comparing these models (see *Table 4.2.*) with the approach taken for OMEGA-O_3, the environmental problems addressed are similar. However, OMEGA-O_3 has been designed to overcome a number of weaknesses that have been identified in these alternative approaches. First of all, the number of measures and the grade of detail chosen to construct the abatement costs curves is considerably higher than in most other assessment models. Costs have been calculated e.g. on the basis of fleet data for road transport vehicles split down to individual technologies, or addressing combustion plants according to the fuel type used and the emission control technology implemented. Furthermore, the mechanisms built in to model the specifics of ozone creation over Europe (*Simpson and Eliassen, 1999*) enable OMEGA-O_3 to achieve results which correspond well with those of a full-scale atmospheric dispersion model, within a defined range. Finally, the step-wise approach chosen for OMEGA-O_3 provides transparency in every turn of the iteration process, making it

easier to understand and interpret its results. This increased transparency reflects the information needs when designing air pollution control strategies, as the pathway towards the optimal solution is as important as the numerical result of the solution itself, if not more important.

Table 4.2. Cost-effectiveness assessment models – an overview

	Substances	**Effects**	**Application**
RAINS *www.iiasa.ac.at/~rains*	SO_2, NO_x, NH_3, NMVOC (PM in prep,)	Acidification Eutrophication Ozone	UNECE CLRTAP EC DG Environment
ASAM *www.iceo.ic.ac.uk*	SO_2	Acidification	UNECE (2^{nd} Sulfur Protocol)
CASM *www.york.ac.uk/inst/se*	NO_x, SO_2	Acidification Eutrophication	UNECE (NO_x Protocol) Transport and Air Pollution Research
OMEGA-O_3 *www.ier.uni-stuttgart.de*	NO_x, NMVOC	Ozone (Acidification)	EC DG Research
OMEGA2 (in prep.) *www.merlin-project.info*	NO_x, NMVOC, SO_2, NH_3, CO, CO_2, CH_4, N_2O $PM_{2.5}$, PM_{10}	Acidification Eutrophication Ozone Aerosols Global Warming	EC DG Research (EC DG Environment)

4.1.4 Focus: Problem Formulation for Tropospheric Ozone

One of the main problems in optimising strategies for ozone lie in the non-linear relationship of ozone precursors in the formation of ozone and in the treatment of NO_x emissions and their role in both acidification and ground-level ozone, both of great concern in Europe. Unfortunately, measures to reduce NO_x in different parts of Europe may have quite different effects on acidification than on ozone. In addition, emissions control of volatile organic compounds (NMVOC) may in some regions be a more cost-effective approach towards ozone control than NO_x reduction. The EU currently consists of 15 countries, and hence 15 sets each of NO_x emissions, NMVOC emissions, NO_x-cost curves and NMVOC-cost curves (assuming independence of these), which should be used as a basis for the optimisation. Thus, it is clear that even for a limited number of precursors and environmental problems, finding the most cost-effective solution among so many variables is a formidable task.

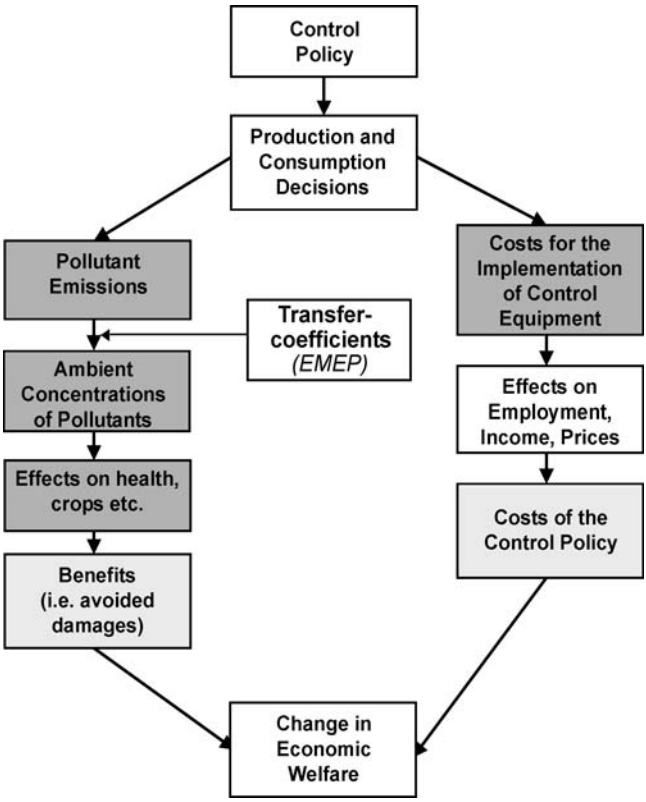

Fig. 4.2. Components of the cost-benefit analysis covered in this book (grey boxes)

Fig. 4.2. shows in detail, which parts of the analysis are covered by the OMEGA Model (*dark grey boxes*) and in addition, benefits are assessed using ECOSENSE (*light grey box to the left*) to complete this side of the framework towards a full cost-benefit assessment approach.

However, the assessment of economic effects has not been included in the model, thus the results do only cover the comparison of direct abatement costs and direct benefits at this stage. The direct costs of the control policy (*light grey box to the right*) which are determined by OMEGA-O_3, i.e. the sum of abatement costs implementing all measures that are needed to achieve the target, are compared with the benefits, i.e. the avoided damage costs, calculated with the ECOSENSE model developed at IER.

4.2 Model Design and Implementation

4.2.1 OMEGA-O_3 - Basic Features and Model Description

The iterative methodology has been designed to address an optimisation problem for a non-linear relationship of two precursors of tropospheric ozone, NO_x and NMVOC. In principle, this methodology can be applied with presently available EMEP data to handle simultaneously the effects of SO_2, NO_x, NMVOC, and NH_3 on acidification, eutrophication, ozone related crop and forest damage as well as health effects. In this case the methodology has been applied mainly to ozone, although with some attention directed to the linkage to acid deposition.

The general methodology of an iterative approach for the optimisation of air pollution control problems was first described in *Simpson and Eliassen* (1999). Based on this idea, the new model, termed OMEGA-O_3 (**O**ptimisation **M**odel for **E**nvironmental Inte**g**rated **A**ssessment [for Ozone]), was developed and will be discussed in the following sections in more detail.

The main difference between the iterative approach and other established optimisation methods, e.g. Linear Programming (LP), is that significantly more information is produced on the pathway towards reaching the optimal result, while LP or other 'classical' optimisation techniques typically only give the final result of the optimisation. However, the pathway towards the solution, in particular the sequence and procedure in which abatement measures are to be applied is vital knowledge for the design of successful air pollution control policies.

The model was implemented in FORTRAN77 and in the course of various applications within the research project INFOS (*Friedrich and Reis, 2000*), a number of features and extensions were implemented. Several presets can be used to determine the targets to be assessed and the way model output is presented. Some of the most important presets and features are listed here:

- ***Countries:*** the model can run for a single country up to all European countries
- ***Thresholds***[1]***:*** OMEGA is able to calculate AOT60, $AOT40_{crops}$ and $AOT40_{forests}$
- ***Method:*** gap closure or fixed reduction approaches can be selected
- ***Gap Closure:*** gap closures from 0% to 100% can be assessed
- ***Emission ceilings:*** the UNECE *Multi-Effect Protocol* and the EC *National Emission Ceilings Directive s*et specific emission targets for each country; these was implemented into the model as well.
- ***Weight for Acid/Ozone***: gap closures can be defined for ozone and acid at

1.calculations for mean ozone are possible as well, but have not been conducted due to the lack of source-receptor matrices

the same time, the respective weight can be set to any value between 0 (*only ozone is considered*) to 1 (*only acidity is considered*)

Targets (target presets) can be set to specify the gap closure, emission ceilings, optimisation method, weight, and selecting thresholds to be assessed.

The optimisation procedure (see *Fig. 4.3.*) typically consists of hundreds of iteration steps, following the abatement cost curve (for each pollutant) of each country to find the least-cost option to achieve a preset target. At each step the emissions of each active[1] country are reduced by a small amount (in this case standardised to 1 ktonne), and the costs of this reduction are determined by the position on the cost curve. Then the changes in AOT levels are calculated for each country reduction, providing the information on the benefits, in this case ΔAOT. By calculating the ration of costs vs. ΔAOT, for each option, the reduction (by country and pollutant) with the best ratio is determined and selected. This emission reduction is then carried out, while the remaining options are reset. The optimisation model sets the new AOT levels for each grid cell, adds up total abatement costs and total emissions reduced at this iteration step and conducts a check, if any/all break criteria are met. If not, the iteration loop is started anew to reduce emissions further. This leads to a gradual reduction of emissions of the - at each iteration step - combination of *[country, pollutant]* which achieves the best ratio of costs vs. reductions (in AOT levels), i.e. following an efficient pathway towards the preset target.

Hence, at each step of the iteration, every country has reached a specific location on its abatement cost curve for NO_x and as well for NMVOC. This location gives a level of abatement costs and the related percentage of emissions abated. As the optimisation proceeds, every next incremental step of reduction becomes more costly for this country[2], the model always searching for the least-cost option to increase the *benefit* (e.g. reduced overall AOT levels for human health, crops or ecosystems, with AOT implicitly reflecting a summarised exceedance of a threshold).

The benefit associated with a given environmental change may be defined in different ways of course, either in absolute terms (i.e. non-violation of a threshold at any costs), or in relative terms (closing the gap towards a threshold by x%). It is important to clarify, that the weighing of *benefits*, respectively the decision, how *important* it is to achieve a specific target (in particular with conflicting targets, e.g. ozone vs. acidification) is not a matter of the optimisation itself, but of (political) preferences that have to be stated for the optimisation model extrinsically. The choice of defining the benefit depends on the targets set, e.g. the reduction of occurrences of extremely high (absolute) AOT values in specific grid cells, or the (relative) reduction of overall exposure. Basically, any benefit definition can be implemented in OMEGA-O_3.

1. a country is active as long as further emission reductions are possible for that country
2. as the abatement cost curves are by definition ascending

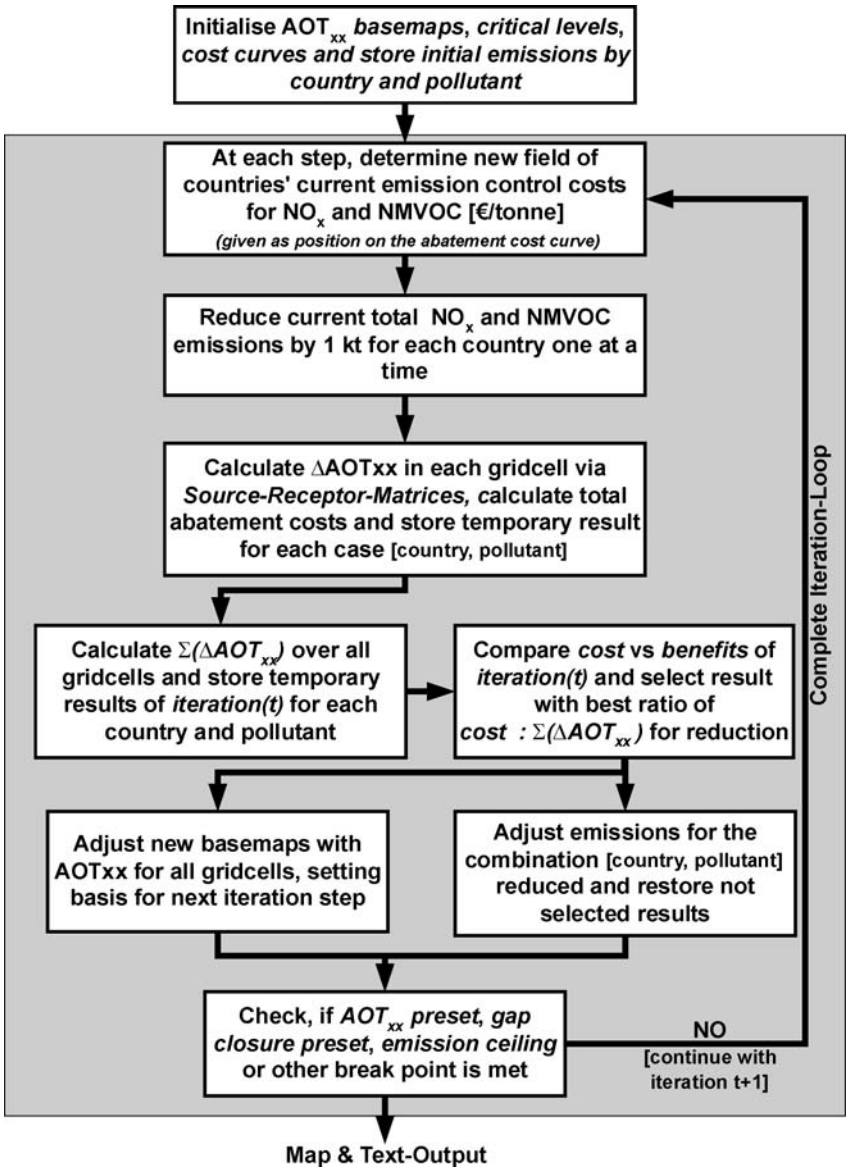

Fig. 4.3. Sketch of iteration procedure implemented in OMEGA-O_3

This iteration process is performed until one of the break criteria is matched, this can be any of the following:

- No active country left (all countries have reached the end of the cost curves),
- no additional benefit achieved (i.e. the additional reduction of either NO_x or NMVOC emissions does not lead to reduced overall ozone AOT, or even an increase of these), or
- target presets achieved (a given gap closure/absolute target for AOTxx reached).

Results of this iterative optimisation are manifold (see *Chap. 5*), besides the graphical expression in maps which are displayed in this work, indicators such as the number of grid cells above critical levels and the total ppm.h above target are given. This way, different optimisation runs can be directly compared and evaluated in terms of targets achieved.

4.2.1.1 Ozone vs. Acidification

In a multi-effect scenario benefits for each effect must be weighed up against all other effects. This is accomplished by assigning weighting factors. With for example a two-effect-problem (acidification, ozone) interest in acid deposition is given by a parameter w_{acid}, and interest in ozone by w_{ozone}, with $w_{acid} + w_{ozone} = 1$. One of the advantages of this approach is that it can easily be extended to cover the same treatment to any number of pollutants and environmental problems. For instance, an interest in tropospheric ozone could be specified with W_{ozone} and an interest in eutrophication with $W_{eutroph}$, with the simple requirement that the sum of all weighting factors is one. Since the main objective of this work was to reduce tropospheric ozone, calculations have mainly been done with $w_{ozone} = 1.0$ (i.e. $w_{acid} = 0$).

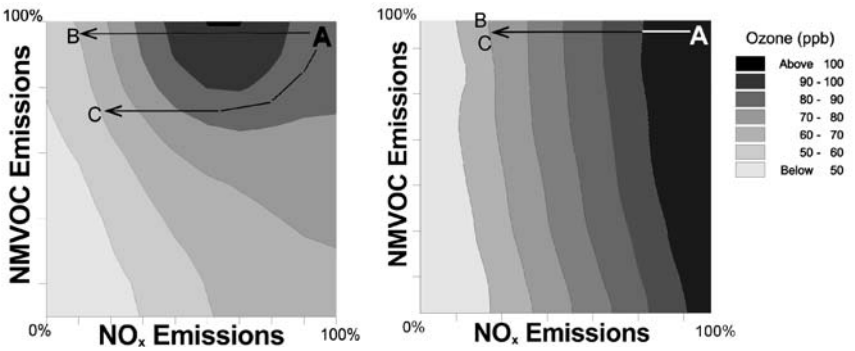

Fig. 4.4. Illustrative ozone isopleth diagrams for high-NO_x regions (left) and low-NO_x regions (right)[a]

a. The arrows illustrate the possible behaviours of non-linear optimisers (A→B) as compared to the iteration model (A→C). In the low-NO_x case both optimisers will choose the same route to reduced ozone. (see *Simpson and Elisassen, 1999* for a detailed description)

To investigate the influence of acidification on the requirements for NO_x emission abatement, some additional model calculations have been conducted with

$$w_{ozone} = w_{acid} = 0.5.$$

Fig. 4.4. finally shows the different way the iteration approach deals with a particular problem of ozone abatement strategies, i.e. the occurrence of high-NO_x and low-NO_x regions, as an expression of the complexity of the relationship between reducing ozone precursor emissions and the resulting decrease in ozone levels.

4.2.2 Data-Model: Input and Output

On the most basic level, input data for the OMEGA model consists of national emissions data of NO_x and NMVOC, cost curves for NO_x and VOC per country, critical or target levels data which specifies the pollution level of acid deposition or ozone deemed acceptable to prevent significant environmental effects in each grid square, initial calculations of base-case pollutant loads, and finally source-receptor matrices relating changes in pollution to changes in emissions from each country. *Fig. 4.5.* gives an overview on the data flow into and from the model.

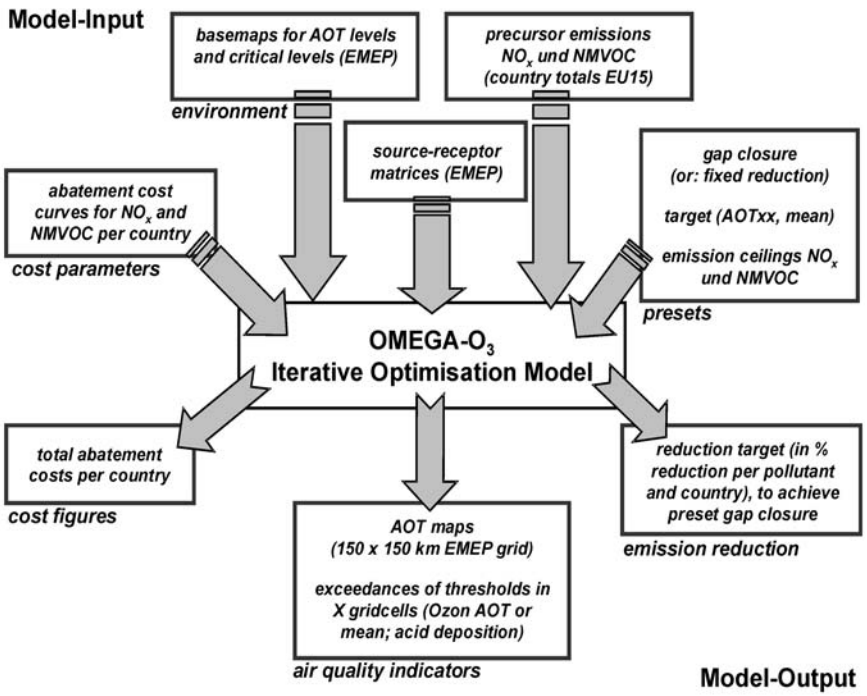

Fig. 4.5. Overview of OMEGA model inputs and outputs

4.2.2.1 Emissions

Emissions are taken from data generated for the 2010 trend scenario or for non-EU countries from the officially submitted (to EMEP) *Current Reduction Plans* (CRPs), respectively EMEP estimates for 2010 in case no officially submitted data is available (*Olendrzynski 1997*). For specific assessment runs, emission ceilings according to the EC National Emission Ceilings Directive (NECD) have been included, as well as emission limits from the UNECE Multi-Effect Protocol for non-EU countries.

4.2.2.2 Costs and Abatement Cost Curves

It is clear that the results of the optimisation model are determined to a large extent by the costs associated with different emission measures. Cost estimates should be entered into the calculations on a country-by-country basis for the effects of each emission measure. Further, a measure or technology which reduces both NO_x and NMVOC should have one cost associated with the reduction of two pollutants, which makes it necessary to split the costs accordingly. However, this latter consideration will become less important in coming years. Passenger cars are the only major source category with both significant NO_x and NMVOC emissions. As most car fleets will have turned over to catalyst cars by the year 2010, this source category will play a relatively less important role then. Other sources categories tend to be dominated by one pollutant or the other; e.g. large combustion sources and heavy-duty traffic by NO_x and solvents and petroleum refining by VOC.

An important aspect is that costs increase only gradually up to a certain point, often referred to as the 'knuckle' point, after which emission reduction becomes dramatically more expensive, showing the behaviour similar to an exponentially sloping curve. These abatement cost curves are of major importance, as they drive the selection of reductions for each country and thus are one of the main parameters determining how an optimised solution will look like.

For the work described here, special care was taken to accurately assess the detailed costs for each available abatement measure, split into the main cost features investment costs (for the initial installation of a measure), operating and maintenance costs (depending on utilisation and operation of a plant or vehicle), energy costs (e.g. for increased energy demand due to additional equipment) and finally savings, i.e. negative costs (e.g. from recovered solvents in closed systems). It is vital to assess these costs as exactly as possible, because they are the main drivers of the optimisation procedure later on. In order to determine, which would be the costs of the abatement measures implemented and to distinguish them from costs occurring because of other developments, the approach of additional costs was taken, i.e. the difference of e.g. the costs of a combustion plant with a low-NO_x-burner and the costs of a plant with a standard burner. Investment costs for the initial installation were annualised over the average lifetime of the equipment, variable costs (O&M etc.) were collected on an annual basis, giving a total annual additional costs per measure as input to the cost curve calculation.

By using activity data for each source group and assessing the implementation degree and total abatement potential, the total costs of abatement could be transferred into specific abatement costs, as unit costs in € per tonne of pollutant abated, which is the only way to effectively compare measures applying to different sources. Taking into account interdependency and exclusiveness of some measures, they were ranked according to their unit abatement costs and transformed into piece-wise linear abatement cost curves as shown in *Fig. 4.6.* and *Fig. 4.7.*. These curves have then been implemented into OMEGA-O_3, giving a detailed abatement cost curve for NO_x and NMVOC for each EU15 Member State. It has to be stated, that abatement cost curves have been applied in within several negotiation processes and have as often been subject to intensive criticism (cf. *Gough et al. 1995 and 1998*), mainly because of the assumptions that had to be made due to the lack of consistent input data from all countries. With the efforts made in the preparation of input data and the detailed sectoral analysis of abatement potentials and costs, this lack of consistency should not be an issue for the cost curves discussed here. *Table 4.3.* and *4.4* show the maximum reductions that could be achieved by implementing all measures included in the abatement cost curves, along with their related total and unit costs.

Table 4.3. Maximum emission reduction achievable for NO_x with measures included in the cost curves

NO_x	**Emissions remaining** [kt]	**Reduction from Base Case 1990**	**Reduction from Trend 2010**	**Total cost at max. reduction** [million €]	**Share of total costs**
Austria	101	-56%	-40%	127	1.3%
Belgium	119	-65%	-40%	304	3.0%
Denmark	107	-61%	-32%	256	2.6%
Finland	133	-51%	-50%	474	4.7%
France	615	-61%	-42%	960	9.6%
Germany	1 185	-60%	-39%	1 566	15.7%
Greece	375	-31%	-28%	358	3.6%
Ireland	49	-57%	-64%	286	2.9%
Italy	855	-58%	-37%	1 409	14.1%
Luxembourg	14	-41%	-12%	9	0.1%
Netherlands	296	-47%	-28%	184	1.8%
Portugal	102	-53%	-53%	354	3.5%
Spain	657	-47%	-39%	1 223	12.2%
Sweden	218	-37%	-32%	182	1.8%
United Kingdom	830	-70%	-51%	2 308	23.1%
EU15	**5 655**	**-58%**	**-41%**	**10 001**	

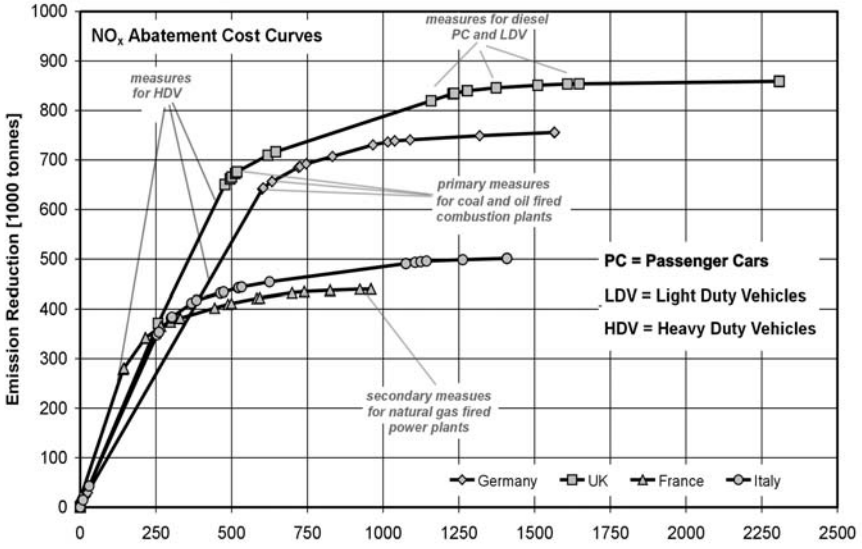

Fig. 4.6. Exemplary abatement cost curves for NO_x – 5 largest EU countries (accumulated total costs vs. accumulated total abatement, all measures on top of the trend scenario for 2010)

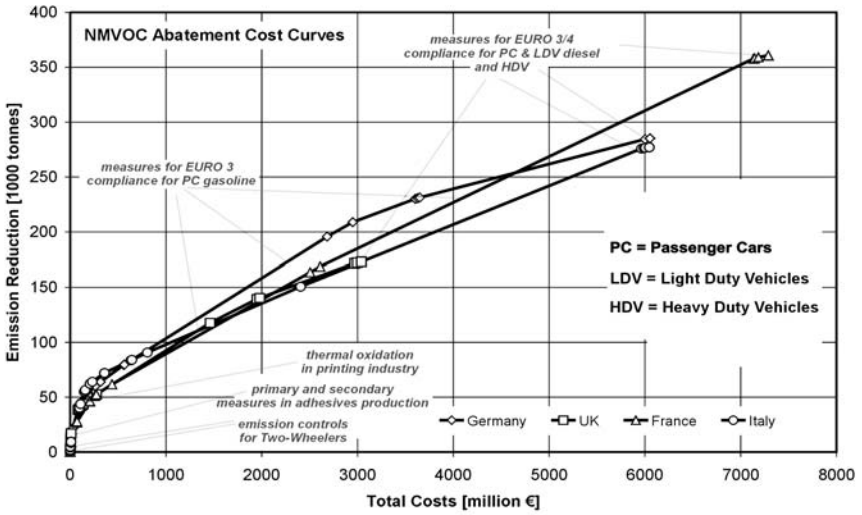

Fig. 4.7. Exemplary abatement cost curves for NMVOC – 5 largest EU countries (accumulated total costs vs. accumulated total abatement, all measures on top of the trend scenario for 2010)

Table 4.4. Maximum emission reduction achievable for NMVOC with measures included in the cost curves

NMVOC	Emissions remaining [kt]	Reduction from Base Case 1990	Reduction from Trend 2010	Total costs at max. reduction [million €]	Share of total costs
Austria	288	-31%	-4%	523	1.6%
Belgium	167	-54%	-14%	650	1.9%
Denmark	61	-64%	-30%	501	1.5%
Finland	97	-41%	-18%	486	1.5%
France	1 108	-54%	-25%	7 288	21.8%
Germany	1 270	-57%	-20%	6 053	18.1%
Greece	198	-39%	-30%	789	2.4%
Ireland	112	-38%	-16%	347	1.0%
Italy	1 394	-42%	-17%	6 046	18.0%
Luxembourg	8	-55%	-26%	53	0.2%
Netherlands	300	-34%	-9%	707	2.1%
Portugal	138	-33%	-12%	665	2.0%
Spain	717	-36%	-19%	5 328	15.9%
Sweden	288	-36%	-11%	1 025	3.1%
United Kingdom	1 408	-46%	-13%	3 040	9.1%
EU15	**7 556**	**-47%**	**-17%**	**33 502**	

The *Figs. 4.8.* and *4.9.* display the average unit costs for NO_x and NMVOC abatement in each EU15 Member State, as well as the EU15 mean. The values range between less than 2 k€/tonne of NO_x abated up to more than 5 k€/tonne. This reflects the structure of for instance the energy sector, where some countries have a large share of coal fired power plants, where comparatively large emission reductions can be achieved at low unit costs, while others, have to take more costly options. NMVOC abatement comes at considerably higher costs, ranging between less than 10 k€/tonne of NMVOC abated and up to 35 k€/tonne. Here as well, the sectoral structure of the solvent use sector, and the composition of the vehicle fleets (e.g. shares of gasoline and diesel cars) are responsible for the differences.

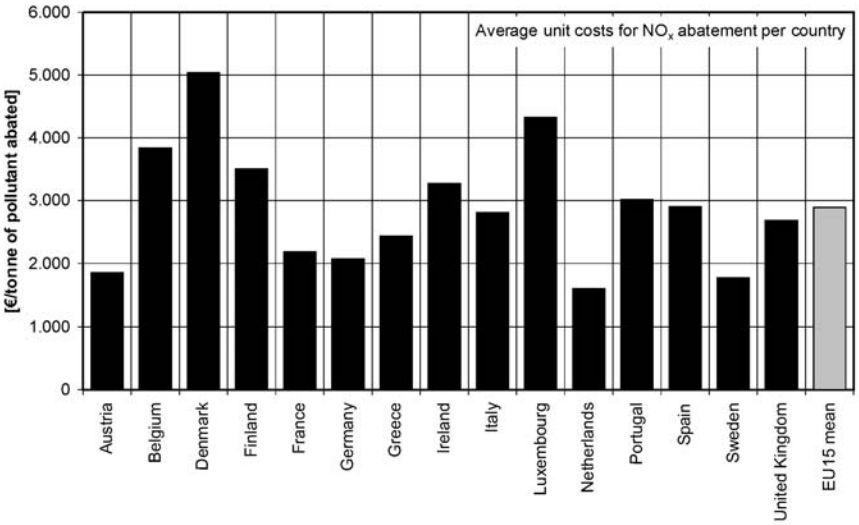

Fig. 4.8. Average unit costs for NO_x abatement per country

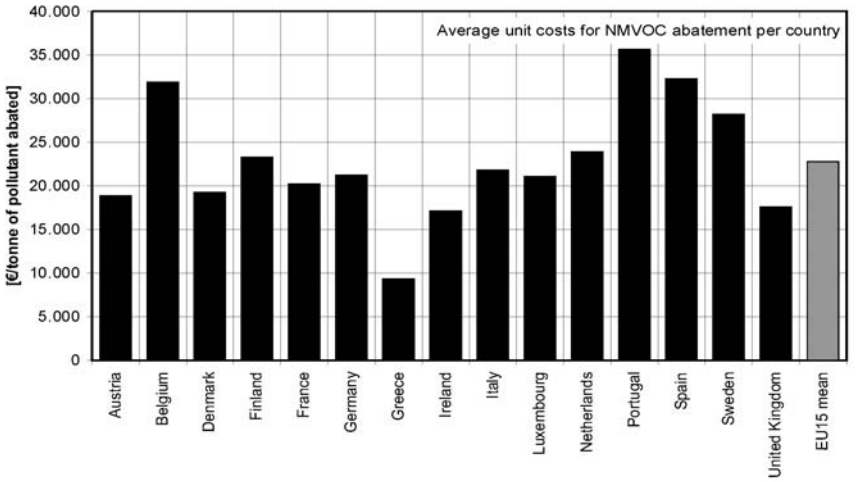

Fig. 4.9. Average unit costs for NMVOC abatement per country

4.2.2.3 Critical Levels, Base-Maps and S-R Relationships

For ozone, critical levels are defined in terms of accumulated exceedance of thresholds. For vegetation $AOT40_{forests}$ (April-September, threshold of 10 000 ppb.h) is used (*Fuhrer et al., 1997*, see *Chap. 2*). For crops, the growing season for modelling purposes is defined as the 3 months May-July, and this statistic is referred to as $AOT40_{crops}$. The critical threshold for AOT40c is currently set to 3000 ppb hours (ppb.h).

