EC4MACS
Modelling Methodology

The GAINS Integrated Assessment Model

European Consortium for Modelling of Air Pollution and Climate Strategies