For health, the UN-ECE workshop on *„health effects of ozone and nitrogen oxides in an integrated assessment of air pollution"* (*UN-ECE, 1997*) agreed that simple statistics such as AOT60 could be used as a preliminary indication of ozone levels above the recommended WHO guideline for integrated assessment modelling purposes. AOT60 is defined in an analogous manner to AOT40 above, but no critical threshold is defined for AOT60 as any ozone level exceeding 60 ppb is thought to be harmful to human health (cf. *Chap. 2*), i.e. AOT60 sets a threshold of zero ppb.h.

Base-case (year 2010) fields of ozone and N-deposition for the year 2010 are taken directly from EMEP acid deposition and ozone model calculations (cf. *Friedrich and Reis, 2000*).

Source-receptor matrices relate changes in pollution at a receptor (country or grid square) *j* to the emissions from an emitter country *i*. The source-receptor (S-R) relationships used here have been presented in EMEP Report 1/96 for acid deposition, and *Friedrich and Reis* (2000) for ozone (AOT40 and AOT60).

In order to deal with the variable nature of ozone S-R relationships, two sets of matrices have been used, one derived from 2010 *current reduction plans* emission levels and the second from a hypothetical low-emission situation (40% of 2010 emissions). For any given country the S-R relationship used in the iteration model is calculated by interpolation between these two base S-R matrices, depending on the level of NO_x emissions at each iteration step (see *Simpson and Eliassen 1997* for more details).

4.2.2.4 Model Output

The model creates a number of output files which can be used for a detailed assessment of the costs and emission reduction requirements for each target calculated and for each individual country included into the optimisation.

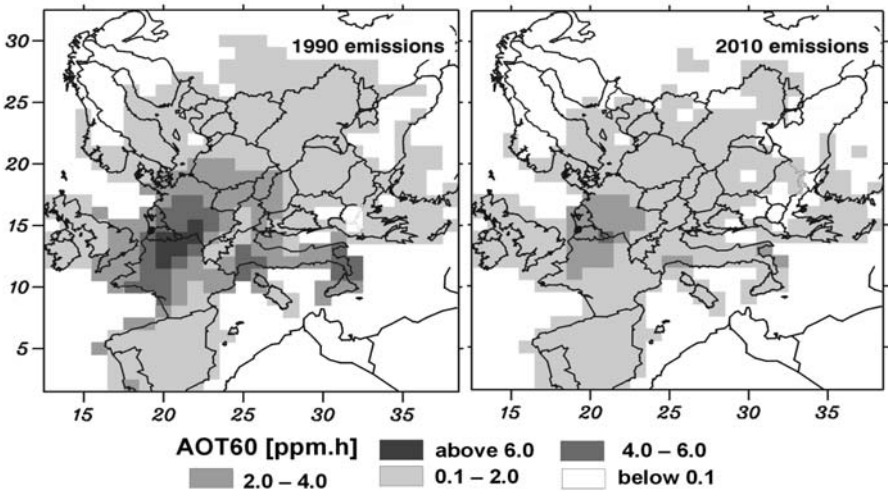

Fig. 4.10. Exemplary model output: maps of AOT60 on a 150 x 150 km EMEP grid

Besides the tables that give emission reductions and list the number of grid cells which are still in exceedance of the set targets, output files which can be used to generate graphical displays of ozone concentrations (in AOT*xx* values) are the most prominent output (see *Fig. 4.10.*). These allow for a quick visual assessment and comparison of different strategies and give a valuable overview on the regional variance and distribution of ozone concentrations. The graphics will consequently be used in the discussion of various analyses in *Chap. 5*.

4.2.3 Detailed Model Formulation

In this section, the core features and variables of the model shall be described.

4.2.3.1 Model definition

On the most basic level, the model distinguishes between

- countries ***C***,
- emissions ***E***,
- cost curves ***K***, and
- benefits.

In addition to that, abatement measures *M* and source sectors *S* are defined in a pre-modelling stage to calculate the abatement cost curves. These sets of data are

stored in indexed fields which allow the direct attribution of emissions and cost curves to countries, of emission reductions to related costs and suchlike.

4.2.3.2 Indices

The iteration process requires a number of running indices to determine the position of the model within the iteration:

i	=	1 .. *n*	with *n* being the number of countries
j	=	1 .. *N*	with *N* being the number grid cells (i.e. 1443 for the $EMEP_{150}$ grid)
p	=	1 .. *l*	with *l* being the number of pollutants emitted/controlled (in this case, NO_x with *p=1* and NMVOC with *p=2*)
{x, y}	=	[1..39, 1..37] matrix of grid cells of the EMEP 150x150 km grid	

4.2.3.3 Countries C_i

The set of countries included at this stage is the 15 European Union Member States (EU_{15}) as of before the accession of countries in 2004, Norway, Switzerland and the countries of Central and Eastern Europe (CEECs).

4.2.3.4 Source sectors S

A sector is determined by a group of uniform or similar activities, which can be regarded as a (more or less) homogenous set marked by activity ***a***, stock ***s***, input ***i*** or other variables. Within a sector *S*, several pollutants can be emitted by an activity, and at the same time, several measures can address the emissions from this sector and reduce one/several/all pollutants with different efficiencies. In this case, emissions of NO_x and NMVOC from each sector were accounted for.

4.2.3.5 Abatement measures M

A measure is defined by its application to a *source sector* ***S*** within a *country* ***i***, reducing emissions $\boldsymbol{E} \in \{E_1, \ldots, E_l\}$, causing $\boldsymbol{\Delta E_p}$ for no/one/some/all pollutant emissions and resulting total abatement costs for a country *i* and pollutant *p* of $\boldsymbol{k} = f(i;p)$ each abatement measure M includes a set of information, such as abatement efficiency of reduction (per pollutant, usually expressed as a change in the emission factor, i.e. ΔEF) $\boldsymbol{ef_p}$, applicability (or the implementation degree) ***a*** and additional relations to express interdependency, exclusiveness and suchlike with other measures.

4.2.3.6 Emissions E_p

Emissions of a pollutant ***p*** within a sector *S* can be given either as a function of an activity ($E = f(a)$), or depending on the stock ($E = f(s)$) or as a function of an input

(E = $f(i)$), thus emissions of pollutant ***p*** of a sector *S* can be defined as $E_p = f\{a;s;i\}$. As a way to facilitate the calculation of specific emission scenarios, a variable for the definition of country-wise emission ceilings (*EC*) was introduced. In this context, a 'ceiling' does not express a maximum of emissions a country is allowed to emit, but expresses the minimum of emissions which OMEGA is not allowed to go below. The variable *EC* can be set for each country and pollutant, thus allowing to calculate scenarios with no reductions for specific countries, with reductions to zero emissions, or anything in between.

4.2.3.7 Abatement cost curves K

The abatement cost curves are calculated as a function $K_{i,p} = f(E_{i,p})$ for all countries ***i***, reflecting that all abatement measures *M* of a country are ranked by their unit costs and transformed into piece-wise linear curves. The cost curves contain the corresponding abatement costs for each emission reduction, enabling OMEGA-O_3 to determine the total abatement costs at each iteration step. In this context, M_i reflects the position on the cost curve for country ***i*** that corresponds with the emission level E_i achieved for pollutant ***p***.

Thus, the total costs of an optimised abatement strategy is the sum of ***K*** over all countries ***i*** and all pollutants *p*.

4.2.3.8 Benefits

Determining the benefits (here, 'benefits' refers to the improvement of the ozone situation, i.e. how much does the reduction of a specific amount of emissions reduce ozone levels) of reducing emissions in each iteration step can be conducted in different ways:

- expressed in physical terms, i.e. ***reduced absolute concentrations*** of pollutant *p* as an *average*, a *maximum* or a sum over all grid cells
- expressed as a *gap closure*, i.e. a ***percentage of the gap between initial AOT and a critical level / AOT limit value closed***, either for each grid cell, or an aggregate level of this (see *Fig. 4.5*)
- as a change in an aggregate *index value*, i.e. by ***summing up the concentrations of pollutants for all grid cells, weighing the concentrations of specific pollutants to derive an aggregate value for "air quality"*** and evaluate the decrease of this index as an indicator for a measures performance
- as a change in *damage costs*, i.e. evaluating the ***damages costs of the resulting pollutant concentrations after applying a measure and quantifying their reduction relative to the damage costs given for a reference case***, hence expressing the benefits in monetary terms to be easily compared to the abatement costs occurring from the implementation of the measure

For this work, *benefits* have been modelled as gap closures towards a critical level,

respectively AOTxx threshold. The main advantage of reducing AOT levels in relative rather than absolute terms is, that the problem of so-called 'binding grids', i.e. grid cells which show extremely high AOT levels under most conditions, is reduced. In the case of absolute reduction targets, e.g. zero exceedance of AOT60 over all grid cells, such binding grids would drive the optimisation model into increasing costs even though little improvement of AOT levels would be achieved, as only individual cells would still exceed the threshold. The gap closure approach, in contrast leads to a more balanced, overall reduction of all grid cells which exceed the threshold by a predefined share. This reflects well that reducing exceedances in a large number of grid cells is favourable (in terms of population exposure and impacts on health, crops and ecosystems) than focusing on one individual extreme grid cells.

As *Fig. 4.5* illustrates, the gap towards the AOT threshold as it is closed by iteration step *n* is calculated as $\overline{ab}/\overline{ad}$, while the gap closure at iteration step (n+1) is equal to $\overline{ac}/\overline{ad}$. By setting a percentage gap closure for AOTxx, the optimisation model tries to achieve this gap closure for all grid cells, breaking only if either this target is achieved, or other stop criteria are matched (e.g. no country left to reduce emissions further etc.). A short evaluation determining the influence of selecting either gap closure or absolute reduction targets is conducted in *Sect. 4.3.3*.

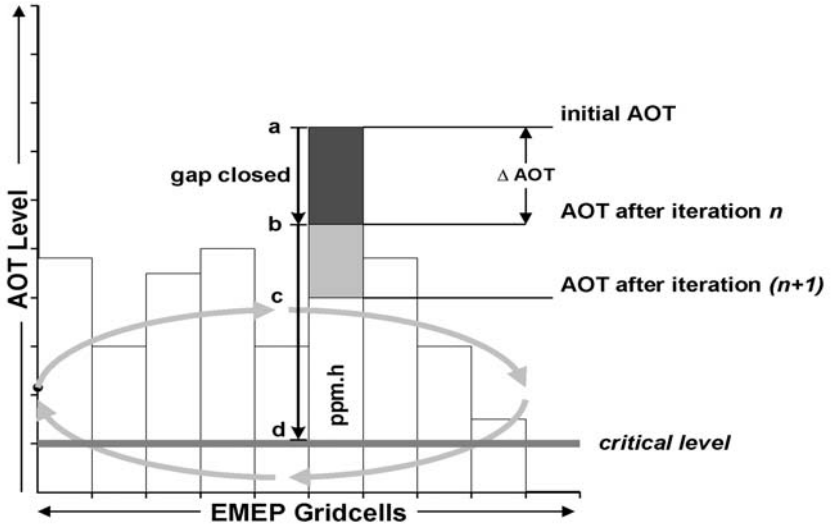

Fig. 4.11. The gap closure approach illustrated

4.2.3.9 The model domain

The model domain covers the (*extended*) EMEP[1] 150 x 150 km grid, with *xy:* 39 x 37 = 1443 grid cells. Within the model, this domain is represented by a set of fields, such as

- a map of initial AOT for ozone $\mathbf{BM}_{0}\{x,y\}$
- a map of critical levels for ozone AOT $\mathbf{CL}\{x,y\}$
- a map showing the resulting ozone AOT $\mathbf{CM}_{opt}\{x,y\}$

4.2.3.10 Source-Receptor Matrices (SR-M)

To express changes in AOT in each grid cell resulting from a change in emissions in a specific country, so-called *country-to-grid* source-receptor matrices (SR-M) have been introduced. For each pollutant's (p) emissions, an SR-M is defined as

$$\boldsymbol{SR\text{-}M_p} = \{\Delta E_{i,p} \mid \Delta CM_p(x_1,y_1) \ldots \Delta E_{n,l} \mid \Delta CM_p(x_x,y_y)\}$$

with the simplification, that all matrices are standardized to a ΔE of 1 kilotonne, giving the resulting change in AOT (ΔCM) for each grid cell *(x, y)* due to a change in emissions (ΔE) in country *i*. Source-receptor matrices have been provided by EMEP for NO_x and NMVOC for each AOT threshold (60, 40 crops, 40 forests) on different levels of initial emissions to allow for an interpolation to reflect the non-linearities implicit in ozone formation.

4.2.3.11 Optimal solutions?

The question "which is the optimal solution" heavily depends on the target selected. In this respect, a limited number of main targets for optimisation in this multi-pollutant multi-effect problem can be identified:

- achieving a set of air quality targets (e.g. pollutant concentrations, population exposure etc.) at ***minimum costs***
- setting a specific amount of money to be spent in countries C_i and ***maximising the improvement in air quality (i.e. the benefits)***
- attempting to ***maximise the cost-benefit ratio*** (for countries, regions, …) under the constraints to comply with air quality limit values

As it has been indicated before, the main target for the model calculations conducted for this study was to achieve air quality thresholds for ozone (expressed as AOTxx) at least costs, thus the target function can be formulated as follows:

1. *http://www.emep.int/grid/grid150.html*, *30.07.2003*

(1) *Minimise costs for a specified target of ozone thresholds:*

$$\sum_{i=1}^{n}\sum_{p=1}^{l} K_{i,p} = f(E_{i,p}) \rightarrow \boldsymbol{min}!$$

(2) *under the following constraints*:
(a) ozone threshold achieved (including no increase in ozone in any cell):

$$CM_{opt}(x,y) \leq CL(x,y) \forall (x,y) = \{1 \ldots 39, 1 \ldots 37\}$$

or
(b) gap closure achieved (with p being the percentage gap closure):

$$CM_{opt}(x,y) \leq BM_0(x,y) - p(BM_0(x,y) - CL(x,y))$$
$$\forall (x,y) = \{1 \ldots 39, 1 \ldots 37\}$$

or
(c) emissions ceilings respected:

$$E(i,p) \leq EC(i,p) \forall i = 1 \ldots n, p = 1 \ldots l$$

Fig. 4.12. finally shows a graphical illustration of how the different parts of the optimisation model correspond. The main part of OMEGA-O_3 model contains the iteration procedures, which are responsible for the stepwise reduction of emissions, the thus resulting changes in concentrations via the *Source-Receptor Matrices* (SR-M) leading to a reduced total of exceedances of the preset threshold. After each emission reduction step, the evaluation is done within the EVAL-Module, checking if the target presets are met, and/or if other criteria are achieved to end the iteration process.

Model output is handled by two modules, one producing plain text output, which can be directly used as input for instance for benefit assessment in the ECOSENSE model. The visualisation module finally generates maps showing AOT values based on the $EMEP_{150}$ grid, allowing not only for a quick visual analysis of different model results, but as well for an assessment of the regional distribution of AOT for different scenarios.

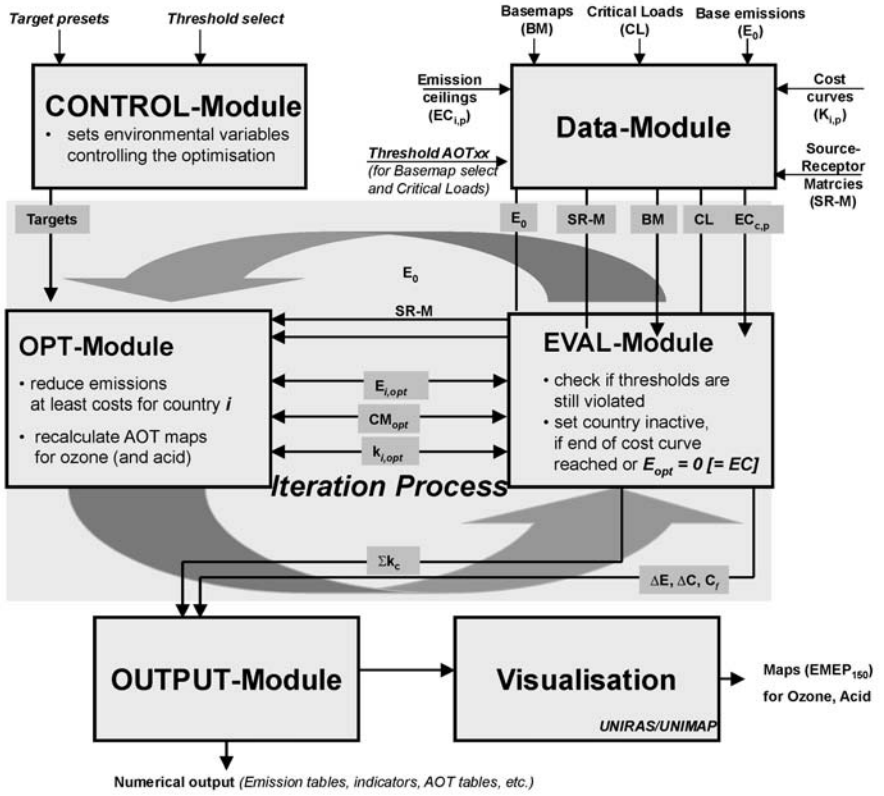

Fig. 4.12. Core structure of the OMEGA-O_3 model

4.2.4 Model Interfaces for Cost-Benefit Assessment

Finally, to conduct a cost-benefit assessment, i.e. comparing the abatement costs for a country or the total EU15 to the respective avoided damage costs (benefits), another model is applied, which has been used in various studies before. ECOSENSE (see *Krewitt et al. 1999*) is a modular assessment tool as it is described in *Fig. 4.13.*, and for this work, the concentration maps provided by OMEGA could be used directly to be compared with a basecase-scenario, in this case the trend scenario for 2010. Thus, the benefits expressed arise from reduced damages expressed in monetary terms which occur from reducing emissions of NO_x and NMVOC in comparison to the trend scenario emissions.

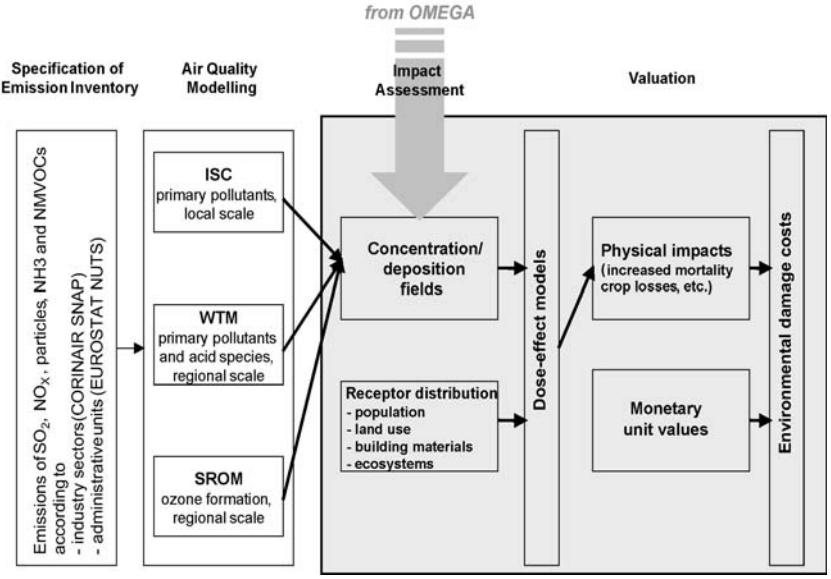

Fig. 4.13. Interface between OMEGA-O_3 and the ECOSENSE model

4.3 Model Evaluation

4.3.1 Uncertainties in Input Data

As in any model application, the question arises, how reliable the results from the OMEGA-O_3 model are, both in comparison to e.g. ozone levels calculated with the full EMEP Lagrangian Model, and in terms of costs and emission ceilings calculated for a specific strategy. Here, the main paths for uncertainties arising in modelling results shall be identified and assessed in a qualitative way. A more detailed and theoretical assessment of the complex issue of dealing with uncertainties using integrated assessment models in general has been conducted by *van der Sluijs* (1996). This work, even though focusing mainly on models for the assessment of climate change, provides a very good and thorough methodological basis.

For the OMEGA-O_3 model, there are two main pathways for a detailed uncertainty analysis:

- *Uncertainties through input data* (emission data, source-receptor matrices, cost curves), and
- *uncertainties through the modelling approach and methodology*.

The second part (cf. *van Asselt et al. 1996* and *Rotmans, 1998*) refers to the way calculations are conducted and implemented in OMEGA-O_3 and how different model inputs are connected. Here the core design of OMEGA-O_3 helps to reduce potential sources for uncertainties through simplicity and transparency. The iteration process deliberately renders the use of complex and non transparent solver algorithms obsolete and hence provides robust and transparent solutions to given targets and makes it easier to spot inconsistencies in the optimisation process. On the other hand, the results from OMEGA-O_3 are to a significant extent driven by the values and quality of the input data, hence the specific sources of uncertainties from these shall be addressed in more detail.

As it is evident from the previous sections, the application of assessment models such as OMEGA-O_3 is prone to large uncertainties, which mainly occur from input data being uncertain. A direct quality assessment, as it is usually done for instance for chemistry transport models by comparing modelled concentrations of trace gases with actually measured concentrations is not possible in this case, because assessment models such as OMEGA-O_3 usually produce annual summary values, such as the AOTxx values, in contrast to, for instance, ozone concentrations in hourly resolution, which would be needed to properly assess ozone peaks and episodes and to compare these to measured values. In addition to that, the calculation of annual values for a large area like the whole of Europe and the thus necessary gridding to maintain a manageable amount of data can only give coarse results, for instance on a 50 km or even 150 km grid. With intermittent measurements typically being available for selected locations for specific time frames, the difference in temporal resolution is the second main reason to prohibit comparisons with measurements. Thus, the indirect evaluations of OMEGA-O_3 results through sensitivity analyses (see *4.3.2*) or by using other, already evaluated model results (e.g. of the Lagrangian EMEP model, see *4.3.1*) as a proxy to assess OMEGA-O_3 output are the best available options for quality assurance.

Finally, it should be stated, that a regional model such as OMEGA-O_3, taking into account the simplification and parameterisations necessary to conduct the model runs, should not be used to calculate absolute values, e.g. trying to reproduce ozone levels at a given time and on a local scale. The model shall be used as a decision support tool to evaluate different options using a well-defined, transparent methodology and give results which assess the relative performance of different options under specific circumstances.

4.3.1.1 Emissions

The emission sets that are used as a starting point for the step-wise assessment of emission reductions and their impacts do not present detailed and accurate forecasts of the emission situation in a target year. As it has been stated before, the trend scenario for 2010 does reflect a possible development, assuming what impact the legislative and political aspects of air pollution control will have on the current situation and thus drafting a picture of the potential future emission situation, as-

suming a business-as-usual development with no additional action being taken. In this respect, an infinite number of other emission data sets for the year 2010, on which the model calculations are based, could be determined, under different assumptions, either more optimistic, or using different methods. In addition to that, the base case emission data sets obtained from CORINAIR 90 and EMEP for 1998, incorporate sometimes considerable uncertainties and (known) errors in the calculation of emissions for sectors and countries even for a current year. Knowing this, the emission targets calculated by OMEGA-O_3 should not be taken for granted, but should be used as a way to assess the different requirements for emission control for different countries or regions, and the order of a magnitude in which emissions would have to be reduced to achieve specific air quality targets. On the other hand, as the emission data sets within OMEGA-O_3 are consistent, the uncertainties should be considerably smaller when the cost-effectiveness of different abatement options is assessed. In this case, options or strategies are compared on the same basis, allowing for a sufficiently reliable assessment, which options are better than others, and to what extent they are more cost-effective.

In general, there is a lot of information available on the estimation of uncertainties of emission data, for example *Placet et al. 2000* on emissions from stationary sources, *Schlünzen and Lenz (2000)* on the sensitivity of simulated ozone concentrations on emission data and *Simpson et al. (1995a* and *b)* on biogenic emissions, as well work conducted in the US (*EPA 1996*). Even more work is currently being done in the frame of greenhouse gas emission inventories (e.g. *Winiwarter and Rypdal*, 2001), where the assessment of uncertainties has been explicitly expressed in the core requirements for good practise in inventory building. However, only little information is yet available on quantification of these uncertainties, with the exception of the work conducted under the EUROTRAC (The EUREKA project on the transport and chemical transformation of trace constituents in the troposphere over Europe, http://www.gsf.de/eurotrac/) subproject GENEMIS (see *GENEMIS 1998*, *1999* and *2000* respectively).There, uncertainty assessment of emission data has been a major task. For road transport in particular, a very detailed approach to quantify errors in the calculation of emissions has been developed (*Kühlwein et al*., 1999, and *Kühlwein and Friedrich*, 2000).

4.3.1.2 Source-Receptor Matrices and Meteorology

Within the modelling input to OMEGA, there are three main aspects of uncertainty to be identified: as in any modelling, the resulting concentrations and hence the source-receptor matrices as an input to the assessment model are subject to uncertainties stemming from a variety of sources (*Simpson 1992* and *Simpson and Malik, 1996*). In addition to that, the parameterisation itself, the calculation of source-receptor matrices from a large number of model runs with the full CTM means that the level of detail is reduced to produce a manageable data set for the assessment model. Finally, the meteorology plays a particularly important role in the case of tropospheric ozone formation.

For the evaluation and uncertainty assessment of CTMs, various model studies and model intercomparisons have been conducted, using reference cases and applying a set of chemical transport models versus measurements to assess how well the models reproduce real-world data (see for example *Schaller and Wenzel 1999* and *2000, Hass et al. 1997, Sillman et al. 1990* and *Simpson et al. 1998*). OMEGA-O_3 Model results have been evaluated vs. full EMEP CTM results, as it is described later on.

The source-receptor matrices calculated by the Lagrangian EMEP model give the relationship between an amount of emissions reduced at one place and the change in ozone concentrations somewhere else. A major issue here is the scope of the 150 x 150 km grid, which does not account for the local peaks of ozone concentrations and thus the changes in ozone might be in the same grid cell overpredicted for some areas, and underestimated for others.

The following section will discuss the impact of meteorological conditions on the modelled ozone concentrations in detail. Though, as this relates as well to the source-receptor matrices mentioned above, it needs to be stated, that to reduce the uncertainty introduced by the variations of meteorology in different years, the matrices have been calculated in a large number of EMEP model runs for 5 different years. These results have then been averaged over these 5 years, resulting in a set of relationships, that are not driven by the extremely high photo-oxidant activities of e.g. the year 1994.

4.3.1.3 Cost Data

Finally, the input data with the largest and most difficult to determine uncertainties are those of the costs of air pollution control options. To begin with, determining the costs of a measure itself usually results in a range of costs rather than a specific figure, so setting a fixed cost figure, which is needed for the cost-effectiveness assessment, already introduces an error. Secondly, as the calculation of costs is being made for a future year, the trend scenario being used to assess the emission control options already being implemented in a business-as-usual development, determining the cost of a measure for this future year is very difficult. Changes in price levels, technological developments and the political and legislative developments will influence the cost structure of air pollution control equipment significantly, which can not be assessed in full at the time being. The abatement cost data for this study have been collected by IPTS (Institute for Prospective Technology Studies, EC Joint Research Centre Sevilla; see *Friedrich and Reis 2000, Chap. 4*) and, to improve data quality, have been submitted to industry experts and suchlike for comments. To enhance data quality in this field, it would be highly recommendable to introduce a standard for the collection and processing of measure data, as it was done in an expert group lead by the European Environment Agency (EEA 1999).

4.3.1.4 Evaluation vs. the Lagrangian EMEP Model

The OMEGA-O_3 Model is a reduced form model, developed with the aim to significantly decrease the amount of computing time used in order to be able to calculate the results for a large number of scenarios or targets. To this end, the model depends on pre-calculated matrices to reflect the atmospheric transport processes and chemical reactions that lead to the formation of ozone from precursor emissions, which are conducted using the full Lagrangian EMEP model.
In order to assess, in how far the use of SR-relationships might be responsible for errors or uncertainties in the modelling results, OMEGA was evaluated vs. the full EMEP model for AOT 40 and AOT60. *Fig. 4.14.* and *Fig. 4.15.* evidently show a very good agreement between the results achieved by OMEGA in relation to the Lagrangian EMEP Model, either for absolute AOT values, as for changes in AOT (ΔAOT), by comparing the values calculated for each grid cell both by the EMEP model and OMGEA-O_3. It has to be stated, though, that both the Lagrangian Model and even more OMEGA are bound to produce results with increasing uncertainties, as emission reductions become more and more stringent and hence the influence of background concentrations and/or meteorology and suchlike becomes more prominent. Hence, the results provided by the model should, particularly for emission reductions of more than 80% and beyond, be regarded with care and the relative changes of concentrations between different scenarios might be a more reliable way to assess the performance of a strategy than the absolute values calculated.

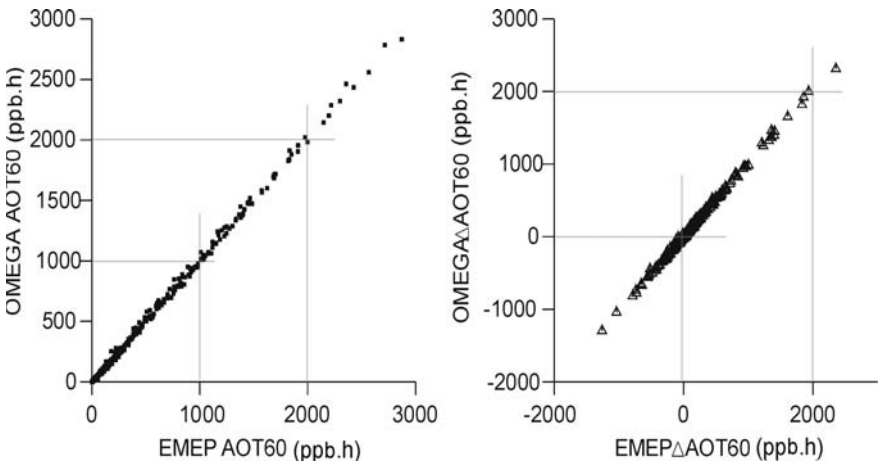

Fig. 4.14. OMEGA-O_3 model results vs. EMEP for AOT60
(Source: *Friedrich and Reis 2000*)

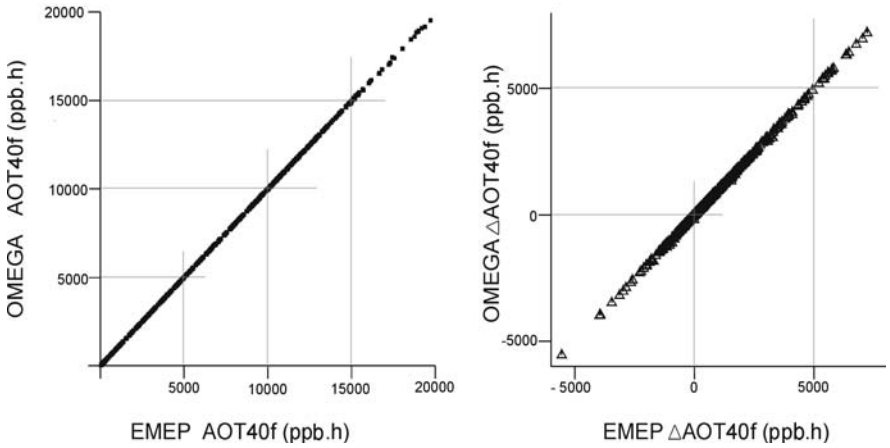

Fig. 4.15. OMEGA-O_3 model results vs. EMEP for AOT40
(Source: *Friedrich and Reis 2000*)

A direct evaluation of OMEGA-O_3 model results versus measurements of ozone concentrations is not feasible, because of the grid cell size of 150x150 km which cannot be compared with point values. However, the EMEP model has been thoroughly evaluated in modelling experiments vs. other CTMs and vs. measurements on a large scale[1]

4.3.1.5 Gap Closures vs. Absolute Reduction Targets

In addition to the assessment of model results as it was conducted in the previous section, another interesting question is, in how far choosing a gap closure approach will lead to results different from that with an absolute reduction attempted.

Figs. 4.16. and *4.17.* show the distribution of EU15 total emissions of NO_x and NMVOC if the optimisation either aimed at a gap closure, or at the absolute reduction of ozone thresholds. The emission reductions for NO_x do vary quite significantly in some cases, while the differences for NMVOC emissions are far less explicit (*Fig. 4.17.*). The main cause of this is, that while attempting to reduce ozone levels by setting absolute reduction targets focuses on areas with the largest exceedances of the critical level, the setting of gap closures towards a threshold aims at a more geographically even distribution of AOT reduction, thus favouring a balanced reduction of ambient concentrations in many grid cells against a comparatively large reduction in only one grid cell.

1.see e.g. the *EMEP/MSC-W Report 2/98, July 1998 "Transboundary Photooxidant Air Pollution in Europe", http://www.emep.int, 03.08.2004*

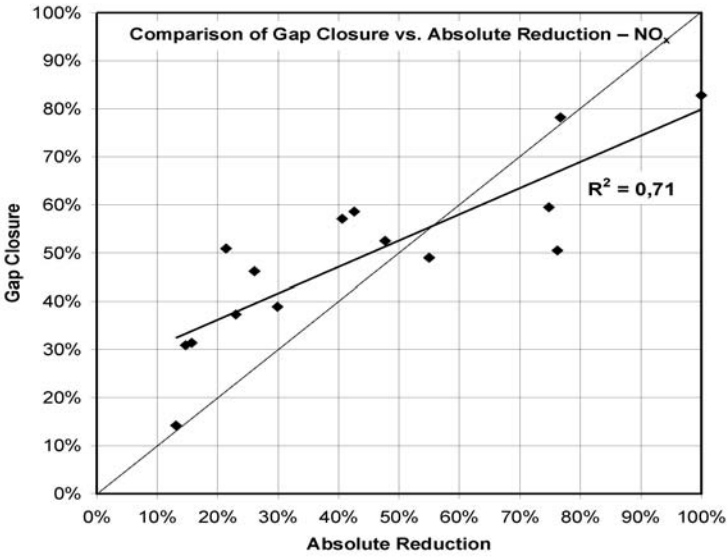

Fig. 4.16. Comparison of gap closure vs. absolute reduction model runs – NO_x

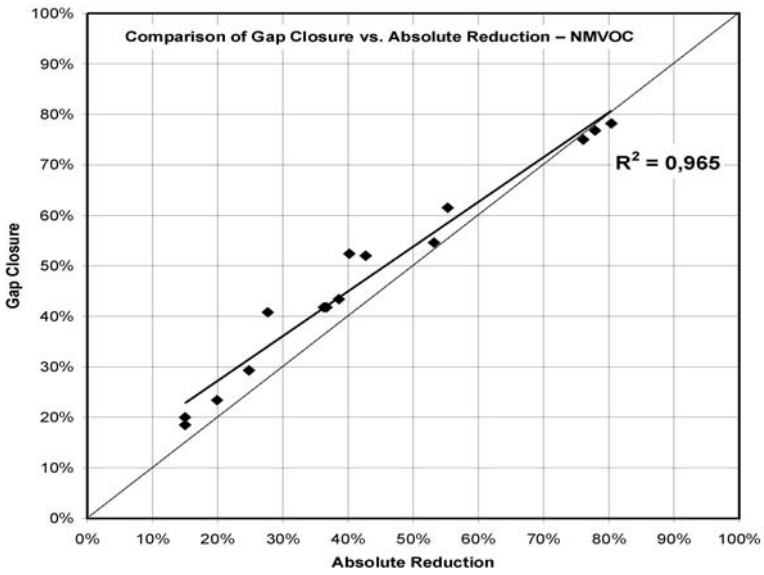

Fig. 4.17. Comparison of gap closure vs. absolute reduction model runs – NMVOC

In order to investigate the influence of the approach selected in OMEGA model calculations were conducted using either approach - closing relative gaps instead of reducing absolute concentrations - at 10% reduction steps of the initial total ozone concentration. While reaching the same target, the reductions of precursor emissions necessary to achieve this differ considerably for NO_x. The gap closure approach leads to a more balanced distribution of reductions among the countries, reflecting the model attempting to reduce ozone concentrations for all grid cells above the threshold, instead of focusing on some grid cells with high ozone levels only. And in the case of NO_x emissions, countries like Ireland, the UK or The Netherlands will be required to reduce their emissions a great deal more when a total reduction is attempted, while they only face moderate reduction requirements in the gap closure case. For NMVOC, the results for the gap closure approach does not show significant differences.

4.3.2 Specific Uncertainties when Modelling Tropospheric Ozone

4.3.2.1 The Impact of Changes in Meteorology

Even though precursor emissions of NO_x and NMVOC are the main driving force for the formation of ozone leading to high concentrations and hence adverse effects on human health or crops and vegetation, the meteorology (in particular variations of solar radiation) used for model calculations plays a significant role and has to be considered when trying to derive conclusions for the compliance of thresholds or limit values. To assess the scope of this variability, the following figures display EMEP Model results showing variations of ozone concentrations for AOT60 (*Fig. 4.18.*) and AOT40 for agricultural crops (*Fig. 4.19.*), using the same emission sets for two different years. Both figures show that the year 1994 (upper row) had considerable higher overall concentrations for AOT60 as well as $AOT40_{crops}$, and both figures indicate a quite different result of e.g. an 80% emission reduction. To some extent, these two examples show as well, how regionally variable ozone concentrations can be under different meteorological conditions, and the picture for $AOT40_{crops}$ gives some evidence, that this threshold is particularly sensitive to changes in meteorology. In the case AOT40 for crops, the considerable contribution of background ozone, estimated at about 30 ppb in Europe (caused by hemispheric transport from the US or Asia) causes significant threshold exceedances even in a year with comparatively low ozone impacts such as 1996.

Having seen these considerable differences occurring from using different sets of meteorological data alone, the importance of choosing an approach for modelling compliance assessments for air quality targets based upon model runs for several years and averaging the results becomes obvious. *Fig. 4.20.* shows an exemplary averaging over 5 years, as it was used for the preparation of source-receptor matrices for OMEGA, where e.g. maximum concentrations are differing by a factor of three between single years.

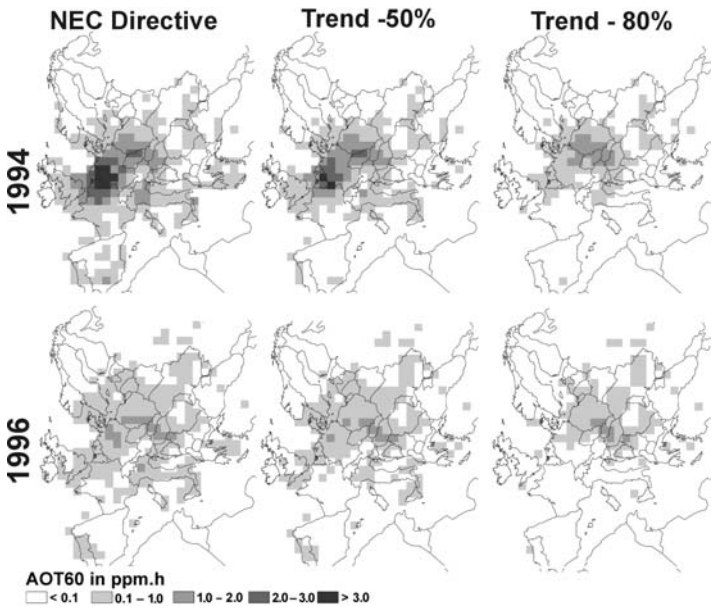

Fig. 4.18. Variations of AOT60 for different meteorologies in the years 1994 and 1996

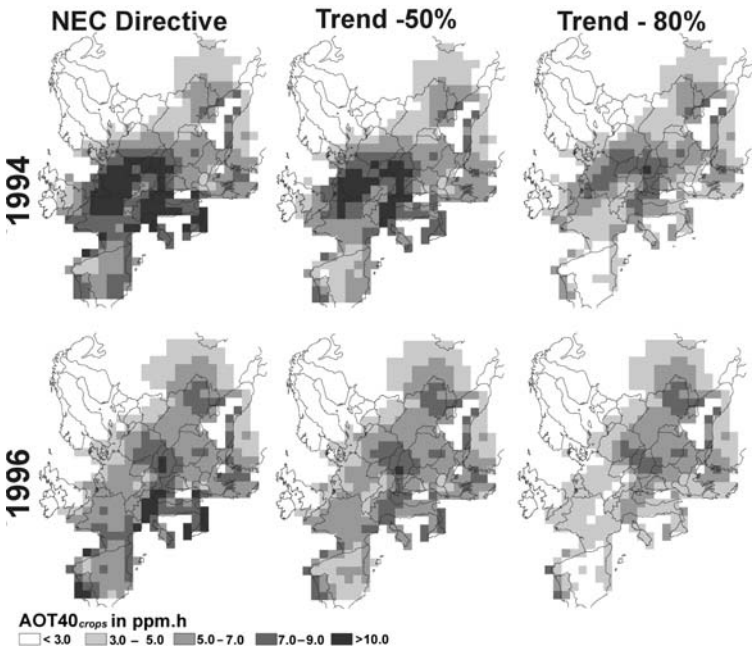

Fig. 4.19. Variations of $AOT40_{crops}$ for different meteorologies in the years 1994 and 1996

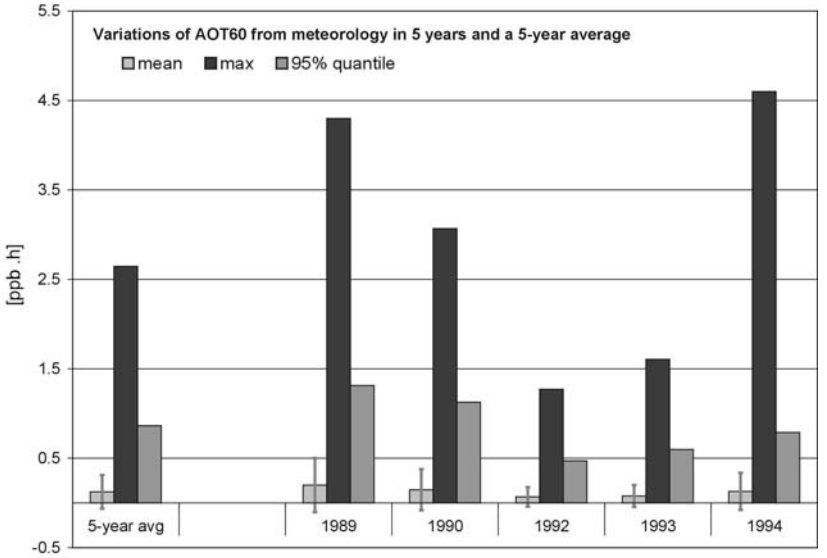

Fig. 4.20. Maximum and mean AOT60 (Accumulated Ozone Exposure over a Threshold of 60 ppb, including deviation from mean) as well as the 95% quantile for AOT60 for different years' meteorology (calculated with the EMEP Lagrangian Model)

4.3.2.2 Changes in VOC Speciation

While the CTM does account for the speciation of VOCs using splits for specific sectors and sources, this level of detail cannot be achieved with current approaches for parametric optimisation tools. The number of model runs to find a least cost solution and the increased demand for data would render the model useless, as it would, for example, have to determine emission reduction by species at each step. In addition to that, there is little or no information at all available on abatement efficiency of particular technologies.

However, as it was discussed in *Sect. 2.2.3*, the relative contribution of different VOC species does vary significantly and the following two examples shall demonstrate, that this is not merely a theoretical issue. *Fig. 4.21.* displays a comparison of the VOC split of NMVOC emissions from a gasoline operated vehicle without any emission control with a vehicle that is equipped with a three-way-catalyst (TWC). While the share of low-reactive saturated hydrocarbons and olefines increases from about 45% to 55%, more reactive alkines in particular are reduced significantly. This indicates, that emissions of NMVOC of vehicles with TWCs are bound to have a lower specific ozone forming potential, than emissions from older, uncontrolled vehicles.

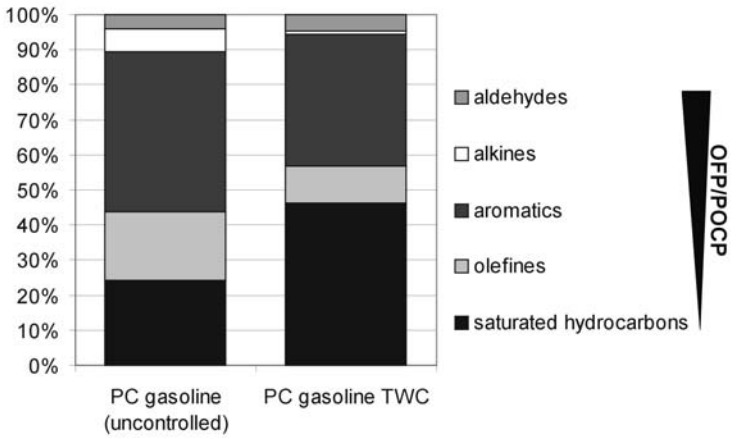

Fig. 4.21. Comparison of VOC species by major substance groups for uncontrolled and controlled (i.e. equipped with a three-way catalyst TWC) passenger car gasoline (Source: *J. Theloke, IER, pers. com.*)

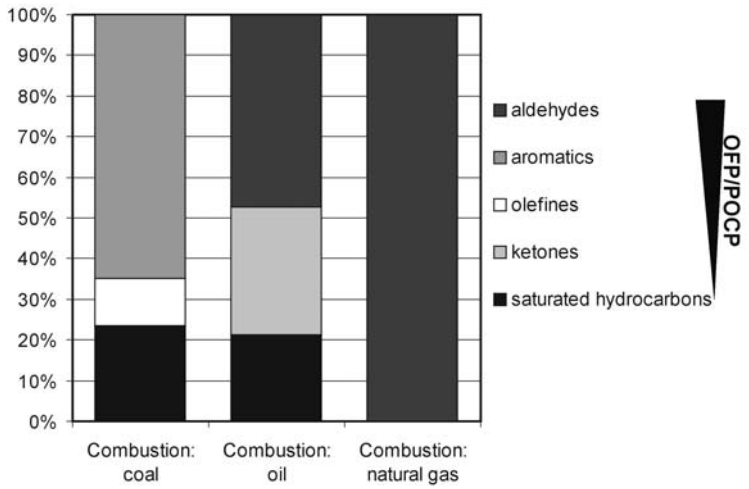

Fig. 4.22. Comparison of VOC species by major substance groups for combustion in power generation for different fuels (Source: *J. Theloke, IER, pers. com.*)

The impact of changes in speciation is even more pronounced in the combustion of fossil fuels, e.g. in power generation. In the process of projecting emission development for the business-as-usual trend scenario for 2010, a switch from solid and liquid fuels towards natural gas was identified, and could be confirmed by other projections as well. While natural gas operated combustion plants do have lower emissions of NMVOC and NO_x in general, the NMVOC emitted consists to almost 100% of highly reactive aldehydes (*Fig. 4.22.*). NMVOC from coal fired plants, in contrast, show a mix of low-reactive saturated hydrocarbons and olefines, and medium to high reactive aromatics, while combustion of oil shows a completely different VOC split. These examples show, that by not taking into account the VOC split of NMVOC emissions in the optimisation, resulting ozone concentrations are subject to further uncertainties. However, for this study, this problem was solved by re-calculating the most important scenarios with the full EMEP ozone model on the basis of the emission targets calculated by OMEGA-O_3.

4.3.3 Uncertainty Treatment in Other Studies

A significant amount of work on the assessment of uncertainties has been conducted for the calculation of emission data, trying to determine their accuracy e.g. for national reporting obligations etc. Uncertainties of input data have, among others, been investigated by *EPA 1996* or *Winiwarter et al. 2000*. In addition to that, uncertainties in the calculation of emissions from road transport (*Kühlwein et al. 1999, 2000*) and for NMVOC emissions from solvent use (Theloke, *pers. comm.*) have recently been assessed at the Institute for Energy Economics and the Rational Use of Energy (IER), University of Stuttgart. Furthermore, interactions between tropospheric and stratospheric ozone could, in combination with significant reductions of ozone precursor emissions, be of interest (see *Christ et. al. 1996*).

For integrated assessment modelling, *Warren and ApSimon* (1999) have investigated uncertainties of the modelling of abatement strategies recently and determined the main parameters for uncertainties to be from the setting of critical loads, the interannual variability of meteorological data and the included costs curves. However, there are few studies available yet which have conducted in-depth analyses of how uncertainty treatment can be adequately incorporated into assessment models. A first workshop[1] was initiated by the EMEP Centre for Integrated Assessment Modelling (CIAM) at the International Institute of Applied Systems Analysis (IIASA) in January 2002, bringing together researchers and policy makers to discuss vital aspects of uncertainty in integrated assessment modelling and to stimulate further research in this field.

1.h*ttp://www.unece.org/env/tfiam/uncertainty_conclusions.pdf, 30.07.2003*

5 Modelling Results for Tropospheric Ozone

5.1 Cost-effectiveness Analysis

5.1.1 Closing the Gaps towards Ozone Thresholds for Health and Vegetation

In this section, model results are discussed that have been calculated to assess, to what extent ozone thresholds for the protection of human health, crops and ecosystems could be achieved by implementing abatement measures that are currently available. The approach taken for assessment runs follows the concept of 'gap closure', i.e. reducing the distance between current levels of ozone AOT and target levels set for the protection of human health, crops or forests. Gap closures are usually expressed in percentage values, hence a gap closure of for instance 50% indicates reducing the exceedance of a target value by half.

The cost-effectiveness assessment is conducted using the abatement cost curves described in the previous chapter. Early model runs indicated, that a gap closure between 20% and 40% would be feasible with the reduction potential of the available measures, and thus two sets of gap closures were modelled (15% and 33% for human health and forest ecosystems, 15% and 20% for crops). These model results are then taken as a basis for a cost-benefit assessment, comparing abatement costs to avoided damages.

5.1.2 Focus: Human Health

As human health usually presents the most important aspect when dealing with the assessment of air pollution control strategies, the discussion starts with an analysis of two different gap closures for AOT60 (*Fig. 5.1.*).

Based upon the trend scenario for 2010, two gap-closures are analysed, 15% and 33%, reflecting the reduction degree possible with the set of available measures as they have been defined in *Chap. 3*. While the 15% gap closure shows only moderate reduction of AOT60 values, the 33% gap closure displays considerably less exceedances, especially in Southern Europe. In northern Europe, the region between France, Germany, Belgium and The Netherlands in particular, still encounters exceedances of AOT60 between 2 and 3 ppm.h.

5.1.2.1 Focus: Agricultural Crops and Ecosystems

For forest ecosystems and agricultural crops, the AOT40 threshold allows for an exceedance of 10 ppm.h (forests), respectively 3 ppm.h (crops). Furthermore, the period for calculating the AOT40 values is different for crops and forests, covering the respective main vegetation periods, i.e. 3 months from April to June for agricultural crops, and 6 months from April to September for forests. As *Fig. 5.2.* indicates, even at the 33% gap closure thresholds are exceeded considerable in the BeNeLux region and in Italy, while the overall level can be reduced to some extent.

The maps for $AOT40_{crops}$ show exceedances of the threshold in almost all grid cells in the trend scenario. And even though the 15% gap closure shows significantly lower values, it becomes obvious, that compliance with this threshold will be extremely difficult to achieve (see *Sect. 5.2.1*). In addition to that, with applying all abatement measures included in the cost curves, a 33% gap closure could not be achieved at all, the maximum gap closed amounted to about 20%

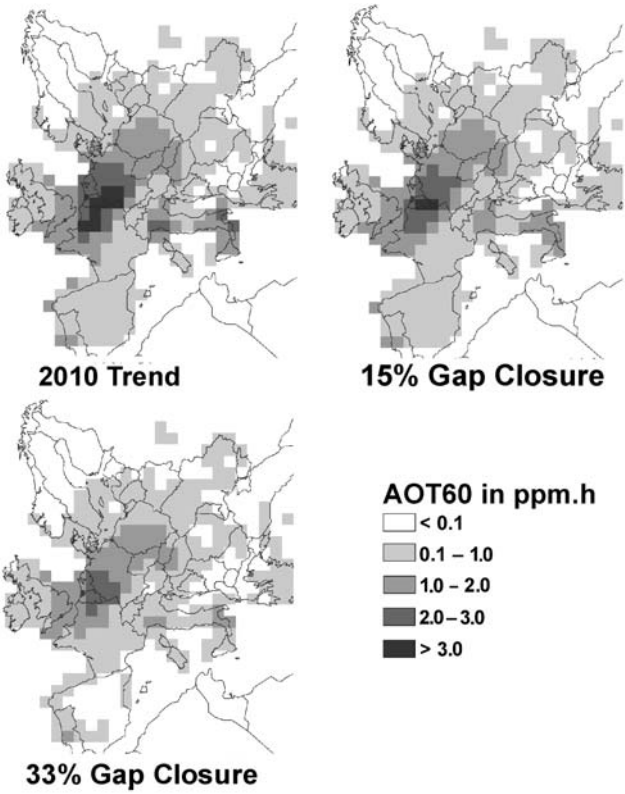

Fig. 5.1. Assessment of ozone abatement strategies to achieve gap closures of AOT60

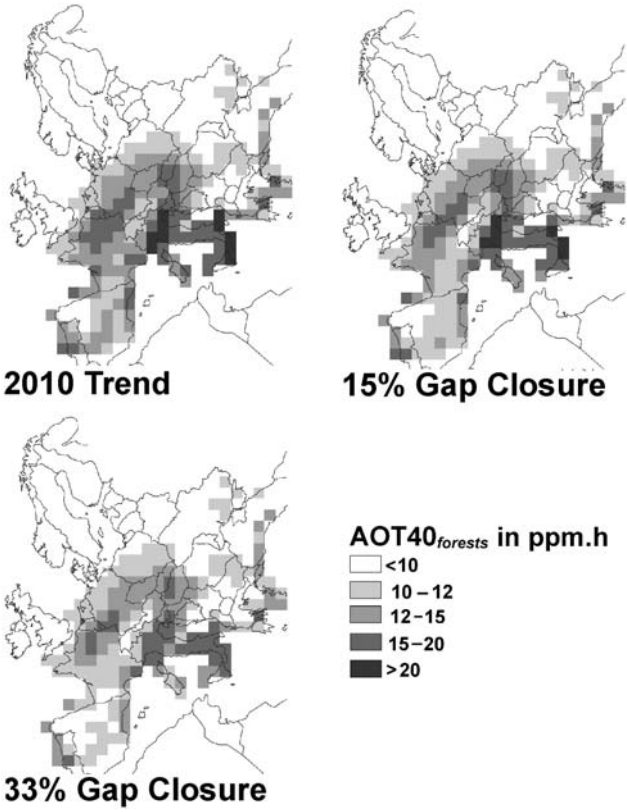

Fig. 5.2. Assessment of ozone abatement strategies to achieve gap closures of AOT40 for forests (10 ppm.h indicate the allowed exceedance of 40 ppb for forests)

These gap closure scenarios have been modelled to conduct a cost-benefit analysis. The targets have been selected in a way, that the emission reductions could be achieved with the measures available and the countries would not reach the extreme regions of their cost curves, where each additional tonne of pollutant abated could lead to exponentially higher costs. The costs and (monetary) benefits of these scenarios are evaluated in the following *Sect. 5.1.2*. comparing abatement costs with avoided damages due to reduced ozone levels. *Table 5.1.* gives an overview on the resulting emissions of ozone precursors and the total abatement costs for all 15 EU countries for the three scenarios discussed above..

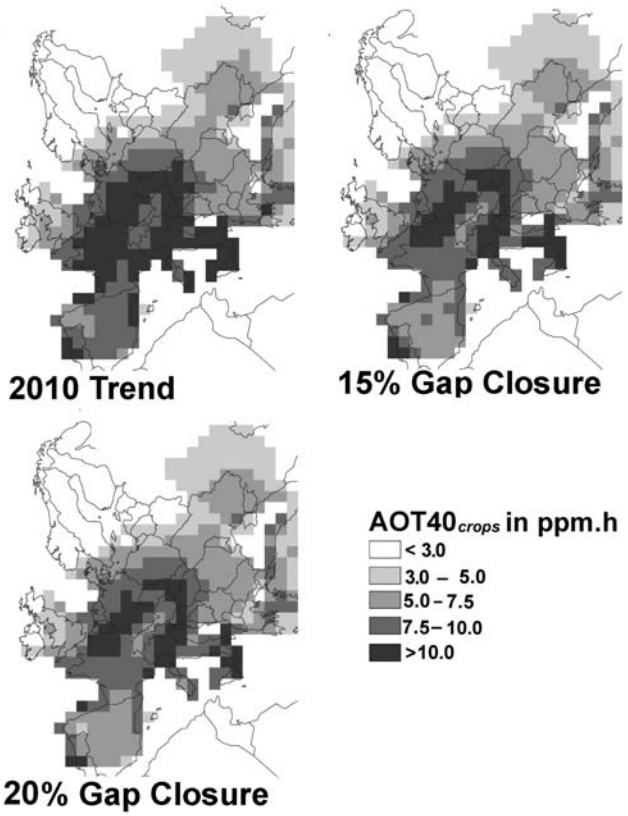

Fig. 5.3. Assessment of ozone abatement strategies to achieve gap closures of AOT40 for crops (3 ppm.h indicate the allowed exceedance of 40 ppb for agricultural crops)

Table 5.1. Total abatement costs and emission reductions for selected scenarios for the EU15

	Target ***(Gap Closure)***	**Total abatement costs**	**Emissions** ***(in Million tonnes)***		**Reduction** ***(from to Trend 2010)***	
Threshold			**NO_x**	**NMVOC**	**NO_x**	**NMVOC**
AOT60	33%	39.5 bill. €	7.13	7.54	-25%	-18%
AOT40 ***crops***	15%	16.6 bill. €	7.46	8.40	-22%	-8%
AOT40 ***forests***	33%	9.14 bill. €	7.87	8.59	-17%	-6%

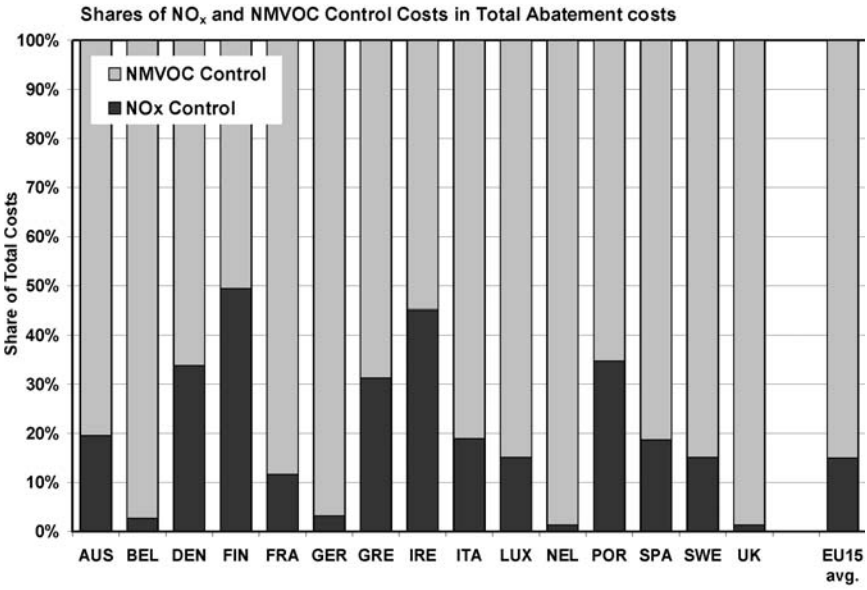

Fig. 5.4. Share of NO_x and NMVOC abatement costs in total abatement costs for the AOT60 33% Gap Closure Scenario by country and as an EU15 average

To achieve the 33% gap closure for AOT60 proves to be the most costly scenario and requires significant emission reductions on top of the trend scenario. Thus, this scenario shall now be evaluated in terms of the costs it imposes on the EU countries, as well as the benefits (i.e. avoided damage costs) each country experiences. *Fig. 5.4.* shows, that one the one hand NMVOC emission control is on average more expensive than NO_x abatement. In addition to that, it indicates that countries like Belgium, Germany, the Netherlands and the UK face even lower control costs for NO_x abatement, as they are required to reduce their NO_x emissions only moderately to achieve the 33% gap closure of AOT60, hence staying in the low-cost region of their abatement cost curves.

5.1.3 Discussing costs and benefits for EU Member States

Abatement costs and avoided damage costs due to reduced ozone levels do vary significantly between countries, partly because their starting points for emission reductions (and hence their unit costs) are different and partly because of the different impacts and reductions of ozone concentrations they experience.

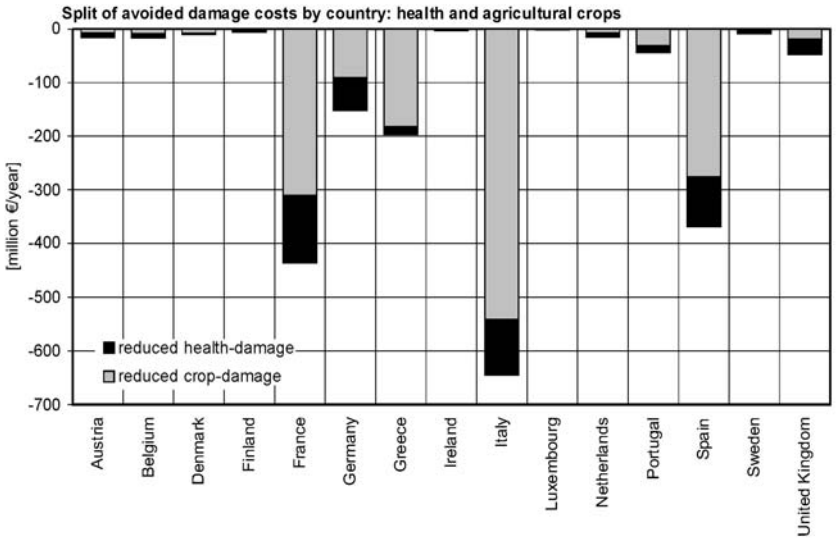

Fig. 5.5. Detailed split of avoided damage costs from direct ozone impacts in health and crop damages per country

Fig. 5.5. shows the avoided damage costs for each country, calculated with ECOSENSE split into health impacts and reduced losses of agricultural crops. At the time being, there is no monetary evaluation of damages or avoided damages to forest ecosystems (*ExternE 1999*). Ozone damages to materials have not been accounted for as well, as they can be assumed to be negligible (*Rabl and Eyre 1998*, *Rabl 1999* and *Rabl and Spadaro 1999*). As *Fig. 5.5.* indicates, the major part of the benefits arises from reduced crop losses, while health impacts seem to be significantly lower. A major reason for this is that high ozone concentrations mostly lead to morbidity effects (see *Chap. 2*), which are represented by comparatively low monetary values. The regional distribution shows that the southern European countries benefit by far most, with Italy, France, Greece and Spain amounting to more then 75% of all avoided damage costs.

Comparing the benefits with the costs for each country (*Fig. 5.6.*) it becomes obvious, that the distribution of benefits and costs is not homogeneous. Germany and the UK, for example, face rather high abatement costs, while their benefits are quite low. These imbalances and the thus arising need to distribute the burdens to harmonize them among the EU member states have been discussed in detail in *Friedrich and Reis* (2000). However, a brief discussion and analysis will be conducted later in this chapter.

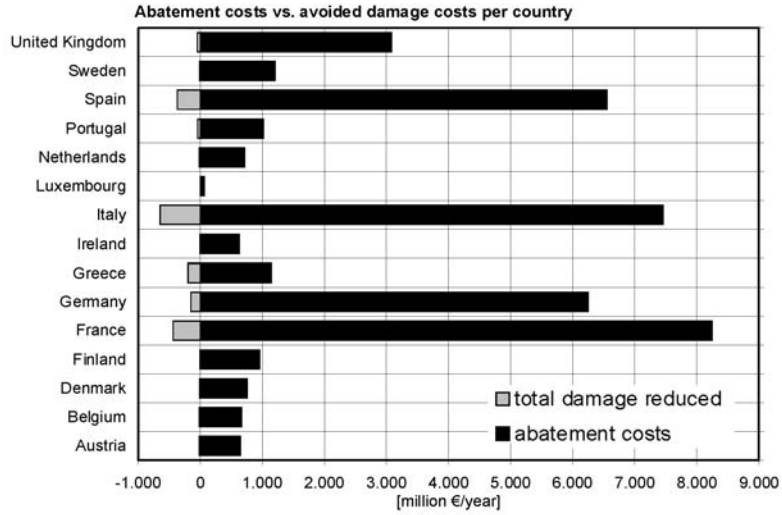

Fig. 5.6. Abatement costs vs. avoided damage costs per country

It can also be seen from the comparison of abatement costs and avoided damage costs (i.e. benefits) in *Fig. 5.6.*, that the costs outweigh the benefits for this approach by far. This is partly, because the actual damages from ozone, in monetary terms, either on human health and on agricultural crops are rather low compared to those caused by other air pollutants. Within the research on *Externalities of Energy* (*ExternE 1999*), a number of air pollutants have been assessed in terms of the damages they cause, and as *Table 5.2.* indicates, the damage costs per tonne of pollutant emitted can be several times higher for SO_2 or particulate matter

Table 5.2. Exemplary comparison of damage costs for different air pollutants for the UK

Pollutant	**Statistics used**	**€ / t of pollutant**
SO_2	YOLL[a] *(VSL[b])*	6 027 *(195 600)*
NO_x	YOLL *(VSL)*	7 580 *(25 549)*
PM_{10}	YOLL (VSL)	8 000 *(27 140)*
NO_x (via ozone)		1 500
CO_2		3.8 – 139

a. YOLL = mortality impacts based on 'years of life lost' approach
b. VSL = impacts evaluated base on 'value of statistical life' approach
Source: ExternE 1999

On the basis of these results, ozone abatement would, from a cost-benefit assessment, not be efficient at all, in particular, since abatement costs exceed the monetary benefits by far. However, as the following results indicate, a more general approach does significantly improve the ratio between costs and benefits of ozone abatement.

Within this study, the reduction of emissions of NO_x and NMVOC was taken into account only, omitting for instance the simultaneous reduction of other pollutants by implementing air pollution control measures (e.g. the three-way catalyst removing CO, NMVOC and NO_x). This already leads to an underestimation of the benefits. In addition to that, the initial assessment of avoided damage costs only takes into account direct impacts from ozone on health, crops and ecosystems. By extending this approach towards a total assessment of avoided damage costs using ECOSENSE, the resulting benefits are considerably higher, as impacts of reduced concentrations of other secondary pollutants, e.g. aerosols and suchlike, are accounted for as well.

Fig. 5.7. gives an overview on total benefits, i.e. all avoided damage costs from reduced emissions of NO_x and NMVOC in this case, for the EU15, not taking into account benefits outside of these countries yet. Comparing these figures with the results for ozone related damages only as they have been displayed in *Fig. 5.5.*, it is remarkable, that the overall benefits are considerably higher and even though they do not completely outweigh the abatement costs for the specific gap closure scenarios, the difference between costs and benefits is not too large.

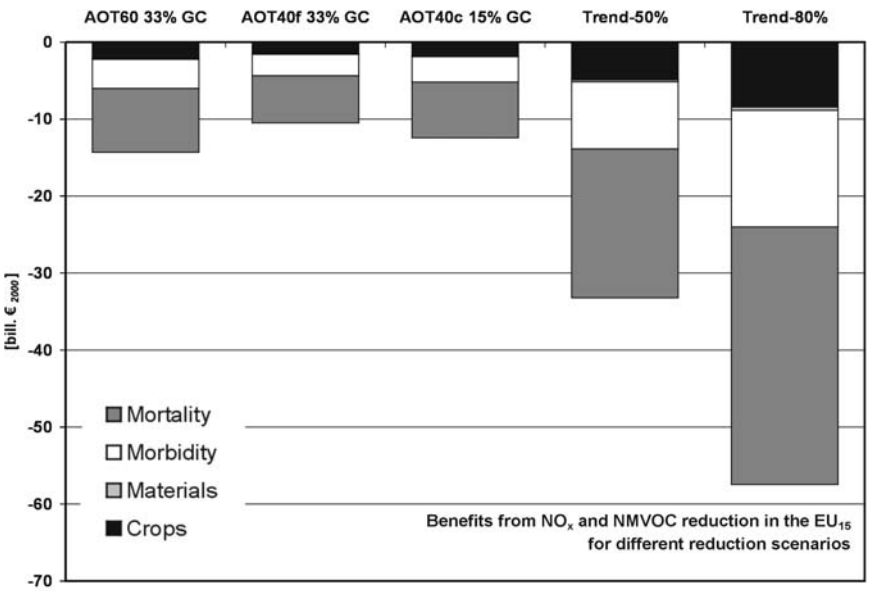

Fig. 5.7. Overview of benefits (as avoided damage costs) in EU15 countries for different scenarios

The main reason for this significant difference is the reduction of aerosols due to reduced NO_x emissions which again result in extended life expectancy and fewer cases of bronchitis due to a reduced exposure to PM10 (e.g. Ammonium Nitrate NH_4NO_3).

The following *Fig. 5.8.* shows benefits vs. abatement costs per country, indicating that in most cases, countries which face comparatively high abatement costs do gain significant benefits as well. Some exceptions can be identified, however, such as the UK, Sweden, Ireland and Finland, where benefits are small, or almost negligible. Still, the five largest emitters account for about 85% of the total benefits.

A fact that should not be neglected either is that due to transboundary transport of air pollutants, emission reductions within the EU15 affects the neighbouring countries as well. As it is indicated in *Fig. 5.9.*, some countries in Central and Eastern Europe, which have been taken into account in particular because of the accession process to the European Union, would experience considerable benefits, up to about 0.5 bill. € in the case of Poland. In addition to these effects in the accession countries, other European countries would further benefit from emission reductions of EU15 countries, and *Fig. 5.11.* summarises and compares the benefits calculated for the EU15 to the overall benefits of each scenario. On average, the EU15 benefits account for about 85% of the total benefits.

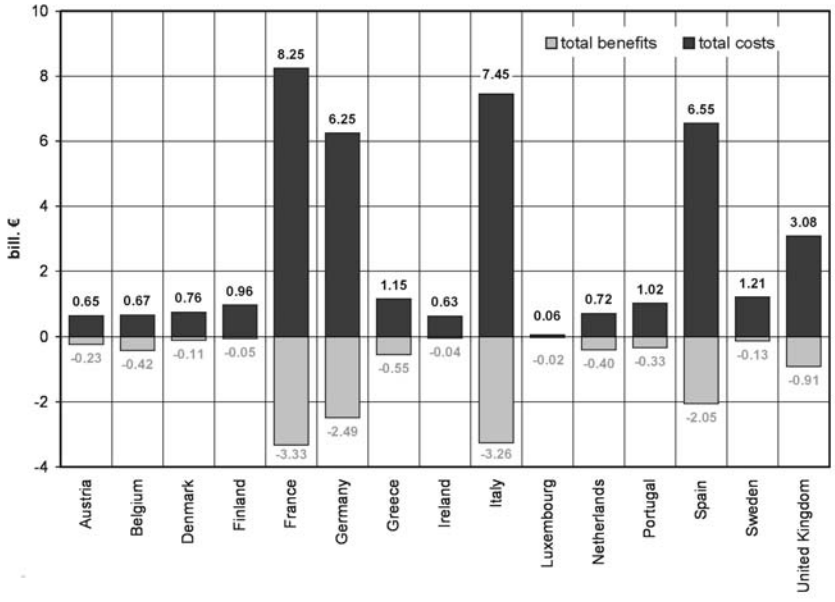

Fig. 5.8. Total benefits in EU15 countries for the AOT60-33% gap closure scenario compared to abatement costs

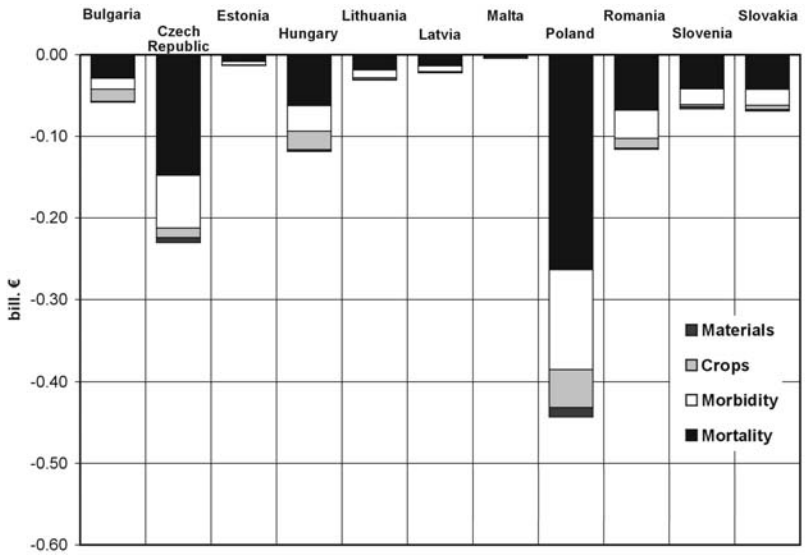

Fig. 5.9. Total benefits from reducing NO_x and NMVOC in the EU15 in the AOT60-33% gap closure scenario in selected Accession Countries in Central and Eastern Europe

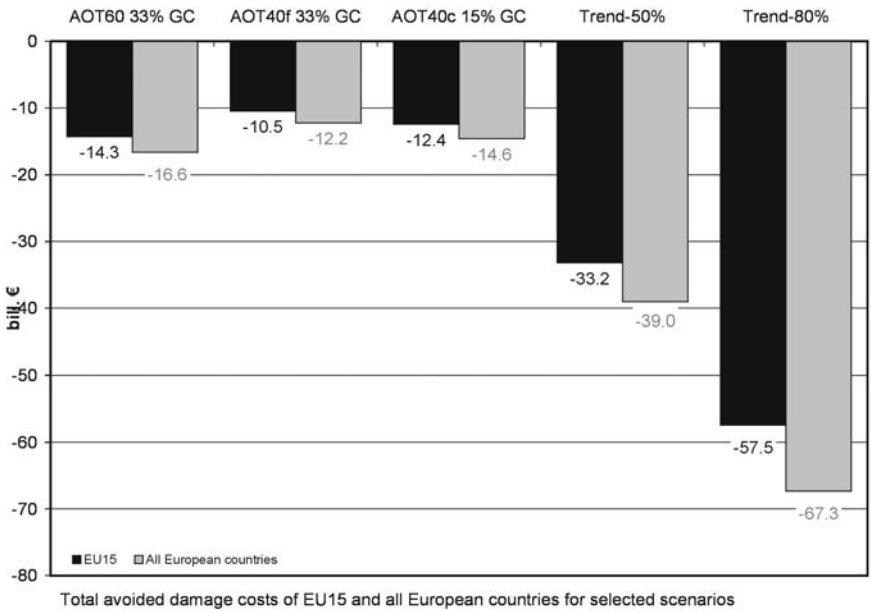

Fig. 5.10. Comparing total avoided damage costs in the EU15 countries and all European countries

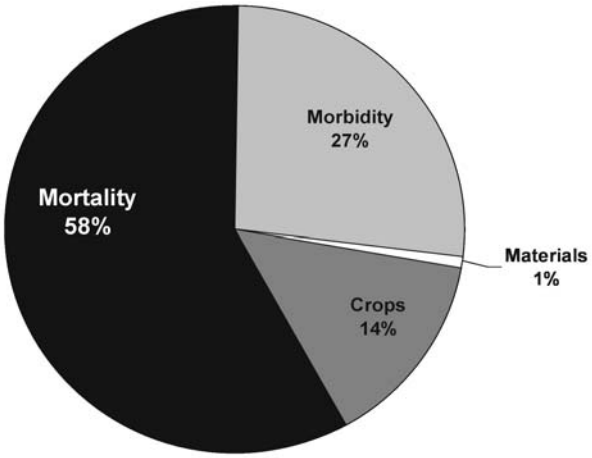

Fig. 5.11. Shares of impact categories for all avoided damage costs due to NO_x and NMVOC reduction, including ozone and other impacts

Finally, it is important to take a closer look at the composition of these calculated benefits, since, as it was indicated in *Table 5.2.*, different approaches for the assessment of health impacts might lead to considerable variations in costs. *Fig. 5.11.* shows, that only about 15% of the avoided damage costs in the EU15 are related to crop yield and materials. The lion's share of damages is health related, either addressing morbidity impacts, or increased mortality risks. It has to be stated, that uncertainties in this field are significant, however, the ECOSENSE model used for these calculations does take into account the state-of-the-art of research findings in this field.

5.1.4 Analysing the Distribution of Burdens and Benefits

To be able to improve the analysis of the distribution of costs and benefits, *Fig. 5.12.* gives the relation in total numbers. A more detailed assessment of the small countries in the grey box is displayed in *Fig. 5.13.*. While the UK faces both low costs and low benefits, the difference between a country like Germany and Italy on the other hand is considerable.

The situation for the smaller European countries is displayed in *Fig. 5.13.*, showing Greece as a definite winner in comparison to the other countries with high total benefits at similar costs compared to e.g. Portugal or Sweden. The previous figures give a first idea about how differently costs and benefits are distributed among countries, but they do not reflect the actual economic impact both abatement costs and avoided damage costs would have on each country.

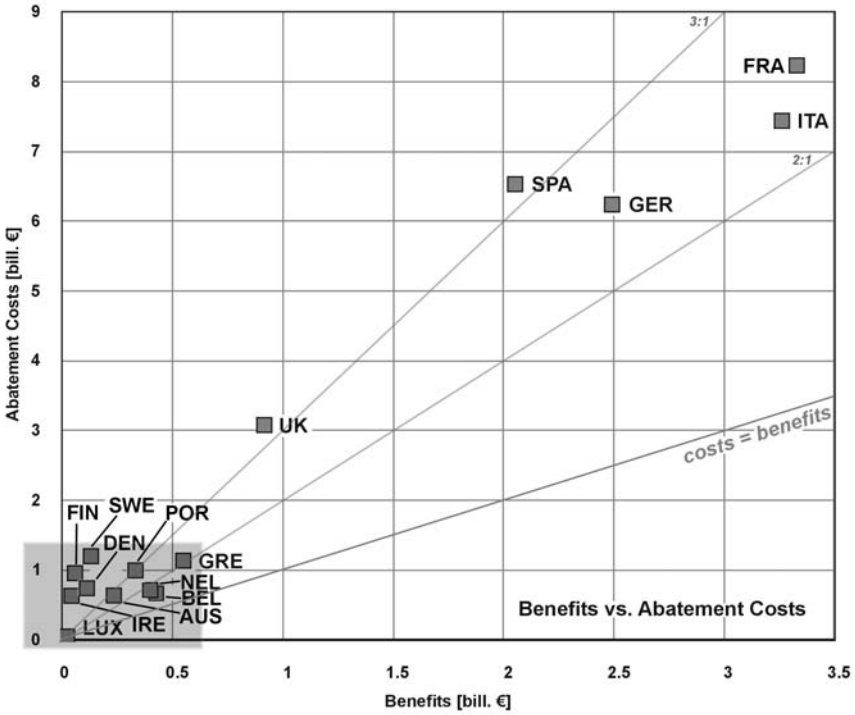

Fig. 5.12. Comparing Abatement Costs and Avoided Damage Costs per country

To this end, both abatement costs and avoided damage costs have been set in relation to the countries' projected GDP in the investigation year 2010. *Fig. 5.14.* shows the cost-benefit ratio in relative terms for those countries with the highest ratio, all southern European countries interestingly. The same is given for the remaining countries in showing significantly smaller relative benefits than the previous ones. *Fig. 5.14.* clearly indicates, that Greece and Spain would have to spend a significant share of their GDP (about 1%). This shows, how important the design of a workable burden sharing mechanism would be, in order to alleviate the imbalances imposed on countries with less economic power, for instance (see as well *Brekke and Dreze, 1998*).

The fact that benefits from reducing ground level ozone concentrations are still smaller than the related costs does lead to the conclusion, that from a single-pollutant view on cost-benefit terms, ozone abatement is not 'beneficial'. However, within a multi-pollutant assessment, taking into account synergy effects and hidden benefits of simultaneous reduction of other pollutants, this is likely to be reversed.

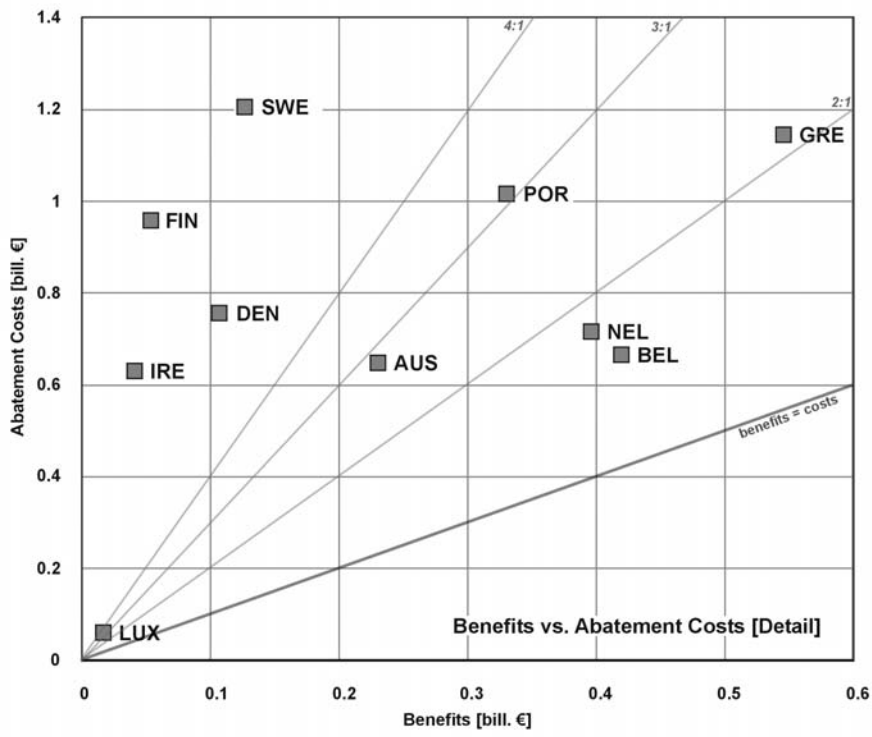

Fig. 5.13. Comparing Abatement Costs and Avoided Damage Costs per country (*detail from Fig. 5.12.*)

In order to put the order of magnitude of abatement costs relative to GDP into perspective: the total government spending for air pollution control in Germany in 2000 amounted to about 0.0021% of GDP. At the same time, latest research findings of the UNITE[1] project estimates external costs caused by transport of up to 2% of total EU GDP.

1.http://www.its.leeds.ac.uk/projects/unite/, 15.07.2004

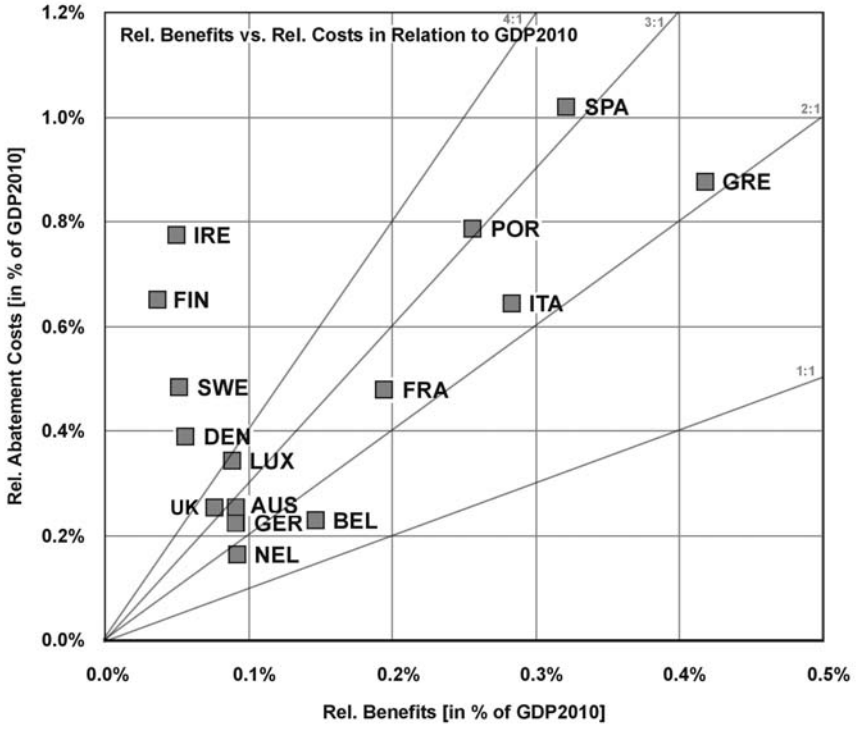

Fig. 5.14. Cost-benefit-ratio for the AOT60 33% Gap Closure scenario relative to GDP_{2010}

5.1.4.1 The Need for Burden Sharing for European Air Pollution Control Strategies

The results presented here give clear evidence about the in some cases significant differences between countries' burdens (i.e. costs of reducing emissions) and benefits (i.e. reduced damage costs). Thus, in order not distort the economic structure within the European Community, and even more in order not to overly burden countries with comparatively lower economic ability, the implementation of a burden sharing mechanism should be included in any air pollution control strategy, which will likely impose considerable additional costs to specific EU Member States. The theory and possible applications of burden sharing in the case of ozone abatement strategies have been thoroughly investigated in *Friedrich and Reis* (2000) and shall not be discussed in detail here.

However, as a general recommendation for the design of air pollution control strategies, the assessment of benefits and costs, along with the consideration of the economic ability of countries to bear the occurring abatement costs should be con-

sidered a vital and obligatory instrument. In this respect, the base principles of „polluter pays“, „beneficiary pays“or „ability to pay“ discussed in the frame of environmental policy application can only be guidelines to start with, as the political design of the European Community imposes restrictions that have to be taken into account. As any air pollution control strategy, which will burden some countries more than others is not likely to stand a chance to be adopted – either by unanimous voting, or the qualified voting approaches taken recently – the design of the strategy needs to be balanced with the aim to be acceptable for all Member States. This will become of even greater importance with the accession process, as the increasing number of countries and the specific circumstances of the Central and Easter European economies will make it more difficult to reach a common basis. Finally, as was stated before, there are secondary benefits, that have not been taken into account for in this study, such as other pollutants being reduced as well by implementing measures to reduce NO_x and NMVOC emissions. Such side benefits could be considerable and should be accounted for in the design of a burden sharing mechanism to make sure, that the mechanism itself does not lead to imbalances (cf. *Ekins 1996*).

5.2 Additional Emission Reductions

5.2.1 Which Ozone Levels can be Achieved

As the analysis in *Sect. 5.1* has indicated, moderate reductions of ozone precursors on top of the trend scenario only lead to a slight improvement of modelled ozone concentrations. Compliance with either the AOT60 or the AOT40 thresholds could not be achieved for all modelled grid cells. Thus, in a next step, the OMEGA-O_3 model was applied with a different setting, using generic cost curves which would allow even a complete emission reduction to determine, to what extent reductions of anthropogenic emissions of ozone precursors could reduce ozone levels at all. The results of this section were then used to set more ambitious goals for emission reductions, which would most likely result in compliance with thresholds and limit values, and additionally to assess, if some thresholds and limit values would be achievable at all.

5.2.1.1 Focus: Human Health

The following *Fig. 5.15.* displays gap closures achieved by additional reductions of precursor emissions for each 20% step, up to a maximum where about 90% of the initial amount of ozone has been abated. The maps show a remaining pattern of exceedances over Central and Eastern Europe, as only emission reductions in EU15 countries have been modelled.

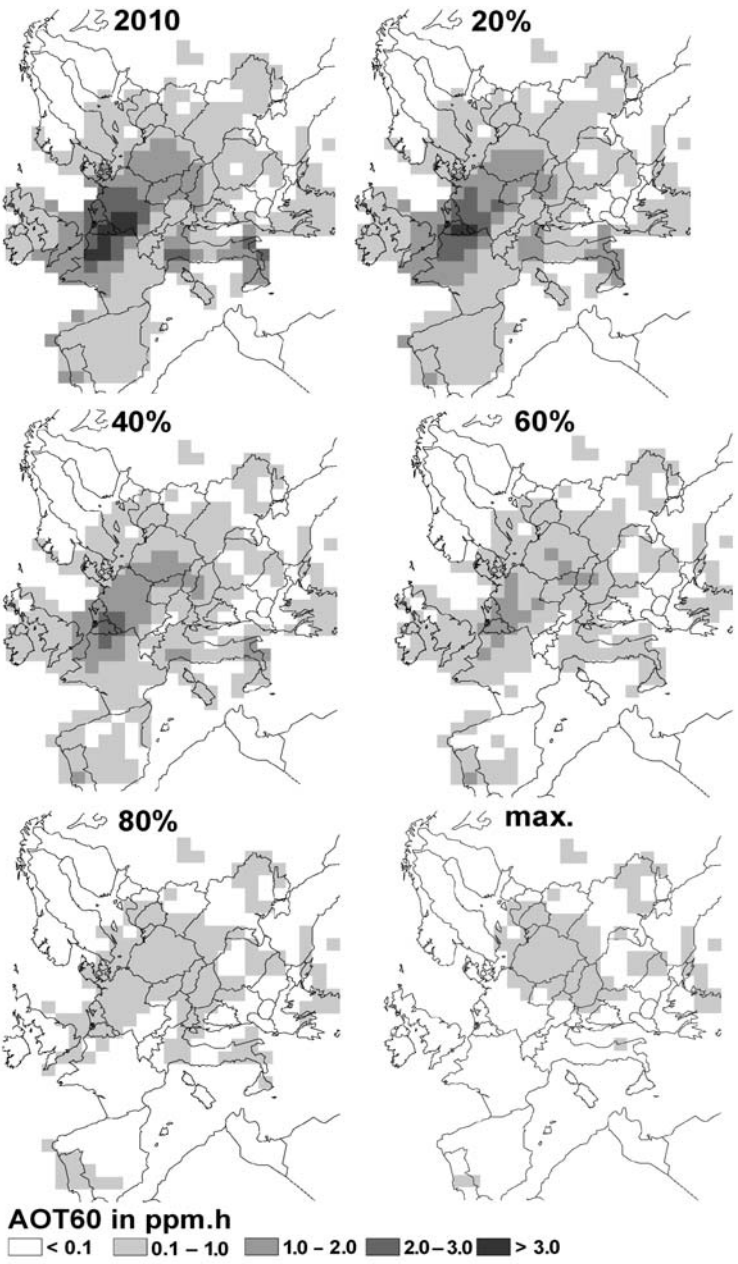

Fig. 5.15. Assessment of feasible reductions of ozone levels for AOT60 at different gap closures

If Central and Eastern European countries would be included in the modelling, these exceedances would most probably disappear and it is very likely, that the emission reductions needed to achieve preset gap closures would be less stringent, in particular for Germany and Austria. *Fig. 5.16.* displays the emission reductions associated with each gap closure given in *Fig. 5.15.*, starting from about 9 megatonnes in the trend scenario.

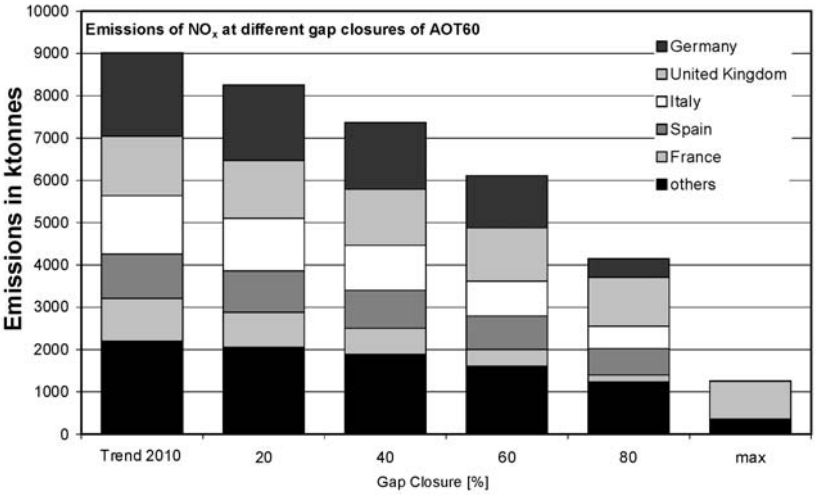

Fig. 5.16. NO_x emissions for each gap closure as displayed in *Fig. 5.15.*

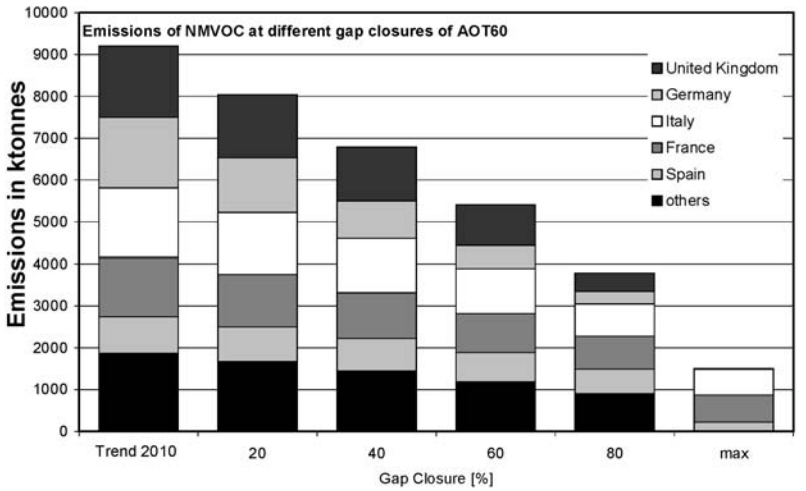

Fig. 5.17. NMVOC emissions for each gap closure as displayed in *Fig. 5.15.*

As the figures above indicate, a 50% reduction of emissions would result in approximately 75% Gap Closure for AOT60, which shall serve as an interim target for the later evaluation of long term reduction targets. Furthermore, the maximum gap closure is achieved at approx. 80% emission reduction, thus setting this reduction target as the ultimate goal for the analysis of future targets.

5.2.1.2 Focus: Agricultural Crops and Forest Ecosystems

As it has been briefly mentioned above, the threshold of AOT40 for crops is considerably more difficult to achieve than the one for forest ecosystems. This is partly because of allowing an exceedance of 10 ppm.h in the case of forests, as it can be seen in *Fig. 5.19.*, that even at moderate gap closures exceedances of 10 ppm.h are reduced to zero. *Fig. 5.18.* displays different gap closures calculated for $AOT40_{forests}$, with a possible reduction of ozone levels to up to 97% of the initial exceedances.

However, to achieve this, anthropogenic emissions of NMVOC would have to be reduced to almost zero, while NO_x emission reductions would be beyond 90% compared with the trend scenario as well. The situation for $AOT40_{crops}$ as it shows in *Fig. 5.19.* might raise serious doubts, if this threshold can be achieved at all. With a maximum reduction of ozone levels by about 68% from the initial level in the trend scenario, a total of 263 grid cells still show exceedances of the threshold. It has to be stated, though, that the $AOT40_{crops}$ is extremely sensitive to meteorology variations and even given an identical emission situation, the ozone levels could be completely different in two consecutive years. A detailed evaluation of the thresholds will be conducted in *Sect. 5.3*.

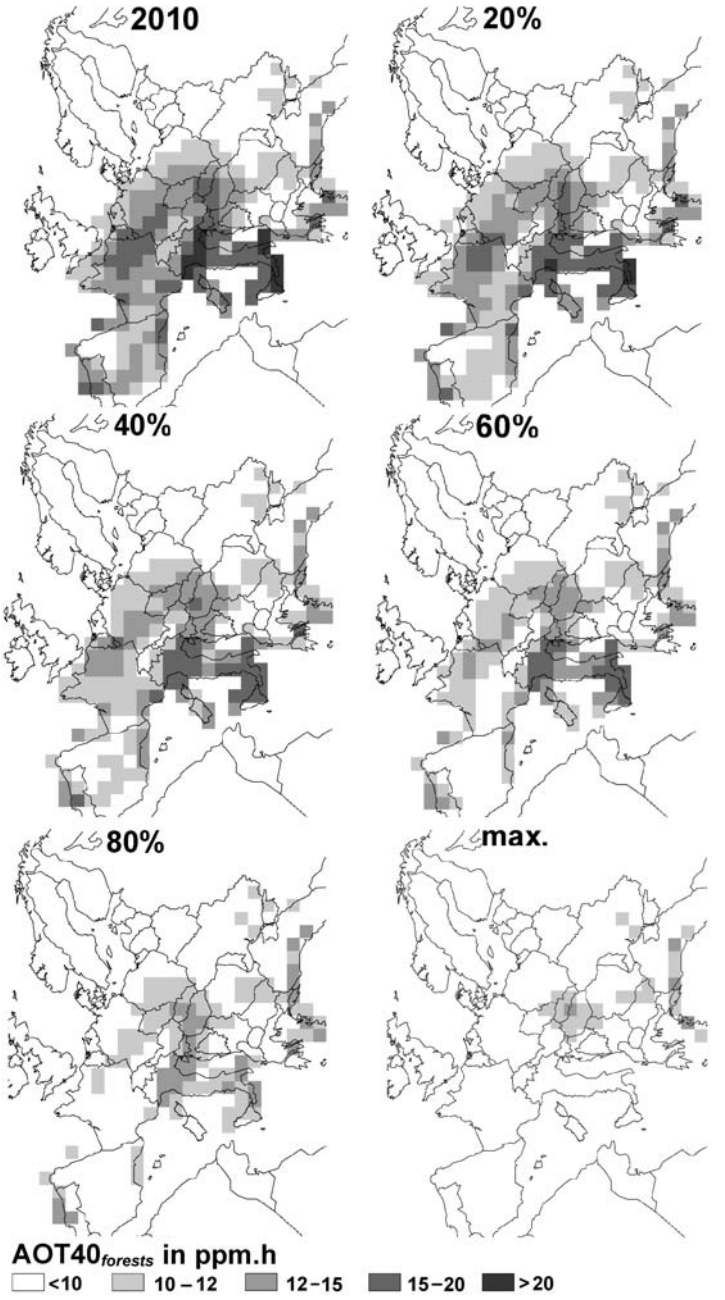

Fig. 5.18. Assessment of possible reductions of ozone levels for AOT40 for forests

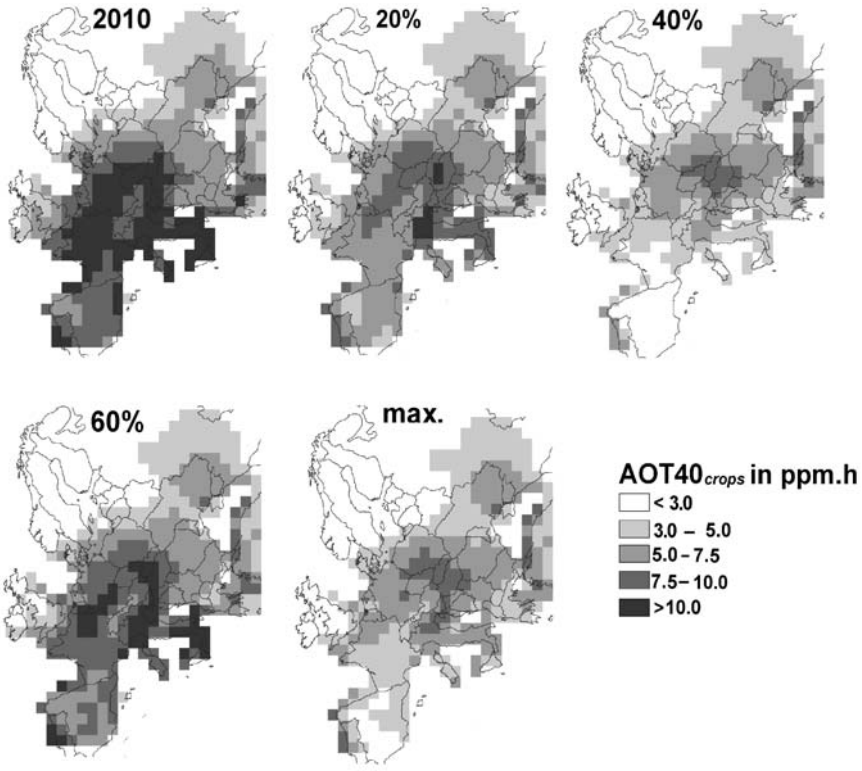

Fig. 5.19. Assessment of possible reductions of ozone levels for AOT40 for crops

5.2.2 Assessing the Regional Variability of Reduction Options

Another interesting question is in how far different countries or regions contribute to the overall ozone production in Europe. *Fig. 5.20.* displays a set of model calculations conducted to evaluate different emission sets for AOT60. In the *„Big5"*-case, the emissions of the five largest emitters (Germany, France, UK, Italy and Spain) have been reduced as far as possible, showing a significant reduction of the peaks in the central and western parts, but with remaining moderate exceedances over most of Europe. But, the comparison with the *EU15*-case shows, that the resulting concentrations are only marginally different, showing the five largest emitters are the main drivers for ozone formation over Europe. The assessments of emission reductions in northern or southern European countries have been added to show the regional influence, as the *Northern*-case (Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Luxembourg, The Netherlands, Sweden, UK) clearly indicates the emission drift to the south and the east, reducing the concentrations within

the countries that reduce emissions as well as slightly in the south.

The *Southern*-case[1], however, does not show any influence on the concentrations in Northern Europe, while a significant reduction is achieved in Italy, Spain and Greece. These calculations give an impression about the regional aspect of precursor emissions, transboundary transport and to some extent, the local scale impact of emission reductions as well.

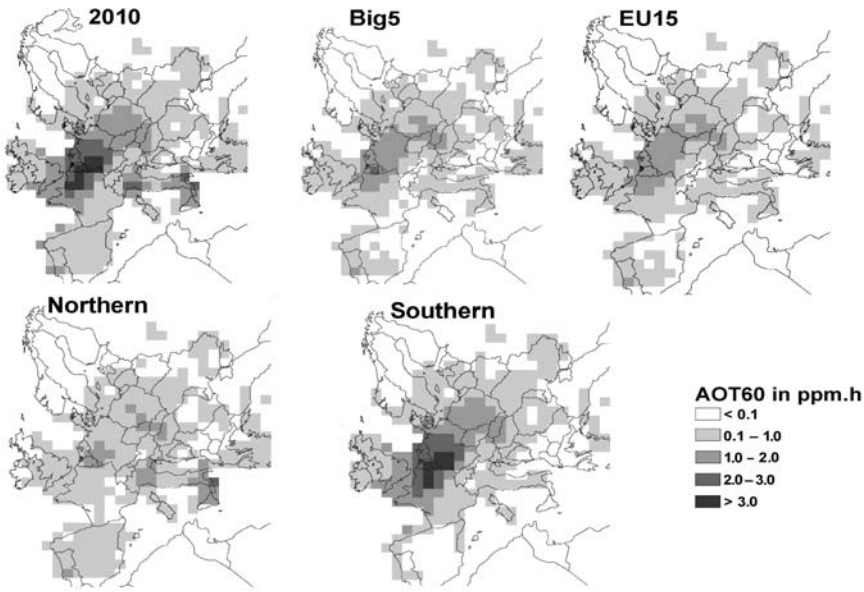

Fig. 5.20. Sensitivity calculations – emission reductions in different regions and the resulting modelled health related ozone values (AOT60)

5.2.3 Deriving Emission Targets for Europe

The modelling results of the previous sections have clearly given evidence, that neither the trend development until 2010, nor the recently adopted NEC Directive will likely lead to a sufficient reduction of ozone levels over Europe. But, as additional model runs have shown, more stringent reduction targets could well lead to a significant reduction of ozone concentrations, even possibly achieving thresholds for health and forest ecosystems. *Fig. 5.21.* shows AOT60 values for three different emission scenarios, the NEC Directive's proposed emission ceilings as well as a

1. Greece, Italy, Portugal, Spain

50% and a 80% reduction of emissions relative to the trend scenario for 2010. The 50% and 80% reduction have been set as a result of the analysis of the previous section, with the target of 50% reduction from the trend scenario emissions as an intermediate goal, and an 80% reduction from the trend as an ultimate goal to reduce ozone concentrations significantly below harmful levels. These targets do not reflect an uniform emission reduction in all countries, in fact, NO_x emission reductions would range between 10% and 80% for specific countries, with corresponding NMVOC emission reductions between 17% and 81%.

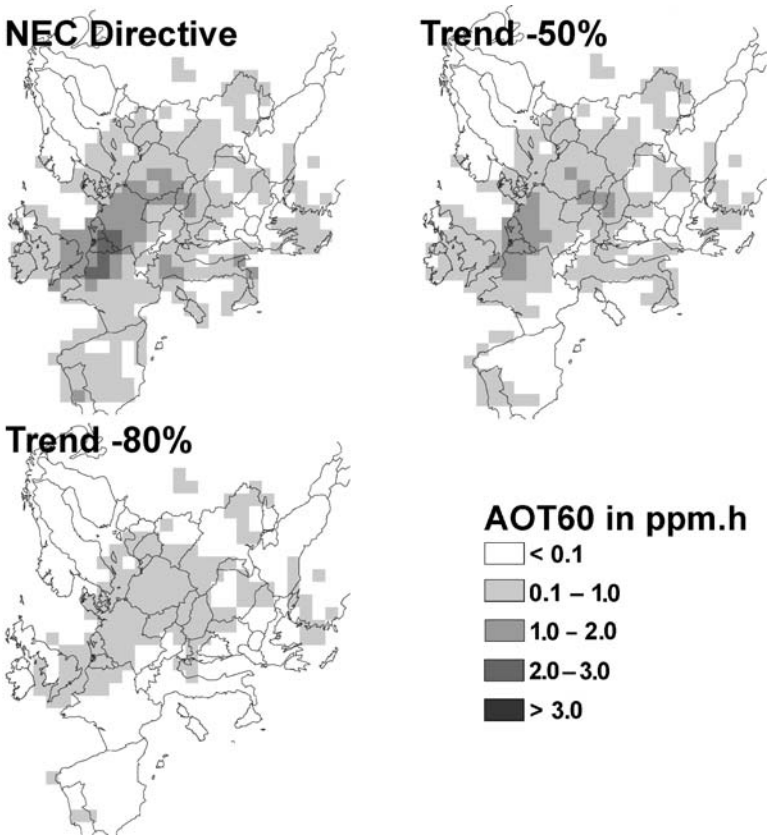

Fig. 5.21. AOT60 levels for a 50% and 80% reduction of emissions from the trend scenario in relation to ozone thresholds due to the EC National Emission Ceilings Directive (NEC Directive)

In terms of gap closure, the *Trend-50* Scenario reflects a 75% Gap Closure for the health related AOT60 threshold, while the *Trend-80* Scenario would achieve an 90% Gap Closure for the same threshold. This already indicates, that a significant improvement of the ozone situation could be achieved by reaching this intermediate goal, while reducing ozone levels below a certain level, here a 90% Gap Closure for AOT60, would require quite stringent abatement strategies.

While a 50% reduction of NO_x and NMVOCs results in a considerable reduction of ozone levels, even at 80% the AOT60 threshold will not be achieved completely. However, the regional distribution of the remaining exceedances indicates – as has been confirmed by further model assessment – that a significant contribution comes from Central and Eastern European countries, Poland and the Czech Republic in particular, which have not been included into the further reductions. It is very likely, that should these countries reduce their emissions beyond their current reductions plans in the process of their integration into the European Community, full compliance with AOT60 could be possible in most of the grid cells.

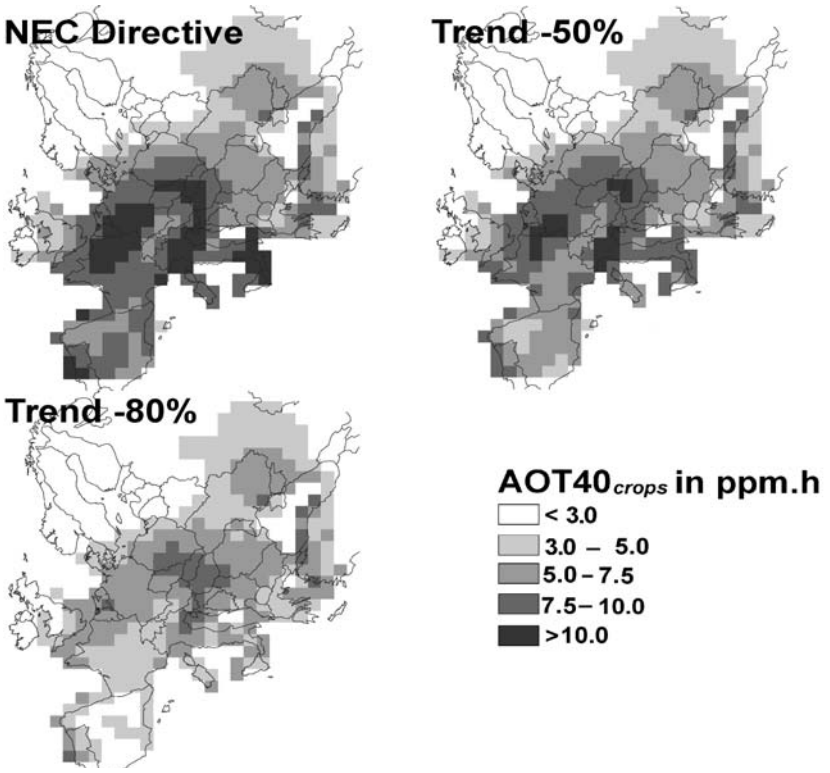

Fig. 5.22. $AOT40_{crops}$ levels for a 50% and 80% reduction of emissions from the trend scenario

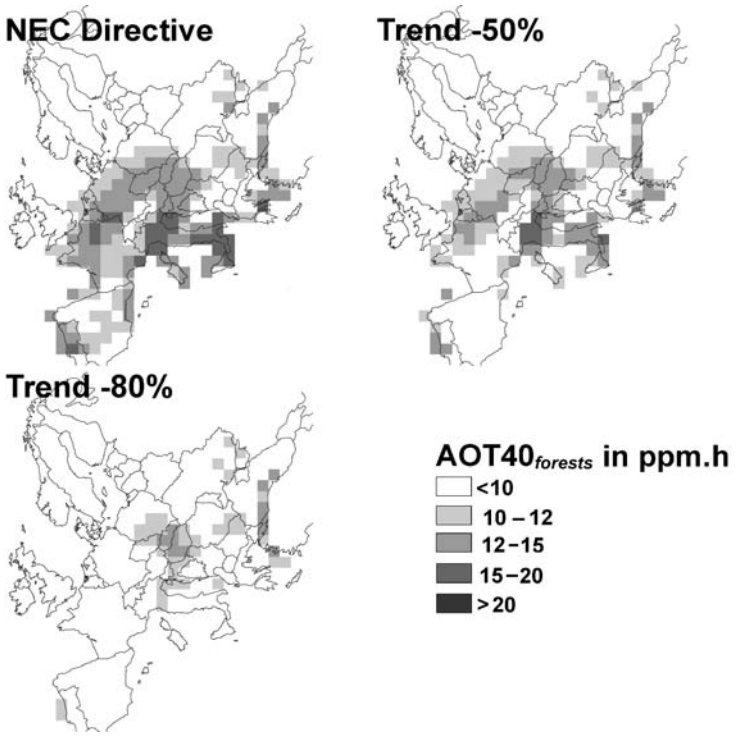

Fig. 5.23. AOT40$_{forests}$ levels for a 50% and 80% reduction of emissions from the trend scenario

Still, as *Fig. 5.22.* indicates, it seems that the AOT40 threshold for crops is not likely to be reached by any means, as far as the model results can tell. Even when reducing emissions of ozone precursors by 80% from the trend scenario, which reflects an extremely difficult target to reach, the critical levels of 3 ppm.h are exceeded in the vast majority of grid cells all over Europe, with the peak concentrations being modelled for central to southern countries.

Finally, *Fig. 5.23.* displays the results for AOT40 for forests, where at an 80% reduction of precursor emissions, thresholds could be achieved in the major part of Europe. Here, too, some remaining exceedances can be attributed to emissions from Central and Eastern European countries not being reduced beyond their current reduction plans. Evaluating the impact of a 50%, respectively a 80% reduction of emissions not only on the regional distribution and occurrence of exceedances, but on the actual reduction of ozone concentrations in total. *Fig. 5.24.* gives an overview on the remaining concentrations for each reduction set.

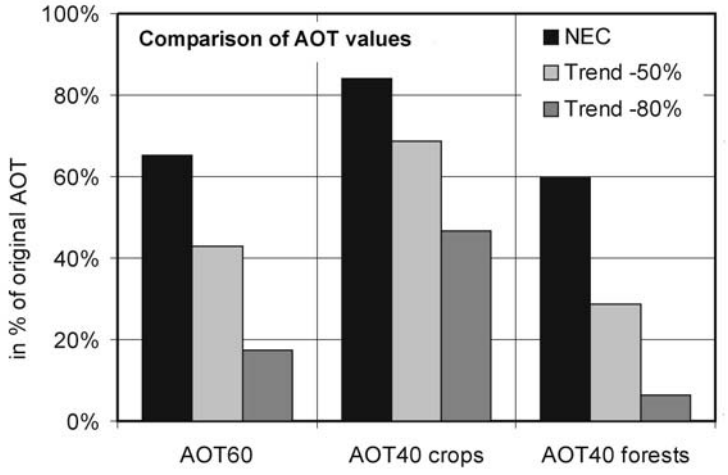

Fig. 5.24. Resulting AOT values for different emission reductions (Trend 2010 = 100)

5.3 Ozone Thresholds and Limit Values

5.3.1 The EC Ozone Daughter Directive

The EC Daughter Directive on *Air Pollution by Tropospheric Ozone* (replacing Directive 92/72/EEC) to the Air Quality Framework Directive, sets a target value for the protection of human health of 120 μg/m³, which shall not be exceeded on more than 25 days per year (averaged over 3 years). With this target, the European Commission tries to reduce adverse health effects of ozone exposure to some degree, but this limit value does not reflect a level at which no adverse effects on human health or even crops or ecosystems could be expected. Recent findings of WHO even indicate that there is no robust evidence to set any threshold for human health related to the exposure to ground level ozone, hence postulating an indicator counting all ozone exceedances of 35 ppb (assumed to be the background concentration over Europe) called SOMO35 (sum of means over 35 ppb) instead. The Daughter Directive is going to be reviewed in the frame of the CAFE strategy and it is likely that more stringent limit values will be determined as research on effects of ozone exposure is still ongoing. However, *Fig. 5.25.* displays an assessment of compliance with the requirements of the Ozone Daughter Directive, plotting the days in exceedance of the target value of 120 μg/m³ (calculated as 60 ppb) for the base case of the year 1990, the trend scenario for 2010 and the reduction case achieving a 33% gap closure of AOT60 which has been used in the cost-benefit assessment before.

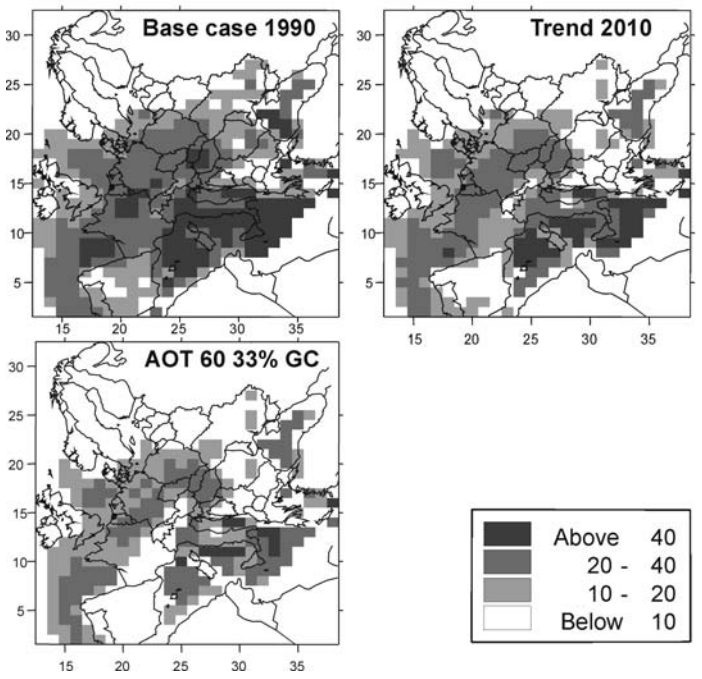

Fig. 5.25. Modelled days in exceedance of 60 ppb (~120 μg/m_3) for different emission sets

A significant improvement of the situation from 1990 to 2010, and even more with the additional reductions of the gap closure case can be seen for most of Europe, even though exceedances between 20 and 40 days are still registered in the western European countries. Hence, at this stage, the investigation of further reduction options to achieve compliance with the EC Ozone Daughter Directive has to be conducted (see *Sect. 6.1.2*). With the variability due to changes in meteorology, it is rather difficult to assess compliance with the 25 days of exceedance set in the Daughter Directive.

5.3.2 Assessing the Potential of the National Emission Ceilings Directive

Besides the Directives immediately addressing ozone concentrations or precursor emissions, the EC National Emission Ceilings Directive (NECD) limiting NO_x and NMVOC emissions, among others, will have a certain impact on the Ozone situation in the year 2010, on which it is targeted. *Fig. 5.26.* shows the results of model calculations with the Lagrangian EMEP Model, which indicate that none of the

AOT thresholds are likely to be achieved even when the emission limits given by the NEC Directive are going to be met by all countries involved.

These calculations are based on model runs conducted for 5 different years, hence using different meteorological conditions, and then being averaged to ensure, that not just specifically bad meteorological situations will cause exceptionally high ozone concentrations in a specific year. Still, for AOT60 in particular, the maximum values can be reduced to below 3 ppm.h and in many areas of Europe, the AOT40 levels for forests are reduced to some extent. However, as stated before, the threshold for agricultural crops is exceeded significantly in almost all grid cells.

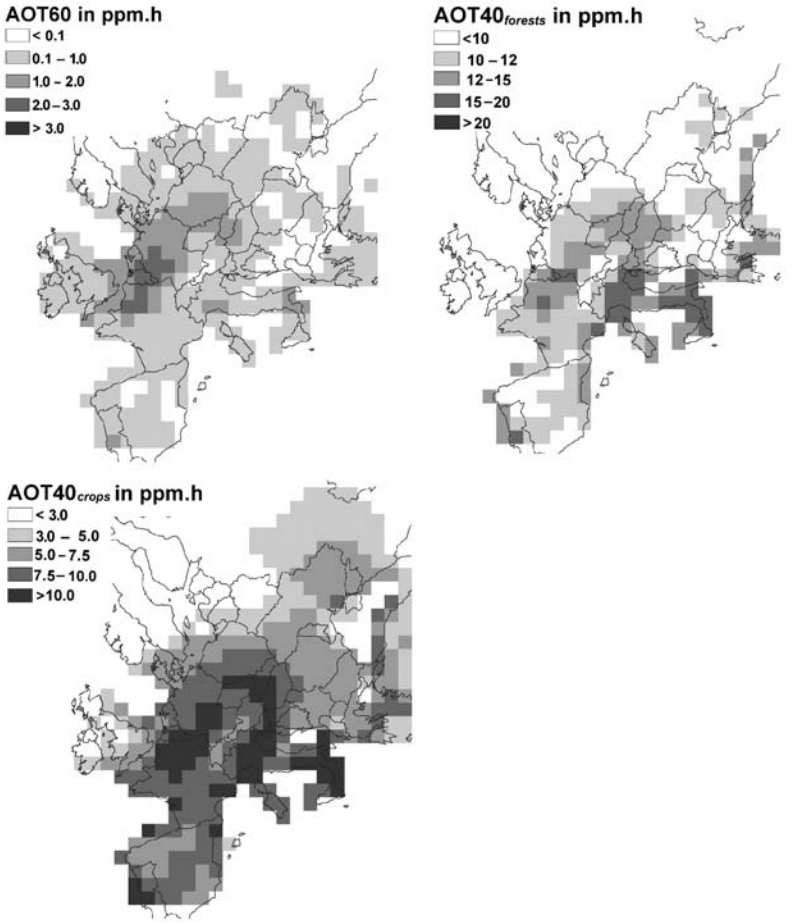

Fig. 5.26. Ozone AOT values resulting from a full implementation of the NEC Directive

5.3.3 From Ozone Thresholds to Population Exposure

The EC Ozone Daughter Directive, however, does not set limit values according to AOT thresholds, but aims at reduction of ozone peak values giving a limit value of 120 μg/m³ to be exceeded on not more than 25 days per year. *Fig. 5.27.* displays the number of days in exceedance of this limit value for different emissions sets again, calculated with the EMEP Lagrangian Model. Even though the peak values are mostly located over sea areas, it becomes obvious that with the emissions ceilings set by the NEC Directive, exceedances of 120 μg/m³ will occur on more than 20 days a year over most of Europe. The 80% emission reduction shows a significant improvement of the situation and assuming some additional emission reductions in Central and Eastern European countries, the limit value of the Daughter Directive could possibly be achieved completely in that scenario.

Apart from the ozone concentrations and the exceedance of thresholds and limit values, the exposure (i.e. population in a grid cell multiplied by ppm.h) of the population should be assessed to determine, if the additional emission reductions would lead to significantly lower exposure levels. *Fig. 5.28.* shows the accumulated exposure of the population in each EMEP grid multiplied by the AOT60 levels for the cell, hence giving a good overview on the changes in exposure from a 50% and 80% reduction.

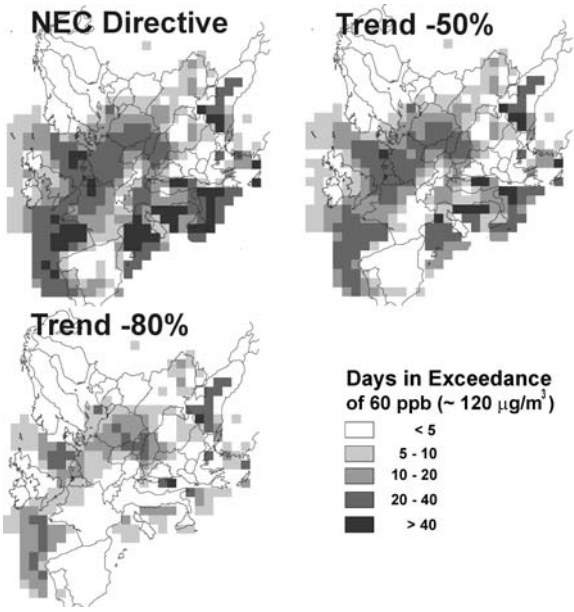

Fig. 5.27. Days in Exceedance of 120 μg/m³ (Ozone Daughter Directive threshold) for emissions sets calculated by the EMEP Lagrangian Model

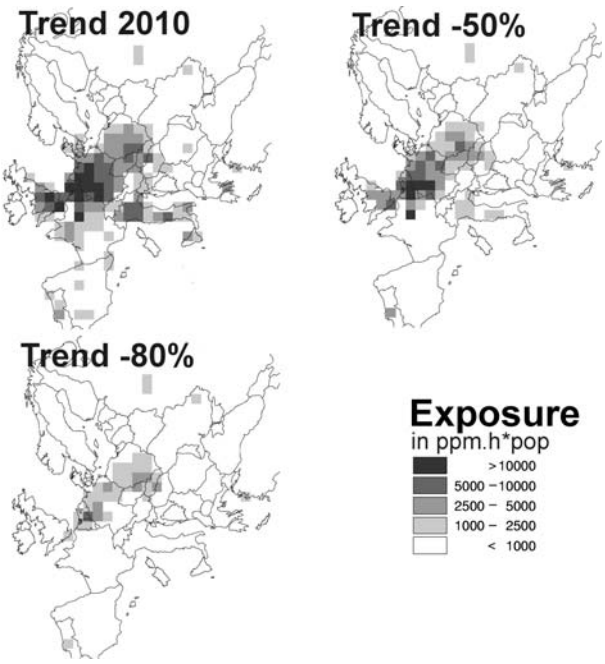

Fig. 5.28. Assessing population exposure (i.e. population x ppm.h) for different scenarios

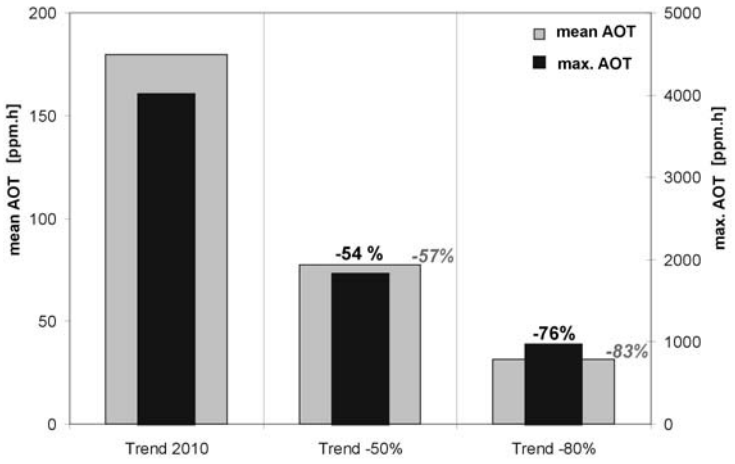

Fig. 5.29. Mean (left) and maximum (right) AOT60 values for different emission sets

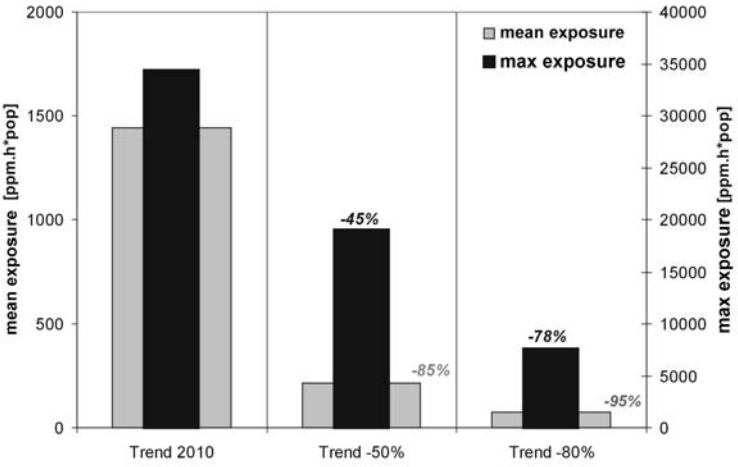

Fig. 5.30. Mean (left) and maximum (right) values for population exposure to ground level ozone for different emission sets

The *Figs. 5.29* and *5.30* summarise the results discussed before and show, that mean AOT60 values (- 83%) as well as the peak AOT60 values (-76%) would be significantly reduced in the Trend-80% case. A similar picture shows for population exposure, showing a decrease of 78% for the maximum and even of 95% for the mean population exposure (*Fig 5.30.*).

However, achieving an additional 80% reduction from the trend scenario for 2010 would mean to cut emissions to less then 2 million tonnes of each NO_x and NMVOC from the EU15. If this can be achieved at all, it will depend on the speed and momentum with which low- or zero-emission technologies will be developed and by the means of legislation and/or cooperation implemented. Some options for further emission abatement are given in the next section,

5.3.4 Contributions from the Accession Process

In addition to activities and legislative action to reduce air pollutant emissions in Europe, there is a different process which could have an impact on future air quality, even though it is not concerned with environmental targets in the first place. With the EU growing towards the east and several countries of Central and Eastern Europe (CEECs) having become full Members creating a community of 26 countries, these countries will have to fulfil obligations such as air quality limit values as well. However, there will most likely be derogations and target years for compliance, which are considerably later than those for current Member States.

Fig. 5.31. shows an exemplary comparison of emission reductions modelled for the EU15 only and including three CEECs, Poland, Hungary and the Czech Republic, which have been selected because of their significant emissions of ozone precursors (see *Sect. 6.3.3*.). The AOT maps show a slight improvement of the situation at a 50% emission reduction from the trend scenario, and a considerable reduction of grid cells showing exceedances of AOT60 in the Trend -80% case. These results will be evaluated further in *Chap. 6*.

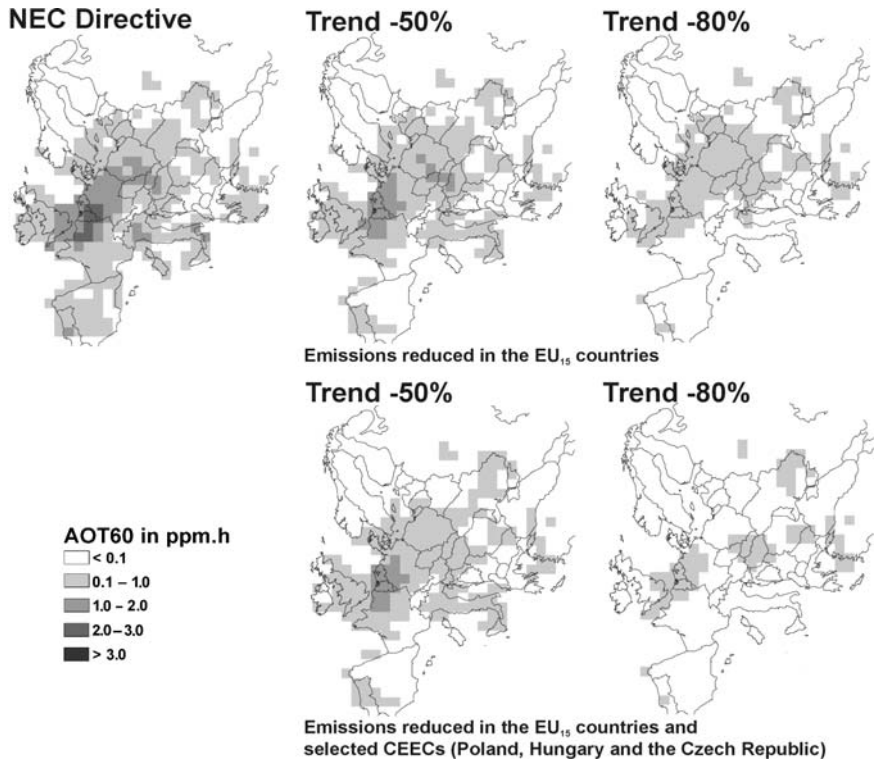

Fig. 5.31. Model results for AOT 60 (calculated with the EMEP Model) comparing emission reductions in the EU15 with additional reductions assumed for Poland, Hungary and the Czech Republic

6 Evaluation of Results

6.1 Introduction

The previous chapters have thoroughly discussed scenario design, model development and application and individual results of modelling exercises. Here, some aspects of potential measures to achieve significant additional reductions of ozone precursors will be elaborated on, focusing on transport and the energy sector mainly. This is necessary, as the analysis of reductions that would be needed to achieve compliance with ozone limit values in the year 2010 go beyond the capability of currently available abatement options.

Furthermore, the results from the assessment of current legislation (i.e. the National Emission Ceilings Directive and the Ozone Daughter Directive) are evaluated, including the contribution of the accession process of Eastern European countries and its potential impacts. The hidden benefits due the increased implementation of air pollution control legislation should be taken into account in the discussion of costs and benefits of an enlarged EU.

6.2 Future Abatement Options

6.2.1 Emission Situation in the 2010 Trend Scenario

In *Chap. 3*, the emission situation of the base year 1990 has been analysed in detail and the trend scenario for the year 2010 was developed (see as well *Friedrich and Reis, 2000*). And as further emission abatement options have to be identified to achieve additional emission reductions as stated before, a close look should be taken upon the sectoral structure of ozone precursor emissions as it is anticipated to be in the trend. *Fig. 6.1.* shows that NO_x emissions will still be dominated by road transport sources, with the vital aspect, that almost 80% of these road transport NO_x emissions will be coming from heavy duty vehicles. Other mobile sources will contribute another 18% of total emissions, with the largest shares within this sector coming from off-road vehicles and machinery (50%) and marine sources (34%). Finally, both public power generation as well as industrial combustion are responsible for a total of 29% of NO_x emissions, with additional options for abatement.

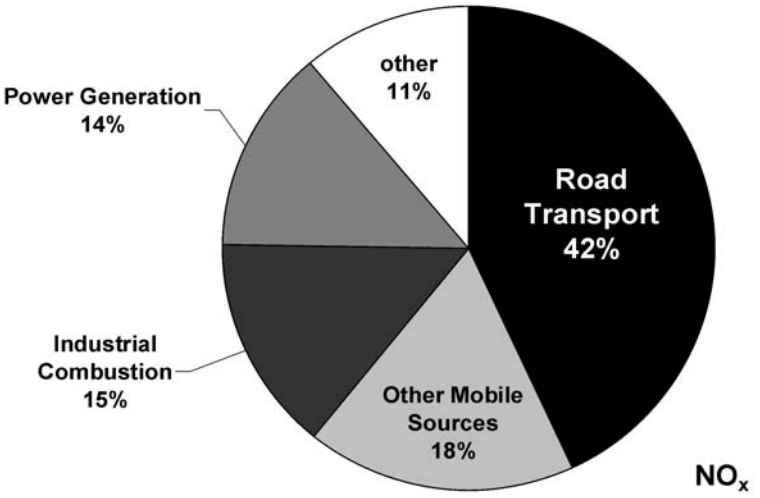

Fig. 6.1. Sectoral split of NO_x emissions in the Trend 2010 Scenario

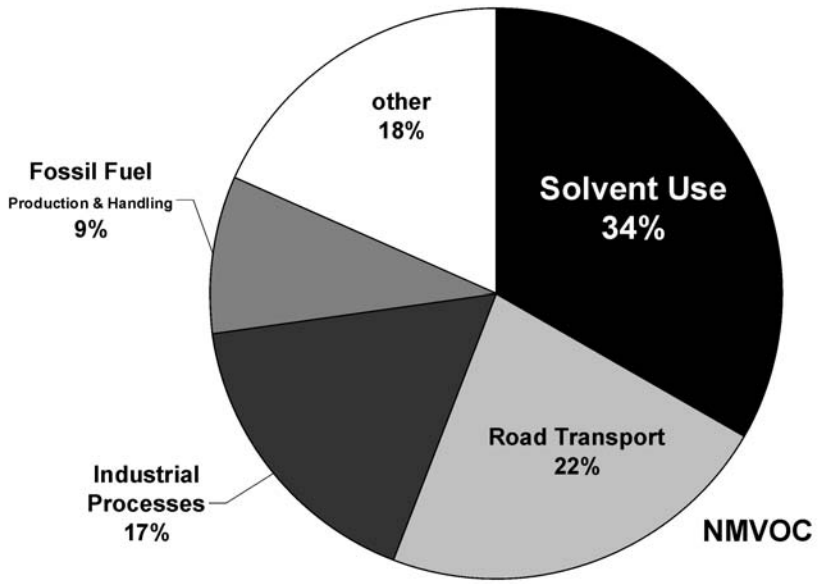

Fig. 6.2. Sectoral split of NMVOC emissions in the Trend 2010 Scenario

The situation for NMVOC emissions has solvent use as the largest contributing source group (see *Fig. 6.1.*), even though the EC Solvent Directive will be implemented completely by then (according to the timetable, until 2007). This is mainly, because the Directive only addresses specific activities within this source sector and a large share of the emissions from solvents have yet to be regulated. Here, domestic applications of paints and other solvents could prove to be a valuable target for reduction, as they amount to about 27% of total NMVOC emissions of the sector. Within road transport, the share of NMVOC emissions from evaporative losses from gasoline operated vehicles will have decreased significantly through the implementation of carbon canisters through the vehicle fleet. Hence, the remaining 22% of total NMVOC emissions coming from road transport will mainly originate from exhaust emissions, and to some extent from 2-stroke engines of mopeds and motorcycles

6.2.2 Sectoral Analysis

6.2.2.1 Road Transport

In the following sections, some of the most promising abatement options beyond the trend scenario 2010 will be discussed, among which fuel cells could prove to be a remedy for some of the most eminent air pollution problems of these days. However, fuel cell operated vehicles will lead to reduced specific emissions, without having an impact on activity rates, and hence not addressing other impacts of increased individual transport. On the other hand, large reduction potentials, specifically in the view of the large proportion of NO_x emissions from heavy duty vehicles, lie in behavioural and structural changes. For instance, incentives to shift goods traffic to more efficient and less polluting railways or changing mobility concepts as a whole, leading to decreases in private transport could lead to considerable emission reductions. Still, as these changes are difficult to quantify in the scope of the frame of this book, they focus here will be on technical solutions.

All major car manufacturers are operating fuel-cell driven prototypes such as the NECAR by Merceds Benz, and many companies producing equipment for heat and power generation have been researching the use of stationary fuel cells in recent years. *Table 6.1.* gives an overview on currently available fuel cell types and their possible applications. An in-depth assessment of the implementation of fuel cells and other alternative propulsion systems in road transport vehicles has been conducted by *Krüger* (2000).Different alternative fuels and propulsion systems, are currently in development, among which fuel cells seem the most promising technology. Several car manufacturers are working on prototypes of fuel cell vehicles, which have virtually no in-use NO_x or NMVOC emissions. In addition to that, methanol and natural gas operated combustion engines have comparatively lower in-use emissions than gasoline or diesel operated systems and in particular vehicles using compressed natural gas (CNG) show increasing market shares lately.

Fig. 6.3. shows a comparison of direct emissions of different alternative propulsion systems, compared to a EURO IV compliant passenger car gasoline. Even though many problems still have to be solved, such as the best way to produce the amounts of hydrogen needed, or if alternative fuels such as methanol or other substances might be easier to handle, the technology is approaching a stage where its applicability is a question of a few years (*OECD 1996b*).

Table 6.1. Fuel cell types, their characteristics and possible applications

	AFC[a]	**PAFC**[b]	**MCFC**[c]	**SOFC**[d]	**PEMFC**[e]
Electrolyte	Alkaline (aqueous)	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Operating Temp.	80°C	190°C	650°C	1000°C	80°C
Fuels	Extremely pure H_2	Hydrogen (H_2) Reformate	H_2/CO/ Reformate	H_2/CO_2/ CH_4 Reformate	H_2 Reformate
Reforming	External	External	External/ Internal	External/ Internal	External
Oxidant	O_2	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
Efficiency	60%	40-50%	50-60%	45-55%	40-50%
Power density	High	Moderate	Moderate	High	High
Application	Space	Power Gen. Transport	Stationary Powe Generation	Stationary Power Generation	Transport

a. Alkaline Fuel Cell
b. Phosphoric Acid Fuel Cell
c. Molten Carbonate Fuel Cell
d. Solid Oxide Fuel Cell
e. Proton Exchange Membrane Fuel Cell

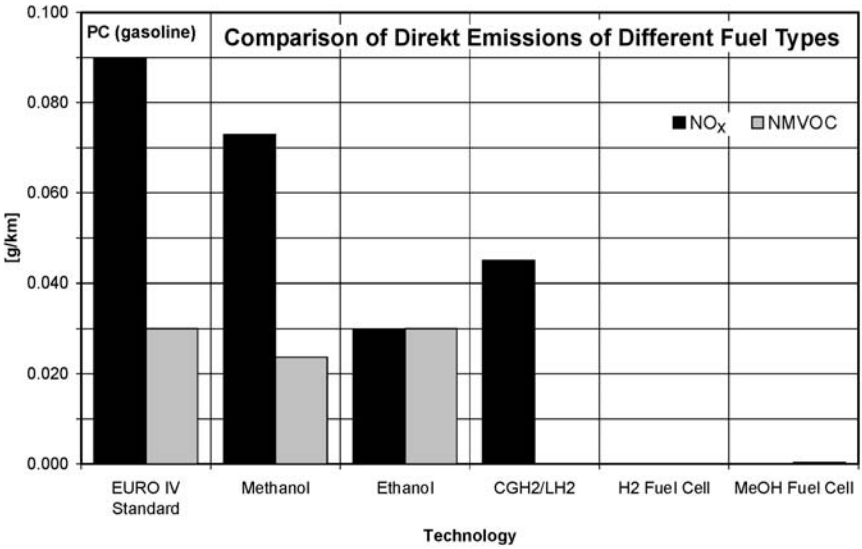

Fig. 6.3. Comparing ***direct*** emissions of alternative propulsion systems to a EURO 4 compliant passenger car gasoline

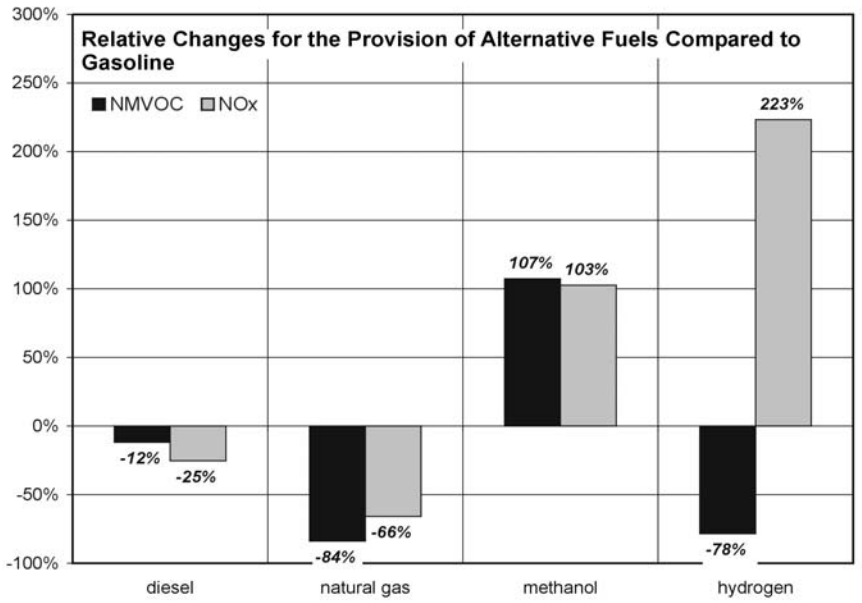

Fig. 6.4. Comparing emissions for the provision of specific fossil fuels to gasoline for 2000

The potential for further emission reductions from road transport vehicles is very high, from moderate reductions through the use of methanol and ethanol as comparably cleaner fuels to almost zero emissions with different fuel cell types. However, as the switch to either of the alternative fuels would need a major restructuring of the whole distribution system, this alone will present a major obstacle and influence the speed of a possible implementation (see *Krüger and Voß*, 2000). A major issue in the development of the potentials of these alternative fuels are the ways of provision. As an example, while hydrogen operated fuel-cell vehicles have virtually no direct emissions of air pollutants other than CO_2, the assessment of emissions originating from the provision of hydrogen (see *Fig. 6.4.* and *Krüger, 2001*) shows significantly higher NO_x emissions than for all other fuels, as the energy input needed to generate hydrogen is considerable.

A major improvement, which has already entered the legislative process of the European Commission, is the more stringent EURO 5 emission standard for heavy duty vehicles (HDV), which is targeted to come into force in 2008. This standard will cut NO_x emissions from HDVs by 50% and will hence have a considerable impact on road transport emissions. However, regarding the typical fleet renewal rates, a significant drop in NO_x emissions from that source group will most likely be noticed beyond 2015 only. While this activity addresses conventional propulsion systems, there are a number of technologies which might have an even larger impact on road transport emissions as a whole (cf. *Reis et al. 1999*).

At the time being, emission limits have been set for the next 5-10 years, with EURO 5 for Heavy Duty vehicles coming into force in 2008. With respect to the considerable technological challenge these alternative fuels and propulsion systems still present, it should be expected that they will probably not achieve a significant market share before the year 2010. On the other hand, as zero-emission vehicle programmes in California show that national or even European initiatives to promote a faster implementation of these technologies could make a difference.

Apart from the technological aspects, the costs of these alternatives have to be considered, as most applications are not yet marketable. Thus, it is difficult to assess the cost, or respectively the excess costs of e.g. a fuel cell operated vehicle in relation to one with a conventional engine. And in addition to that, the development process for these technologies causes their relative costs to decrease more or less constantly, as much as their efficiency and applicability improves. *Table 6.2.* shows some rough cost estimates and their difference between 1994 and 2000 for different PEM fuel cells as it has been assessed by the *Institute for Prospective Technology Studies* in the frame of a European research project For additional information on fuel cells and their application in road transport, see *MEET 1998* and *Papameletiou 1994*. Finally, it has to be stated, that based on current data at the time being, a scientifically sound assessment of the costs of implementing these advanced technologies in the road transport sector, and hence the abatement costs for the reduction of the respective ozone precursor emissions, cannot be conducted. However, it is important to show that these measures are available and will most probably have a significant impact on emission from road transport vehicles in the time after 2010.

Table 6.2. PEM Fuel Cells[a] – Efficiency and cost estimates

Oil PEM	**1994**	**2000**
Efficiency [%]		
- hydrogen fuelled	50	55
- ext. reformate oil, hydrogen rich gas	30	35
stack[b] costs [€/kW]	100 000	10 000
system[c] costs [€/kW]	100 000	20 000
Methanol PEM		
Efficiency [%]	38-45	40-50
Stack costs [€/kW]	100 000	7 000-10 000
System costs [€/kW]	–	3 000-25 000
Natural gas PEM		
Efficiency [%]	40	45
Stack costs [€/kW]	100 000	10 000
System costs [€/kW]	–	15 000

a. *Source:* Papameletiou D., pers. comm., IPTS Seville
b. *stack* refers to the group of cells where electrochemical reaction is produced
c. *system* refers to the complete fuel cell system including fuel processor and power conditioner section

6.2.2.2 Energy

In the energy sector, one major trend has already been identified for the trend scenario development (see *Chap. 3*), as in most countries, the share of natural gas used in power plants increases while the use of coal and oil diminishes. While this does already lead to a considerable reduction of NO_x emissions, along with improvements in efficiency and after treatment options, there are additional options to reduce NO_x from energy production. One of them is energy saving, which might appear obvious, but with many European countries having no or little insulation e.g. at houses, or where stand-by controls in electrical devices consume a significant amount of energy, the potential for savings is considerable.

In addition to that, the use of regenerative energy sources such as solar, wind, water and in some regions geothermic sources can contribute to a reduction of power generated on the basis of fossil fuels. Finally, combined heat and power systems with high efficiencies and the possible application of stationary fuel cells in decentralized energy concepts promise to reduce the emissions of NO_x from this sector

further. The costs for this reduction will depend among other parameters on the further development of the European electricity market, where the latest deregulations have led to significant changes in provider structure and price formation.

6.2.2.3 Solvent Use

Regarding the use of solvents, the EC Solvents Directive will be in force by the year 2007, hence a large number of abatement measures for commercial and industry applications of organic solvents will be implemented in the trend scenario already. Currently, a study financed by the EC DG Environment (E1/ETU/980084) investigated the potential reductions, costs and benefits of a directive covering the use of decorative paints and varnishes for professional and non-professional use. This study includes industry partners, as the reduction of emissions from non-professional use of paints can most likely only be achieved by production-side measures such as the substitution of solvents in paints or suchlike. In a first assessment, the potential reduction from paint application is assumed by the study to be approx. 50% from current levels. At this stage, a detailed assessment of the costs for the implementation of a directive like this cannot be made, though.

In addition to paint application, the rather diffuse sector of household solvent use, i.e. the private sector use of detergents, glues, adhesives etc. should be addressed. Similar to paint application, the only feasible approach would be through product standards, limiting solvent content, or respectively substituting solvents in these products completely. Given regulatory incentives and sufficient time to switch to low- or no-solvent products might actually not impose additional costs on the production side.

6.2.2.4 Other Mobile Sources

For off-road mobile equipment, Directive 97/68/EC and the specifications in 2000/25/EC set regulations for off-road diesels, introducing two stages of implementation: *Stage I* was already implemented in 1999 and *Stage II* will be implemented from 2001 to 2004, depending on the engine power output. The equipment covered by the standard includes industrial drilling rigs, compressors, construction wheel loaders, bulldozers, off-road trucks, highway excavators, forklift trucks, road maintenance equipment, snow plows, ground support equipment in airports, aerial lifts and mobile cranes. Agricultural and forestry tractors have the same emission standards but different implementation dates (as specified in Directive 2000/25/EC). Engines used in ships, railway locomotives, aircraft, and generating sets are not covered by the standard.

With most of the equipment covered by the standard is operated by diesel engines, more or less the same abatement technologies as available for heavy duty vehicles (see *Chap. 3*) can be applied. The anticipated reduction of NO_x emissions and thus the potential for further abatement, however, are extremely difficult to assess, as data on the number and the application of off-road machinery is more or less not

available. Still, as the relative importance of this source group increases with further diminishing emissions from road transport and energy production, a significant decrease of emissions from this sector can be expected from the implementation of this directive. Considering the sometimes long average lifetime of off-road equipment as covered by the regulations, a full implementation of the standards should not be expected before the year 2015.

Another source group to be addressed could be air & sea travel, with air traffic in particular being projected to increase by some hundred percent within the next decade. At the time being, no specific measures or technologies can be identified, besides possible substitutions of inland flights by trains for example, or the general technological development of more fuel efficient aircraft.

6.3 Recommendations for Policy Makers

6.3.1 Achieving Compliance with Thresholds and Limit Values

6.3.1.1 AOTxx Thresholds

The model calculations analysed in the previous sections have shown, that achieving the AOT60 thresholds for the protection of human health is possible under certain circumstances, even though the emission reductions would have to be extremely stringent. At an additional reduction of 50% from the trend scenario for 2010, especially the peak concentrations would be avoided, while at an 80% reduction, including Central and Eastern European countries, AOT60 would be achieved almost all over Europe. The same applies to AOT40 for forests, where a full compliance would be possible even with less stringent emission ceilings. However, all modelling results indicate, that the $AOT40_{crops}$ threshold will not likely be achieved in any way, with considerable exceedances of 3 ppm.h occurring in the majority of grid cells even at an 80% reduction from the trend. Here, a thorough review of this threshold should be conducted, as setting a target which cannot be met at least from a modelling point of view makes it difficult to assess different air pollution control strategies with respect to their performance to protect agricultural crops. Judging from the results of this study, $AOT40_{crops}$ is more or less impossible to achieve, even with the most stringent emission reductions.

6.3.1.2 Ozone Daughter Directive Limit Values

Regarding the exceedances of the 120 $\mu g/m^3$ limit value, only few grid cells face more than 25 days in the case where an 80% emission reduction from the trend is evaluated. Furthermore, additional calculations have indicated a significant reduction in population exposure, recommending a long-term target of an additional 80% (respectively ~70% reduction below the NEC Directive levels for NO_x and

NMVOC) reduction of trend scenario emissions overall to achieve the ozone targets of the Daughter Directive.

6.3.2 Targets for further Emission Reductions – The National Emission Ceilings Directive Evaluated.

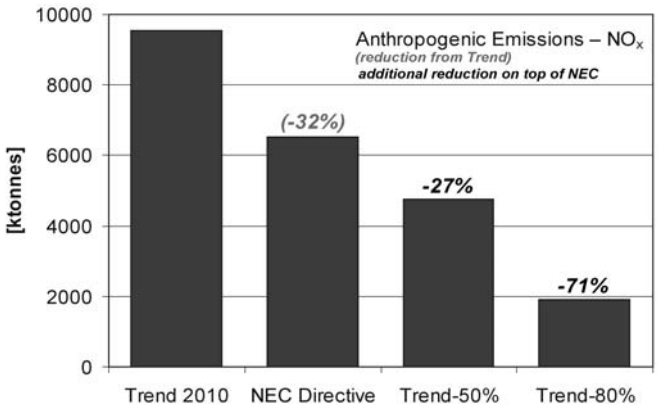

Fig. 6.5. EU15 NO_x emission targets resulting from the assessment of further abatement options

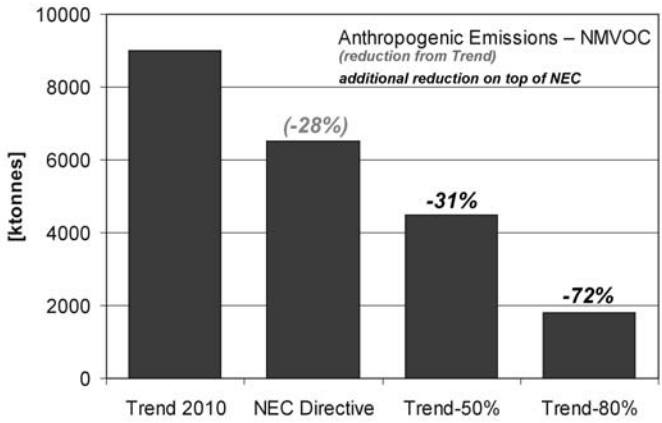

Fig. 6.6. EU15 NMVOC emission targets resulting from the assessment of further abatement options

With the national emission ceilings being designed to address the most pressing air pollution problems, the evaluation for ground level ozone does not look too promising. In none of the cases modelled, the limits sets for NO_x and NMVOC emissions as given in the directive managed to achieve any of the thresholds or limit values.

However, as *Fig. 6.5.* and *Fig. 6.6.* show, the NEC Directive already reflects emission levels of roughly 30% below the trend scenario for 2010, which assumed a business-as-usual development. From this follows, that within the next 5-10 years, considerable efforts will have to be taken in the field of air pollution control, if these emission ceilings shall be met. As the National Emission Ceilings Directive has just recently been adopted, time will be an critical issue with its implementation

In the view of the fact, that the feasibility for the most stringent emission reduction of 80% from the trend is questionable, it should be set as the ultimate target, with the interim target of 50% reduction from the trend scenario. Still, besides the technical feasibility, the costs for implementing such a stringent emission target has to be calculated. And as the costs of reducing ozone by its own might be significantly higher than the benefits from ozone reduction alone, this strongly advocates a more general approach, in a multi-pollutant multi-effect assessment.

6.3.3 Air pollution Control Strategies and the Accession Process

One interesting feature of the accession process is that the countries joining the European Community will be subject to the same emission control activities, with respect to somewhat less stringent timetables. As *Sect. 5.3.4.* has indicated, there is a rather clear improvement of the situation for AOT60 when three selected Central and Eastern European countries (Poland, Hungary and the Czech Republic) are assumed to reduce their emissions by 50% and 80% from the trend scenario as well. For these countries, the emissions in the trend year 2010 have been set at the level of their current reduction plans as officially reported to EMEP (see *Table 6.3.*).

Fig. 6.7. clearly shows, that exceedances of 60 ppb (~120 $\mu g/m^3$) as set as a limit value by the EC Ozone Daughter Directive could be significantly reduced by including these three major emitters in eastern Europe. On the other hand, these countries will experience substantial benefits from the emission reductions in the EU15 countries thus proving mutual benefits from the enlargement process and the inclusion of countries from Central and Eastern Europe into a pan-European air pollution control strategy.

Table 6.3. 1998 emissions of selected CEECs and current reduction plans for 2010 as reported to EMEP

	NO_x			NMVOC		
	1998	**2010**	***change***	**1998**	**2010**	***change***
Czech Republic	443	283	*-36%*	269	220	*-18%*
Hungary	591	550	*-7%*	141	137	*-3%*
Poland	1 897	1 397	*-26%*	730	800	*+10%*

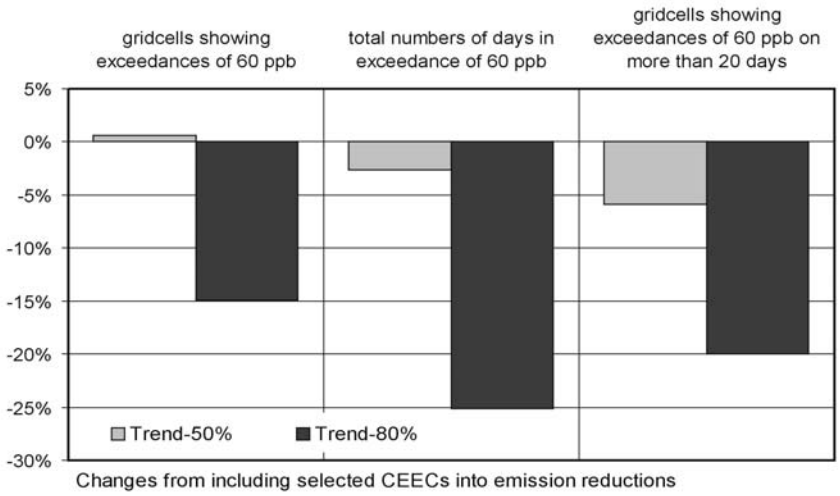

Fig. 6.7. Changes in for different thresholds for the whole EMEP grid when including emission reductions from selected CEECs relative to EU_{15}-only reductions - % changes relative to the situation without taking reductions in Eastern Europe into account

7 Conclusions and Outlook

7.1 Conclusions

7.1.1 General Recommendations for European Air Pollution Control Strategies

In recent years the ozone threshold for human health, 110 µg/m³ (over an 8 h mean), was substantially exceeded, exposing a large share of the European population to ozone levels, which are assumed to have adverse health effects according to research findings. In the view to this, the European Commission issued the Directive on Air Pollution by Ozone (92/72/EEC) already in 1992, setting ozone thresholds and air quality targets in order to improve ambient air quality in the EU. Furthermore, measures to reduce precursor emissions have been implemented or will be implemented initiated by the EC Large Combustion Plants (LCP) Directive, the EURO 1 – 5 emission standards for road transport vehicles, the EC Solvent Directive, or the Directive on Paint Application, which is currently in preparation. With the Air Quality Framework Directive now providing a general framework for all relevant air quality related issues, the Daughter Directive on Ozone (2002/3/EC), which was recently adopted gives new short and long term objectives aimed at the protection of human health, of agricultural crops and ecosystems (see Sect. *2.4.2.*).

In addition to EC activities, supranational bodies such as the UNECE or the WHO have addressed air quality issues and the UNECE protocols to the Convention on Long Range Transboundary Air Pollution have lead to significant reductions of ozone precursor emissions as well.

One focus of this book was to analyse, whether these activities and all related legislation and regulations in place and in pipeline will be sufficient to reduce precursor emissions to an extent which will result in ambient concentrations of ground-level ozone that comply with currently set or proposed thresholds and limit values. Relevant thresholds and limit value are, among others: for human health an average value of 120 µg/m³ (~ 60 ppb) during any 8 hour period, not to be exceeded; for crops the AOT40 (accumulated exposure over 40 ppb) value should not exceed 3 ppm.h accumulated from May to July and for forests AOT40 should not be in excess of 10 ppm.h from April to September.

A trend scenario was developed for the year 2010, assuming a business-as-usual development, because it is close enough to allow projections of future activity levels with sufficient accuracy, but it allows sufficient time for market penetration of

abatement measures. In addition to this trend scenario, the recently adopted EC National Emission Ceilings Directive (NEC) was taken as a reference to assess compliance with target values, as it sets a new baseline for the development of emission control strategies for the EC and the member states. *Fig. 7.1.* shows the emission sets of the trend scenario in comparison to the NEC Directive and the additional reduction scenarios calculated to assess compliance with ozone thresholds. A similar picture is given for NMVOC emissions in *Fig. 7.2.,* with both figures showing, that in order to achieve the emission levels the model calculations of this study have found to be needed to reduce ozone concentrations to a tolerable degree, most countries would have to cut the emission limits set for the NEC Directive again to about a third.

As it is indicated by *Table 7.1.*, the emission targets set by the NEC Directive will lead to a limited improvement from the trend scenario only, whereas a 50% respectively an 80% reduction from the trend scenario emissions would be recommended to achieve sufficiently reduced ozone levels. For example, in 458 grid cells AOT60 is exceeded in the trend scenario.

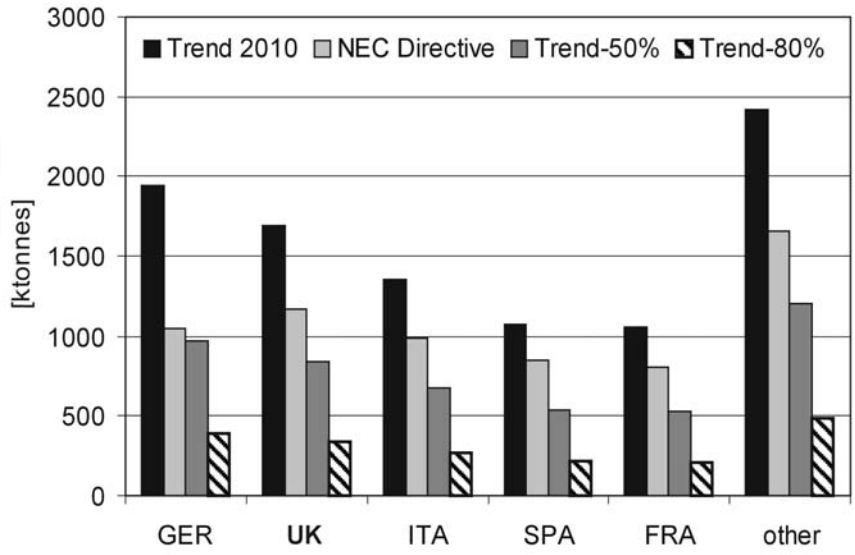

Fig. 7.1. Anthropogenic NO_x Emissions for different targets for the 5 largest emitters

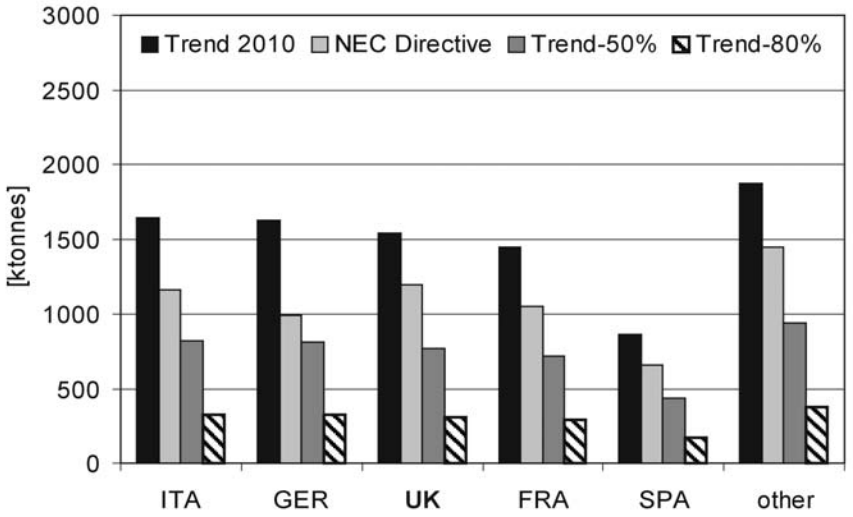

Fig. 7.2. Anthropogenic NMVOC Emissions for different targets for the 5 largest emitters

Table 7.1. Remaining exceedances of ozone thresholds in % of EMEP grid cells for the trend scenario 2010

	AOT60	**AOT40$_{crops}$**	**AOT40$_{forests}$**
NEC Directive emissions	65.3	84.1	59.7
Trend - 50%	43.0	68.6	28.6
Trend - 80%	17.4	46.8	6.3

In addition to the gaps closed towards compliance with AOT60 or AOT40 (crops and forests) thresholds, *Table 7.2.* displays the assessment of exceedances of the EC Ozone Daughter Directive (60 ppb), giving e.g. the decrease in grid cells showing more than 20 days in excess of 60 ppb as an indicator of an improved situation. It indicates that the total number of days above 60 ppb is reduced to almost a third, with maximum and the mean days of exceedance significantly reduced as well.

Hence, a first conclusion of this study is that the emission targets currently set by the NEC Directive will not suffice to achieve the air quality limit values by the Ozone Daughter Directive or the critical thresholds recommended for health or

crops and ecosystems. As the ultimate target, an emission limit equivalent to an 80% reduction from the trend scenario (see above) should be aimed at, probably setting a 50% reduction from the trend as an intermediate target.

Table 7.2. Days over 60 ppb (~ 120 µg/m³) for the EU15 Member States for different emission sets

	NEC Directive	Trend -50%	Trend -80%
Σ days over 60 ppb per year	9 225	6 765	3 574
No. of grid cells > 20 days in exceedance of 60 ppb	177	125	38
max. days in exceedance of 60 ppb in a grid cell	101.6	82.2	43.2
mean days in exceedance of 60 ppb in a grid cell	6.4	4.7	2.5

7.1.2 Conclusions from Cost-Effectiveness and Cost-Benefit Analyses

The analysis in *Chap. 5* has led to the conclusion, that if ozone abatement is assessed in terms of abatement costs vs. benefits (calculated as reduced damage costs), the costs will outweigh the benefits by approximately a factor of 2.8 for the EU15 aiming at a 33% gap closure of AOT60.

Fig. 7.3. shows the results of the AOT60 33% Gap Closure, giving a split of benefits arising from reduced health and crop damages in comparison to the abatement costs calculated for the EU15. It has already been mentioned in the previous chapters, that this mainly stems from the comparatively less severe health impacts of ground level ozone in contrast to, for example, particulate matter. Thus, if the political decision for ozone abatement would be based solely on a cost-benefit assessment of this single effect, control of ozone precursor emissions would not likely to be implemented beyond a certain extent.

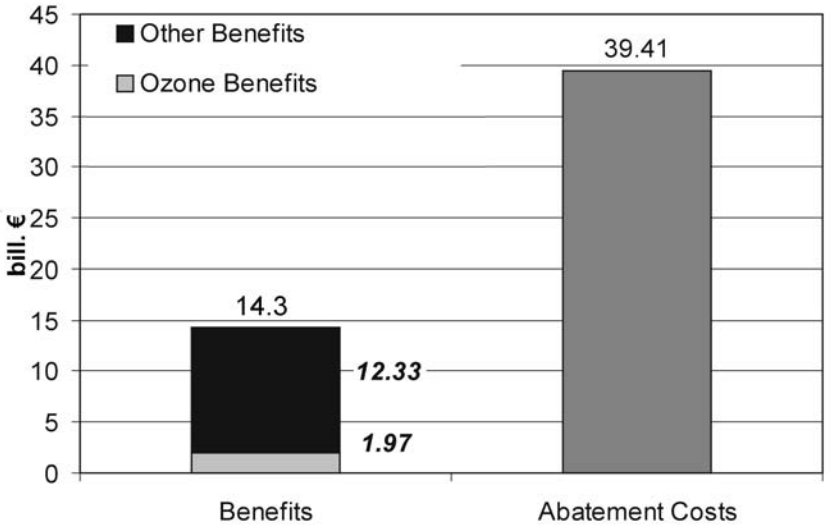

Fig. 7.3. Benefits (as avoided damage costs) vs. abatement costs for the EU15, AOT60 33% gap closure scenario

However, NO_x emissions do have an impact on acidification and eutrophication as well, hence an assessment of all relevant pollutants and effects should be conducted in a multi-pollutant multi-effect framework. In addition to that, tropospheric ozone contributes to global warming as well (see *Sect. 2.3.5*), hence benefits of ozone abatement will have to be evaluated in a far broader context. Only that way, the overall benefits of reducing a pollutant (or a number of pollutants) as well as synergy effects between abatement measures, which could reduce abatement costs significantly, can be evaluated correctly.

And as the brief assessment of the contribution of emission reductions by selected countries in Central and Eastern Europe (in this case the Czech Republic, Hungary and Poland) shows, the accession process and the implications of the enlargement towards an EU_{26} or more will have an impact on the planning and implementation of air pollution control strategies as well. Thus, any further modelling studies should cover the whole of Europe, even though data availability for economies in transition might prove to be a problem, to ensure, that a harmonised and long-term abatement strategy can be put in place.

An additional conclusion from the assessment of the distribution of costs and benefits among countries is the need to consider mechanisms for burden-sharing, as the differences investigated are considerable (see *Section 5.1.3*). The basis for this has been laid in *Friedrich and Reis* (2000), where different approaches and burden

sharing options have been discussed. One aim of this burden sharing could be to equalize the share of GDP spent for ozone precursor emission abatement by setting transfer payments between the EU15 countries. This way, it would be less difficult for those 'poorer' member states to comply with emission targets, contributing to the improvement of air quality levels all over Europe.

7.2 Outlook

7.2.1 Towards a Multi-pollutant-multi-effect Assessment

It has already been stated above, that one main conclusion from this study is to recommend the assessment of any air pollution control strategy in a multi-pollutant multi-effect framework to make sure that all possible benefits and synergy effects of abatement measures thus reducing abatement costs can be taken into account properly. Even though the modelling results displayed in this work focus on tropospheric ozone only, the approach described here can easily be extended to cover a number of different pollutants and their environmental effects. The OMEGA-O_3 optimisation model, for instance, does already include modules to calculate impacts of NO_x emission reductions on acidification levels, including critical levels and loads.

The importance of this movement towards a more integrated approach is reflected as well by the adoption of the latest protocol to the *Convention on Long Range Transboundary Air Pollution* of the UNECE. The so-called *Gothenburg-Protocol* explicitly addresses the need for a multi-effect approach and along with the NEC Directive sets emission targets for the main air pollutants. In addition to that, the *Air Quality Framework Directive* of the EC and the *Clean Air for Europe* Strategy currently developed by the EC DG Environment indicate the growing awareness, that complex air quality problems, including transboundary pollution transport as well as interconnections between pollutants and effects, can only be properly challenged by integrated approaches.

7.2.2 Further Research Needs

To this end, it is above all important to generate a data basis, which allows for a detailed, accurate and consistent modelling, providing all necessary input data needed to operate complex integrated assessment models (IAMs). As it was described in *Chap. 3* and *4*, a single data source as such is currently not available, hence modelling studies cannot be compared or evaluated even if they try to answer the same questions. A considerable improvement would be to set up a database which does not only comprise emission data, but covers activity data, cost information, as well as necessary background data as to technologies, implementational details and suchlike. The main benefit of a database like this would be a significant reduction of un-

certainties in results from IAMs, provided high data quality in the database would be maintained, and it would be possible, for the first time, to evaluate and compare modelling results for vital targets, thus improving decision support for policy makers, who would not have to rely on the results of a single assessment model to base their decisions on.

Apart from input data improvement, the integration of non-technical measures will be a necessity, as the potentials for emission reduction by changes in technology alone will decrease with the proceeding implementation of legislation setting more and more stringent emission limits for source groups. As these non-technical measures will most likely increase the complexity of the problem, being interconnected and in some cases complementary with technical measures, or excluding those, the traditional approach of calculating single pollutant abatement cost curves will most likely have to be dropped. Here, an approach better suited to deal with complex problems has to be developed, based for example on a matrix approach, where measures are no longer pollutant specific, but consists of a set of parameters which determine their efficiencies to reduce single (or multiple) pollutants along with their specific costs and other implementational details. The assessment models will then be able to combine measures directly and thus determine the cost-effective selection of measures to achieve a set of air quality targets at the same time, and even more, to conduct a cost-benefit assessment automatically to determine which measure is best suited to achieve a preset target. The final step towards a true IAM will then be the integration of a macro economic assessment tool, evaluating the effects of an optimised abatement strategy on vital economic indicators.

7.2.3 Summary

Finally, the results and recommendations of this study shall be summarised, capturing the most prominent results:

- Assuming a business-as-usual trend development, there will still be considerable occurrences of high levels of tropospheric ozone in Europe in the year 2010, even though emissions of ozone precursors are expected to drop significantly.
- Additional emission reductions in the size of about 80% from the trend scenario would result in compliance with AOT60 and $AOT40_{forests}$ thresholds, and, in most years (depending on meteorological conditions) with the limit values of the EC Ozone Daughter Directive.
- Compliance with the $AOT40_{crops}$ threshold could not be achieved in any of the modelled scenarios. This threshold is extremely sensitive to background ozone concentrations and recent studies indicate background levels at about 30 ppb (see e.g. *Mauzerall and Wang, 2002* as well as *Horowitz et al. 2002*, *Fiore et al. 2002a* and *2002b*) may originate in Europe due to hemispheric transport from the US or Asia. Thus, even slight increases in local ozone con-

centrations as well as hemispheric transport and long-term effects of Methane and CO for ozone formation may lead to violations of AOT40 for crops and a revision of the threshold is recommended. Taking into account ozone fluxes, i.e. the real uptake of ozone by sensitive crops, as it is currently discussed by experts, could seems a promising approach here.

- As an 80% emissions reduction from the trend scenario will be extremely difficult to achieve, an intermediate target should be set to a 50% reduction. Within the *Clean Air For Europe* (CAFE) strategy currently being developed, a clear pathway for a step-by-step reduction towards the ultimate goal should be fixed, to give industry and consumers a guidance for the development and utilisation of cleaner technologies. The National Emission Ceilings Directive (NECD), even with the emission ceilings set being achieved by all countries, will not contribute much to the solution of the ozone problem. The emission ceilings as they are fixed in the NECD are not stringent enough to comply with currently operating limit values and thresholds. And with regard to the EC Ozone Daughter Directive (2002/3/EC of Feb 12, 2003), which has entered into force with its publication in the *Official Journal of the European Communities* on March 9, 2002[1], a 50% reduction of NO_x and NMVOC beyond the business-as-usual development should be aimed at for 2010, whereas the long term objective should be 80% reduction by the year 2020.
- From a cost-benefit perspective, the abatement costs of NO_x and NMVOC will be somewhat higher, than the benefits due to avoided damage costs. However, side benefits from the simultaneous reduction of other pollutants, in particular when taking into account reduced emissions of greenhouse gases, can change this imbalance, as was demonstrated when taking into account non-ozone related benefits into the calculation. This strongly advocates the development of even more integrated assessment tools, which do account for a complete set of costs and benefits over all relevant air pollutants and effects.
- The cost-benefit assessment further indicates, that the burdens (in terms of abatement costs) and the benefits (in terms of avoided damage costs) are not distributed equally. To the contrary, some countries would have to spend a by far larger share of their GDP than others. These distributional effects have to be taken into account for the design of an effective and equitable air pollution control strategy.
- The accession of countries from Central and Eastern Europe to the EU and their inclusion into air pollution control strategies provides mutual benefits to both parties. On the one hand, accession countries benefit from reduced emissions in EU Member States and vice versa, and on the other hand, a joint effort to reduce emissions will most probably lead to a situation, where most

1. *see http://europa.eu.int/eur-lex, 30.07.2003*

countries will have to reduce less emissions, as in the case when their neighbouring countries would not be included.

- A major issue to solve for the improvement of integrated assessment modelling (IAM) in the future is that of the availability of detailed and consistent input data. As the discussion of uncertainties shows, the quality of emission data, cost figures etc. is the main driving force that determines, how reliable and useful these modelling results can be. Improved IAMs with improved data will be able to serve as important tools for policy support, aiming at the identification of efficient air pollution control strategies and enabling policy makers to thoroughly balance costs and benefits of such strategies.

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Annex

A CORINAIR SNAP90

Table A.1. CORINAIR 90 SNAP Nomenclature

SNAP GROUP	SNAP SUBGROUP	SNAP ACTIVITY	NAME
SNAP 1: Public Power, District Heating and Cogeneration			
1	1	0	PUBLIC POWER AND COGENERATION PLANTS
1	1	1	PUBLIC POWER AND COGENERATION - COMBUSTION PLANTS = 300 MW
1	1	2	PUBLIC POWER AND COGENER, - COMBUS, PLANTS = 50 AND < 300 MW
1	1	3	PUBLIC POWER AND COGENERATION - COMBUSTION PLANTS < 50 MW
1	1	4	PUBLIC POWER AND COGENERATION - GAS TURBINES
1	1	5	PUBLIC POWER AND COGENERATION - STATIONARY ENGINES
1	2	0	DISTRICT HEATING PLANTS
1	2	1	DISTRICT HEATING - COMBUSTION PLANTS = 300 MW
1	2	2	DISTRICT HEATING - COMBUSTION PLANTS = 50 MW AND < 300 MW
1	2	3	DISTRICT HEATING - COMBUSTION PLANTS < 50 MW
1	2	4	DISTRICT HEATING - GAS TURBINES
1	2	5	DISTRICT HEATING - STATIONARY ENGINES
SNAP 2: Commercial, Institutional and Residential Combusion			
2	0	1	COMMERCIAL, INSTIT, AND RESID, - COMBUSTION PLANTS = 50 MW

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

2	0	2	COMMERCIAL, INSTIT, AND RESID, - COMBUSTION PLANTS < 50 MW
2	0	3	COMMERCIAL, INSTIT, AND RESID, - GAS TURBINES
2	0	4	COMMERCIAL, INSTIT, AND RESID, - STATIONARY ENGINES
SNAP 3: Industrial Combustion			
3	1	0	INDUS, COMBUS, IN BOILERS, GAS TURBINES AND STATION, ENGINES
3	1	1	INDUSTRIAL COMBUSTION - PLANTS = 300 MW
3	1	2	INDUSTRIAL COMBUSTION - PLANTS = 50 MW AND < 300 MW
3	1	3	INDUSTRIAL COMBUSTION - PLANTS < 50 MW
3	1	4	INDUSTRIAL COMBUSTION - GAS TURBINES
3	1	5	INDUSTRIAL COMBUSTION - STATIONARY ENGINES
3	2	0	INDUSTRIAL COMBUSTION - PROCESS FURNACES WITHOUT CONTACT
3	2	1	INDUSTRIAL COMBUSTION - REFINERY PROCESSES FURNACES
3	2	2	INDUSTRIAL COMBUSTION - COKE OVEN FURNACES
3	2	3	INDUSTRIAL COMBUSTION - BLAST FURNACES COWPERS
3	2	4	INDUSTRIAL COMBUSTION - PLASTER FURNACES
3	3	0	INDUSTRIAL COMBUSTION - PROCESSES WITH CONTACT
3	3	1	INDUSTRIAL COMBUSTION - SINTER PLANT
3	3	2	INDUSTRIAL COMBUSTION - REHEATING FURNACES STEEL AND IRON
3	3	3	INDUSTRIAL COMBUSTION - GRAY IRON FOUNDRIES
3	3	4	INDUSTRIAL COMBUSTION - PRIMARY LEAD PRODUCTION
3	3	5	INDUSTRIAL COMBUSTION - PRIMARY ZINC PRODUCTION
3	3	6	INDUSTRIAL COMBUSTION - PRIMARY COPPER PRODUCTION
3	3	7	INDUSTRIAL COMBUSTION - SECONDARY LEAD PRODUCTION
3	3	8	INDUSTRIAL COMBUSTION - SECONDARY ZINC PRODUCTION
3	3	9	INDUSTRIAL COMBUSTION - SECONDARY COPPER PRODUCTION
3	3	10	INDUSTRIAL COMBUSTION - SECONDARY ALUMINIUM PRODUCTION
3	3	11	INDUSTRIAL COMBUSTION - CEMENT
3	3	12	INDUSTRIAL COMBUSTION - LIME

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

3	3	13	INDUSTRIAL COMBUSTION - ASPHALT CONCRETE PLANTS
3	3	14	INDUSTRIAL COMBUSTION - FLAT GLASS
3	3	15	INDUSTRIAL COMBUSTION - CONTAINER GLASS
3	3	16	INDUSTRIAL COMBUSTION - GLASS WOOL
3	3	17	INDUSTRIAL COMBUSTION - OTHER GLASS
3	3	18	INDUSTRIAL COMBUSTION - MINERAL WOOL
3	3	19	INDUSTRIAL COMBUSTION - BRICKS AND TILES
3	3	20	INDUSTRIAL COMBUSTION - FINE CERAMICS MATERIALS
3	3	21	INDUSTRIAL COMBUSTION - PAPER MILL INDUSTRY (DRYING PROCES,)
3	3	22	INDUSTRIAL COMBUSTION - ALUMINA PRODUCTION
3	3	23	INDUSTRIAL COMBUSTION - MAGNESIUM (DOLOMITE TREATMENT)
SNAP 4: Industrial Processes			
4	1	0	PRODUCTION PROCESSES - PETROLEUM INDUSTRIES
4	1	1	PRODUCTION PROC, - PETROLEUM PRODUCTS PROCESSING
4	1	2	PRODUCTION PROC, - FLUID CATALYTIC CRACKING - CO BOILER
4	1	3	PRODUCTION PROC, - SULPHUR RECOVERY PLANTS
4	1	4	PRODUCTION PROC, - STORAGE & HANDL, OF PRODUCTS IN REFINERY
4	2	0	PRODUCTION PROC, - IRON AND STEEL INDUSTRIES AND COLLIERIES
4	2	1	PRODUCTION PROC, - COKE OVEN
4	2	2	PRODUCTION PROC, - BLAST FURNACE CHARGING
4	2	3	PRODUCTION PROC, - PIG IRON TAPPING
4	2	4	PRODUCTION PROC, - SOLID SMOKELESS FUEL
4	2	5	PRODUCTION PROC, - OPEN HEARTH FURNACE STEEL PLANT
4	2	6	PRODUCTION PROC, - BASIC OXYGEN FURNACE
4	2	7	PRODUCTION PROC, - ELECTRIC FURNACE STEEL PLANT
4	2	8	PRODUCTION PROC, - ROLLING MILLS
4	3	0	PRODUCTION PROC, - NON FERROUS METAL INDUSTRY
4	3	1	PRODUCTION PROC, - ALUMINIUM PRODUCTION (electrolysis)
4	3	2	PRODUCTION PROC, - FERRO ALLOYS
4	3	3	PRODUCTION PROC, - SILICIUM PRODUCTION
4	3	4	PRODUCTION PROC, - MAGNESIUM
4	4	0	PRODUCTION PROC, - INORGANIC CHEMICAL INDUSTRY
4	4	1	PRODUCTION PROC, - SULFURIC ACID

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

4	4	2	PRODUCTION PROC, - NITRIC ACID
4	4	3	PRODUCTION PROC, - AMMONIA
4	4	4	PRODUCTION PROC, - AMMONIUM SULPHATE
4	4	5	PRODUCTION PROC, - AMMONIUM NITRATE
4	4	6	PRODUCTION PROC, - AMMONIUM PHOSPHATE
4	4	7	PRODUCTION PROC, - NPK FERTILISERS
4	4	8	PRODUCTION PROC, - UREA
4	4	9	PRODUCTION PROC, - CARBON BLACK
4	4	10	PRODUCTION PROC, - TITANIUM DIOXIDE
4	4	11	PRODUCTION PROC, - GRAPHITE
4	4	12	PRODUCTION PROC, - CALCIUM CARBIDE
4	5	0	PRODUCTION PROC, - ORGANIC CHEMICAL INDUSTRY
4	5	1	PRODUCTION PROC, - ETHYLENE
4	5	2	PRODUCTION PROC, - PROPYLENE
4	5	3	PRODUCTION PROC, - 1,2 DICHLOROETHANE (except 040505)
4	5	4	PRODUCTION PROC, - VINYLCHLORIDE (except 040505)
4	5	5	PRODUCTION PROC, - 1,2 DICHLOROETH,+VINYLCHL,(balanced proc)
4	5	6	PRODUCTION PROC, - POLYETHYLENE LOW DENSITY
4	5	7	PRODUCTION PROC, - POLYETHYLENE HIGH DENSITY
4	5	8	PRODUCTION PROC, - POLYVINYLCHLORIDE
4	5	9	PRODUCTION PROC, - POLYPROPYLENE
4	5	10	PRODUCTION PROC, - STYRENE
4	5	11	PRODUCTION PROC, - POLYSTYRENE
4	5	12	PRODUCTION PROC, - STYRENE BUTADIENE
4	5	13	PRODUCTION PROC, - STYRENE-BUTADIENE LATEX
4	5	14	PRODUCTION PROC, - STYRENE-BUTADIENE RUBBER (SBR)
4	5	15	PRODUCTION PROC, - ACRYLONIT, BUTADIENE STYRENE (ABS) RESINS
4	5	16	PRODUCTION PROC, - ETHYLENE OXYDE
4	5	17	PRODUCTION PROC, - FORMALDEHYDE
4	5	18	PRODUCTION PROC, - ETHYLBENZENE
4	5	19	PRODUCTION PROC, - PHTALIC ANHYDRIDE
4	5	20	PRODUCTION PROC, - ACRYLONITRILE
4	5	21	PRODUCTION PROC, - ADIPIC ACID
4	5	22	PRODUCTION PROC, - STORAGE AND HANDLING OF CHEMICAL PRODUCTS
4	6	0	PRODUCTION PROC, - WOOD,PAPER PULP,FOOD,DRINK & OTHER IND,
4	6	1	PRODUCTION PROC, - CHIPBOARD
4	6	2	PRODUCTION PROC, - PAPER PULP (kraft process)

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

4	6	3	PRODUCTION PROC, - PAPER PULP (acid sulfite process)
4	6	4	PRODUCTION PROC, - PAPER PULP (neutral sulphite semi-chemi,)
4	6	5	PRODUCTION PROC, - BREAD
4	6	6	PRODUCTION PROC, - WINE
4	6	7	PRODUCTION PROC, - BEER
4	6	8	PRODUCTION PROC, - SPIRITS
4	6	9	PRODUCTION PROC, - BARK GASIFIER
4	6	10	PRODUCTION PROC, - ASPHALT ROOFING MATERIALS
4	6	11	PRODUCTION PROC, - ROAD PAVING WITH ASPHALT
4	6	12	PRODUCTION PROC, - CEMENT
4	6	13	PRODUCTION PROC, - GLASS
4	6	14	PRODUCTION PROC, - LIMES
4	7	0	PRODUCTION PROC, - COOLING PLANTS
SNAP 5: Extraction, Treatment and Distribution of Fossil Fuels			
5	1	0	EXTRACTION AND 1ST TREATMENT OF SOLID FUELS
5	1	1	EXTRACT, AND 1ST TREAT, OF SOLID FUELS - OPEN CAST MINING
5	1	2	EXTRACT, AND 1ST TREAT, OF SOLID FUELS - UNDER-GROUND MINING
5	1	3	EXTRACT, AND 1ST TREAT, OF SOLID FUELS - STORAGE
5	2	0	EXTRACTION, 1ST TREATMENT AND LOADING OF LIQ-UID FUELS
5	2	1	EXTRACT,, 1ST TREAT, AND LOADING OF LIQ, FUELS - LAND-BASED
5	2	2	EXTRACT,, 1ST TREAT, AND LOADING OF LIQ, FUELS - OFF-SHORE
5	3	0	EXTRACTION, 1ST TREATMENT AND LOADING OF GASE-OUS FUELS
5	3	1	EXTRACT,, 1ST TREAT, AND LOADING OF GAS, FUELS - DESULFURA,
5	3	2	EXTR,, 1ST TREAT, & LOAD, OF GAS, FUELS - OTHER LAND-BASED
5	3	3	EXTRACT, 1ST TREAT, AND LOADING OF GASEOUS FU-ELS - OFF-SHORE
5	4	0	LIQUID FUEL DISTRIBUTION (except gasoline)
5	4	1	LIQ, FUEL DIST, - MARINE TERMINALS (tankers, handl,, stor,)
5	4	2	LIQ, FUEL DIST, (exc, gasoline) - OTHER HANDLING AND STORAGE
5	5	0	GASOLINE DISTRIBUTION
5	5	1	GASOLINE DISTRIBUTION - REFINERY DISPATCH STA-TION

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

5	5	2	GASOLINE DISTRIB, - TRANSP, AND DEPOTS (exc, serv, station)
5	5	3	GASOLINE DISTRIBUTION - SERVICE STATIONS (incl, refuelling)
5	6	0	GAS DISTRIBUTION NETWORKS
5	6	1	GAS DISTRIB, NETWORKS - PIPELINES
5	6	2	GAS DISTRIB, NETWORKS - PIPELINE COMPRESSOR STATIONS
5	6	3	GAS DISTRIB, NETWORKS - DISTRIBUTION NETWORKS
SNAP 6: Solvent Use			
6	1	0	SOLVENT USE - PAINT APPLICATION
6	1	1	SOLVENT USE - PAINT APPLICATION : MANUFACTURE OF AUTOMOBILES
6	1	2	SOLVENT USE - PAINT APPLICATION : OTHER INDUS, APPLICATION
6	1	3	SOLVENT USE - PAINT APPLICATION : CONSTRUCTION AND BUILDINGS
6	1	4	SOLVENT USE - PAINT APPLICATION : DOMESTIC USE
6	2	0	SOLVENT USE - DEGREASING AND DRY CLEANING
6	2	1	SOLVENT USE - METAL DEGREASING
6	2	2	SOLVENT USE - DRY CLEANING
6	3	0	SOLVENT USE - CHEMICALS PRODUCTS MANUFACTURING OR PROCESSING
6	3	1	SOLVENT USE - CHEMICAL PRODUCTS : POLYESTER PROCESSING
6	3	2	SOLVENT USE - CHEMICAL PRODUCTS : POLYVINYLCHLORIDE PROCESS,
6	3	3	SOLVENT USE - CHEMICAL PRODUCTS : POLYURETHANE PROCESSING
6	3	4	SOLVENT USE - CHEMICAL PRODUCTS : POLYSTYRENE FOAM PROCESS,
6	3	5	SOLVENT USE - CHEMICAL PRODUCTS : RUBBER PROCESSING
6	3	6	SOLVENT USE - CHEMICAL PRODUCTS : PHARMACEUTICAL PROD, MANU,
6	3	7	SOLVENT USE - CHEMICAL PRODUCTS : PAINTS MANUFACTURING
6	3	8	SOLVENT USE - CHEMICAL PRODUCTS : INKS MANUFACTURING
6	3	9	SOLVENT USE - CHEMICAL PRODUCTS : GLUES MANUFACTURING
6	3	10	SOLVENT USE - CHEMICAL PRODUCTS : ASPHALT BLOWING

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

6	3	11	SOLVENT USE - CHEMICAL PRODUCTS : ADHESIVE TAPES MANUFACT,
6	4	0	SOLVENT USE - OTHER USE OF SOLVENTS AND RELATED ACTIVITIES
6	4	1	SOLVENT USE - GLASS WOOL ENDUCTION
6	4	2	SOLVENT USE - MINERAL WOOL ENDUCTION
6	4	3	SOLVENT USE - PRINTING INDUSTRY
6	4	4	SOLVENT USE - FAT EDIBLE AND NON EDIBLE OIL EXTRACTION
6	4	5	SOLVENT USE - APPLICATION OF GLUES AND ADHESIVES
6	4	6	SOLVENT USE - PRESERVATION OF WOOD
6	4	7	SOLVENT USE - UNDERSEAL TREATMENT OF VEHICLES
6	4	8	SOLVENT USE - DOMESTIC SOLVENT USE (other than paint appl,)
6	4	9	SOLVENT USE - VEHICLES DEWAXING
SNAP 7: Road Transport			
7	1	0	ROAD TRANSPORT - PASSENGER CARS
7	1	1	ROAD TRANSPORT - PASSENGER CARS : HIGHWAY DRIVING
7	1	2	ROAD TRANSPORT - PASSENGER CARS : RURAL DRIVING
7	1	3	ROAD TRANSPORT - PASSENGER CARS : URBAN DRIVING
7	2	0	ROAD TRANSPORT - LIGHT DUTY VEHICLES < 3,5 t
7	2	1	ROAD TRANSPORT - LIGHT DUTY VEHICLES < 3,5 t : HIGHWAY DRIV,
7	2	2	ROAD TRANSPORT - LIGHT DUTY VEHICLES < 3,5 t : RURAL DRIVING
7	2	3	ROAD TRANSPORT - LIGHT DUTY VEHICLES < 3,5 t : URBAN DRIVING
7	3	0	ROAD TRANSPORT - HEAVY DUTY VEHICLES > 3,5 t AND BUSES
7	3	1	ROAD TRANS, - HEAVY DUTY VEHIC, AND BUSES : HIGHWAY DRIVING
7	3	2	ROAD TRANS, - HEAVY DUTY VEHIC, AND BUSES : RURAL DRIVING
7	3	3	ROAD TRANS, - HEAVY DUTY VEHIC, AND BUSES : URBAN DRIVING
7	4	0	ROAD TRANSPORT - MOPEDS AND MOTORCYCLES < 50 CM3
7	5	0	ROAD TRANSPORT - MOTORCYCLES > 50 CM3
7	5	1	ROAD TRANSPORT - MOTORCYCLES > 50 CM3 : HIGHWAY DRIVING

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

7	5	2	ROAD TRANSPORT - MOTORCYCLES > 50 CM3 : ROAD DRIVING
7	5	3	ROAD TRANSPORT - MOTORCYCLES > 50 CM3 : URBAN DRIVING
7	6	0	ROAD TRANSPORT - GASOLINE EVAPORATION FROM VEHICLES
SNAP 8: Other Mobile Sources			
8	1	0	OTHER MOB, SOURCES - OFF ROAD VEHICLES AND MACHINES
8	1	1	OTHER MOB, SOURCES - OFF ROAD VEHIC, AND MACHINES: AGRICULT,
8	1	2	OTHER MOB, SOURCES - OFF ROAD VEHIC, AND MACHINES: FORESTRY
8	1	3	OTHER MOB, SOURCES - OFF ROAD VEHIC, AND MACHINES: INDUSTRY
8	1	4	OTHER MOB, SOURCES - OFF ROAD VEHIC, AND MACHINES: MILITARY
8	1	5	OTHER MOB, SOURCES - HOUSEHOLD / GARDENING
8	2	0	OTHER MOB, SOURCES - RAILWAYS
8	3	0	OTHER MOB, SOURCES - INLAND WATERWAYS
8	4	0	OTHER MOB, SOURCES - MARINE ACTIVITIES
8	4	1	OTHER MOB, SOURCES - MARINE ACTIVITIES: HARBOURS
8	4	2	OTHER MOB, SOURCES - MARINE ACTIVITIES: NATIONAL SEA TRAFFIC
8	4	3	OTHER MOB, SOURCES - MARINE ACTIVITIES: NATIONAL FISHING
8	5	0	OTHER MOB, SOURCES - AIRPORTS (LTO cycles and ground act,)
SNAP 9: Waste Treatment and Disposal			
9	1	0	WASTE TREATMENT AND DISPOSAL - WASTE WATER TREATMENT
9	2	0	WASTE TREATMENT AND DISPOSAL - WASTE INCINERATION
9	2	1	WASTE TREAT, AND DISP, - INCINER, DOMESTIC/MUNICIPAL WASTES
9	2	2	WASTE TREAT, AND DISP, - INCINERATION OF INDUSTRIAL WASTES
9	2	3	WASTE TREATMENT AND DISPOSAL - FLARING IN OIL INDUSTRY
9	2	4	WASTE TREAT, AND DISP, - FLARING IN CHEMICAL INDUSTRIES
9	2	5	WASTE TREAT, AND DISP, - INCINER, OF SLUDGES FROM WATER TR,

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

9	3	0	WASTE TREATMENT AND DISPOSAL - SLUDGE SPREADING
9	4	0	WASTE TREATMENT AND DISPOSAL - LAND FILLING
9	5	0	WASTE TREATMENT AND DISPOSAL - COMPOST PRODUCTION FROM WASTE
9	6	0	WASTE TREATMENT AND DISPOSAL - BIOGAS PRODUCTION
9	7	0	W,T,D, - OPEN BURNING OF AGRICULTURAL WASTES (except 10,03)
9	8	0	WASTE TREATMENT AND DISPOSAL - LATRINES
SNAP 10: Agriculture			
10	1	0	AGRICULTURE - CULTURES WITH FERTILIZERS except animal manure
10	1	1	AGRICULTURE - CULTURES WITH FERTILIZERS : PERMANENT CROPS
10	1	2	AGRICULTURE - CULTURES WITH FERTILIZERS : ARABLE LAND CROPS
10	1	3	AGRICULTURE - CULTURES WITH FERTILIZERS : RICE FIELD
10	1	4	AGRICULTURE - CULTURES WITH FERTILIZERS : MARKET GARDENING
10	1	5	AGRICULTURE - CULTURES WITH FERTILIZERS : GRASSLAND
10	1	6	AGRICULTURE - CULTURES WITH FERTILIZERS : FALLOWS
10	2	0	AGRICULTURE - CULTURES WITHOUT FERTILIZERS
10	2	1	AGRICULTURE - CULTURES WITHOUT FERTILIZERS : PERMANENT CROPS
10	2	2	AGRICULTURE - CULTURES WITHOUT FERTILIZ, : ARABLE LAND CROPS
10	2	3	AGRICULTURE - CULTURES WITHOUT FERTILIZERS : RICE FIELD
10	2	4	AGRICULTURE - CULTURES WITHOUT FERTILIZ, : MARKET GARDENING
10	2	5	AGRICULTURE - CULTURES WITHOUT FERTILIZERS : GRASSLAND
10	2	6	AGRICULTURE - CULTURES WITHOUT FERTILIZERS : FALLOWS
10	3	0	AGRICULTURE - STUBBLE BURNING
10	4	0	AGRICULTURE - ANIMAL BREEDING (enteric fermentation)
10	4	1	AGRICULTURE - ANIMAL BREEDING (enteric ferm,) : DAIRY COWS
10	4	2	AGRICULTURE - ANIMAL BREEDING (enteric ferm,) : OTHER CATTLE

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

10	4	3	AGRICULTURE - ANIMAL BREEDING (enteric fermentat,) : OVINES
10	4	4	AGRICULTURE - ANIMAL BREEDING (enteric fermentation) : PIGS
10	4	5	AGRICULTURE - ANIMAL BREEDING (enteric fermentat,) : HORSES
10	4	6	AGRICULTURE - ANIMAL BREEDING (enteric fermentation) : ASSES
10	4	7	AGRICULTURE - ANIMAL BREEDING (enteric fermentation) : GOATS
10	5	0	AGRICULTURE - ANIMAL BREEDING (excretions)
10	5	1	AGRICULTURE - ANIMAL BREEDING (excretions) : DAIRY COWS
10	5	2	AGRICULTURE - ANIMAL BREEDING (excretions) : OTHER CATTLE
10	5	3	AGRICULTURE - ANIMAL BREEDING (excretions) : FAT-TENING PIGS
10	5	4	AGRICULTURE - ANIMAL BREEDING (excretions) : SOWS
10	5	5	AGRICULTURE - ANIMAL BREEDING (excretions) : SHEEP
10	5	6	AGRICULTURE - ANIMAL BREEDING (excretions) : HORSES
10	5	7	AGRICULTURE - ANIMAL BREEDING (excretions) : LAYING HENS
10	5	8	AGRICULTURE - ANIMAL BREEDING (excretions) : BROIL-ERS
10	5	9	AGRICULTURE - ANIMAL BREEDING (excretions) : OTHER POULTRY
10	5	10	AGRICULTURE - ANIMAL BREEDING (excretions) : FUR AN-IMALS
SNAP 11: Nature			
11	1	0	NATURE - DECIDUOUS FORESTS
11	1	1	NATURE - DECIDUOUS FORESTS : HIGH ISOPRENE EMIT-TERS
11	1	2	NATURE - DECIDUOUS FORESTS : LOW ISOPRENE EMIT-TERS
11	1	3	NATURE - DECIDUOUS FORESTS : NON ISOPRENE EMIT-TERS
11	2	0	NATURE - CONIFEROUS FORESTS
11	3	0	NATURE - FOREST FIRES
11	4	0	NATURE - NATURAL GRASSLAND
11	5	0	NATURE - HUMID ZONES
11	5	1	NATURE - HUMID ZONES : UNDRAINED AND BRACKISH MARSHES
11	5	2	NATURE - HUMID ZONES : DRAINED MARSHES
11	5	3	NATURE - HUMID ZONES : RAISED BOGS

Table A.1. (continued) CORINAIR 90 SNAP Nomenclature

11	6	0	NATURE - WATERS
11	6	1	NATURE - LAKES
11	6	2	NATURE - SHALLOW SALTWATERS
11	6	3	NATURE - GROUND WATERS
11	6	4	NATURE - DRAINAGE WATERS
11	6	5	NATURE - RIVERS
11	6	6	NATURE - DITCHES AND CANALS
11	6	7	NATURE - OPEN SEA (> 6m)
11	7	0	NATURE - ANIMALS
11	7	1	NATURE - ANIMALS : TERMITES
11	7	2	NATURE - ANIMALS : MAMMALS
11	8	0	NATURE - VOLCANOES
11	9	0	NATURE - NEAR SURFACE DEPOSITS
11	10	0	NATURE - HUMANS

B Scenario data for emission projection.

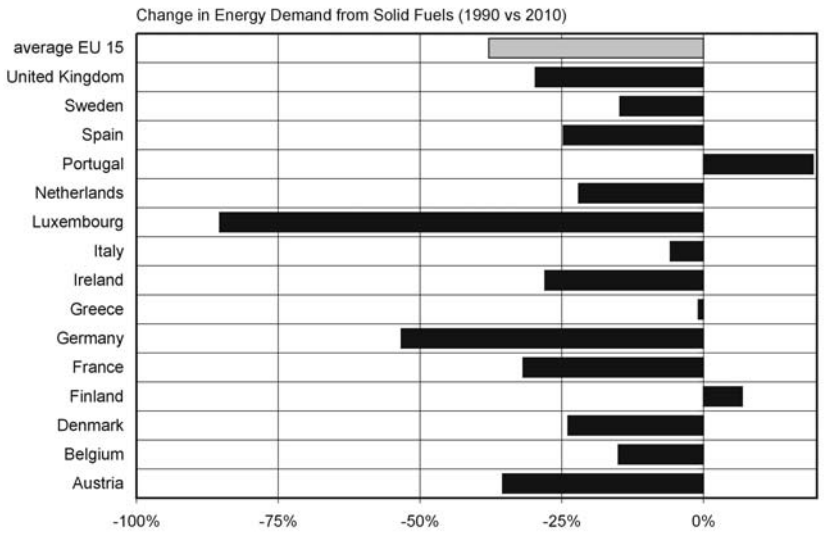

Fig. B.1. Changes in energy demand from solid fuels – 1990 vs. 2010
(Source: DG XVII 1996)

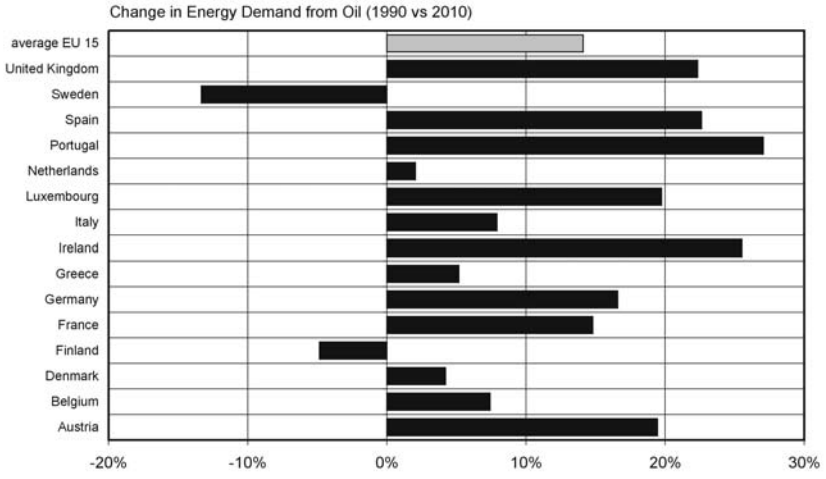

Fig. B.2. Changes in energy demand from oil – 1990 vs. 2010
(Source: DG XVII 1996)

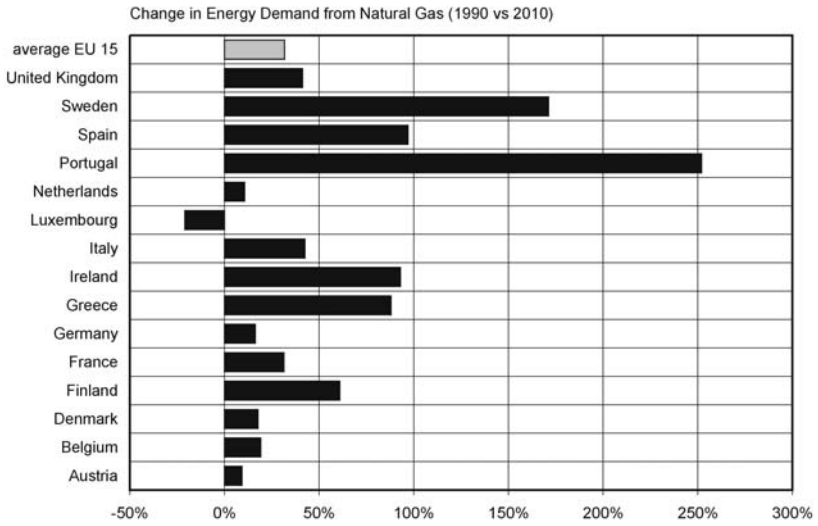

Fig. B.3. Changes in energy demand from natural gas – 1990 vs. 2010
(Source: DG XVII 1996)

Table B.1. Overview on legislation concerning road transport vehicles in the EU

EU Directive	Vehicle Type and Emissions Control
70/156/EEC	Type approval framework Directive
70/220/EEC	Exhaust emissions for gasoline passenger cars and light duty vehicles
72/306/EEC	Heavy duty diesel black smoke emissions
74/290/EEC	Exhaust emissions for gasoline passenger cars and light duty vehicles
77/102/EEC	Exhaust emissions for gasoline passenger cars and light duty vehicles
77/143/EEC	In-service emissions testing
78/665/EEC	Exhaust emissions for gasoline passenger cars and light duty vehicles
83/351/EEC	Exhaust emissions for gasoline and diesel passenger cars and light duty vehicles
87/77/EEC	Heavy duty diesel exhaust emissions
88/77/EEC	Exhaust emissions from heavy duty diesels
88/436/EEC	Revised PM requirements for diesel passenger cars
88/449/EEC	In-service emissions testing
89/458/EEC	Revised CO and HC+ NO_x limits for passenger cars, implemented by 91/441/EEC

Table B.1. (continued) Overview on legislation concerning road transport vehicles in the EU

91/441/EEC	Passenger cars; revised exhaust emissions plus evaporative emissions by ECE R15+EUDC cycles (R 83 Type Approvals B and C for gasoline and diesel respectively)
91/542/EEC	EU Clean Lorry Directive for heavy duty diesel exhaust emissions
92/55/EEC	In-service emissions testing
93/59/EEC	Exhaust emissions for light commercial vehicles (M_1 and N_1)
93/116/EC	CO_2 and fuel consumption reporting for passenger cars
94/12/EC	Passenger cars; revised exhaust emissions standards
96/1/EC	Amendments to 88/77/EEC (Production Conformity, PM for „small engines“)
96/27/EC	Type approval of motor vehicles
96/69/EC	Amends 70/220 & 93/59 exhaust emissions for passenger cars and LDV

Table B.2. Activities covered by the EC Solvent Directive

Activities regulated by the Directive 97/C99/02	**Annex**
adhesive coating	XVII
coating of films, paper, textiles, fabric	XIII
metallic and plastics surfaces	XI
vehicles	V, VI, VII, VIII
coils	X
leather	XVI
adhesive coating	XVII
wooden surfaces	XII
dry cleaning	XIV
impregnation of wood	XV
manufacture of coatings	XVIII
pharmaceutical processes	XXI
printing processes	III
rubber processing	XIX
surface cleaning	IV
vegetable oil extraction	XX
vehicle refinishing	IX

C List of modelled abatement measures

The following tables give a detailed summary of all technical abatement measures that have been taken into account for the generation of country-specific abatement cost curves and their respective measure code.

Table C.1. Abatement measures for the sector *road transport*

Description	Measure code
EURO I compliance, technical measures for Passenger Cars gasoline	T_PCg_M1
EURO II compliance, technical measures for Passenger Cars gasoline	T_PCg_M2
EURO III compliance, technical measures for Passenger Cars gasoline	T_PCg_M3
EURO IV compliance, technical measures for Passenger Cars gasoline	T_PCg_M4
EURO I compliance, technical measures for Passenger Cars diesel	T_PCd_M1
EURO II compliance, technical measures for Passenger Cars diesel	T_PCd_M2
EURO III compliance, technical measures for Passenger Cars diesel	T_PCd_M3
EURO IV compliance, technical measures for Passenger Cars diesel	T_PCd_M4
EURO I compliance, technical measures for Light Duty Vehicles gasoline	T_LDg_M1
EURO II compliance, technical measures for Light Duty Vehicles gasoline	T_LDg_M2
EURO III compliance, technical measures for Light Duty Vehicles gasoline	T_LDg_M3
EURO IV compliance, technical measures for Light Duty Vehicles gasoline	T_LDg_M4
EURO I compliance, technical measures for Light Duty Vehicles diesel	T_LDd_M1
EURO II compliance, technical measures for Light Duty Vehicles diesel	T_LDd_M2
EURO III compliance, technical measures for Light Duty Vehicles diesel	T_LDd_M3
EURO IV compliance, technical measures for Light Duty Vehicles diesel	T_LDd_M4
EURO I compliance, technical measures for HeavyDuty Vehicles	T_HDV_M1
EURO II compliance, technical measures for Heavy Duty Vehicles	T_HDV_M2
EURO III compliance, technical measures for Heavy Duty Vehicles	T_HDV_M3
EURO IV compliance, technical measures for Heavy Duty Vehicles	T_HDV_M4
Technical improvements for Two-wheelers (2-stroke)	T_TW2_TI
Technical improvements for Two-wheelers (4-stroke)	T_TW4_TI
Carbon canister for PC and LDV gasoline	T_PCg_CC

Table C.2. Abatement measures for the *energy sector*

Description	Measure code
Primary Measures for coal fired combustion plants, retrofit	E_COA_Pr
Primary Measures for oil fired combustion plants, retrofit	E_OIL_Pr
Primary Measures for gas fired combustion plants, retrofit	E_GAS_Pr
Primary Measures for coal fired combustion plants, new	E_COA_Pn
Primary Measures for oil fired combustion plants, new	E_OIL_Pn
Primary Measures for gas fired combustion plants, new	E_GAS_Pn
SCR, coal fired plants, retrofit	E_COA_Sr
SCR, oil fired plants, retrofit	E_OIL_Sr
SCR, gas fired plants, retrofit	E_GAS_Sr
SCR, coal fired plants, new	E_COA_Sn
SCR, oil fired plants, new	E_OIL_Sn
SCR, gas fired plants, new	E_GAS_Sn
SNCR, coal fired plants, retrofit	E_COA_Nr
SNCR, oil fired plants, retrofit	E_OIL_Nr
SNCR, gas fired plants, retrofit	E_GAS_Nr
SNCR, coal fired plants, new	E_COA_Nn
SNCR, oil fired plants, new	E_OIL_Nn
SNCR, gas fired plants, new	E_GAS_Nn
Hybrid SCR/SNCR, coal fired plants, retrofit	E_COA_Hr
Hybrid SCR/SNCR, oil fired plants, retrofit	E_OIL_Hr
Hybrid SCR/SNCR, gas fired plants, retrofit	E_GAS_Hr
Hybrid SCR/SNCR, coal fired plants, new	E_COA_Hn
Hybrid SCR/SNCR, oil fired plants, new	E_OIL_Hn
Hybrid SCR/SNCR, gas fired plants, new	E_GAS_Hn

Table C.3. Abatement measures for *residential, institutional and commercial combustion sources*

Description	Measure code
Primary Measures for coal fired boilers	H_COA_PM
Primary Measures for oil fired boilers	H_OIL_PM
Primary Measures for gas fired boilers	H_GAS_PM

Table C.4. Abatement measures for the sector *solvent use*

Description	Measure code
Furniture Coating, good housekeeping	S_FUR_gh
Furniture Coating, substitution	S_FUR_sb
Furniture Coating, process modification	S_FUR_pm
Furniture Coating, thermal oxidation and adsorption	S_FUR_ox
Coil Coating, good housekeeping	S_CCA_gh
Coil Coating, thermal oxidation	S_CCA_ox
Film Coating, thermal oxidation	S_FCA_ox
Surface Cleaning, good housekeeping	S_SFC_gh
Surface Cleaning, substitution	S_SFC_sb
Surface Cleaning, improved design	S_SFC_id
Surface Cleaning, new enclosed system	S_SFC_es
Surface Cleaning, single sealed chamber	S_SFC_sc
Surface Cleaning, double lidded system (DLS)	S_SFC_ds
Surface Cleaning, DLS with carbon adsorption	S_SFC_dc
Vehicle Refinishing, good housekeeping	S_VRF_gh
Vehicle Refinishing, high volume low pressure (HVLP)	S_VRF_hv
Vehicle Refinishing, enclosed gunwash	S_VRF_eg
Vehicle Refinishing, HVLP + high solids	S_VRF_hh
Vehicle Refinishing, HVLP + water borne	S_VRF_hw
Vehicle Manufacture, good housekeeping	S_VMF_gh
Vehicle Manufacture, substitution (medium solids)	S_VMF_ms
Vehicle Manufacture, substitution (water based)	S_VMF_wb
Vehicle Manufacture, thermal oxidation	S_VMF_ox
General Rubber Goods, good housekeeping	S_GRG_gh
General Rubber Goods, process modification	S_GRG_pm
General Rubber Goods, thermal oxidation	S_GRG_ox
General Rubber Goods, carbon adsorption	S_GRG_ca
General Rubber Goods, substitution	S_GRG_sb
Tyre Manufacturers, good housekeeping	S_TYR_gh
Tyre Manufacturers, process modification	S_TYR_pm
Tyre Manufacturers, thermal oxidation	S_TYR_ox
Tyre Manufacturers, carbon adsorption	S_TYR_ca
Tyre Manufacturers, substitution	S_TYR_sb
Printing Industry, good housekeeping	S_PRN_gh
Printing Industry, thermal oxidation	S_PRN_ox

Table C.4. (continued) Abatement measures for the sector *solvent use*

Description	Measure code
Furniture Coating, good housekeeping	S_FUR_gh
Adhesive and Sealand Use, thermal oxidation	S_ADH_ox
Adhesive and Sealand Use, good housekeeping	S_ADH_gh
Adhesive and Sealand Use, high solids	S_ADH_hs
Adhesive and Sealand Use, process modification	S_ADH_pm

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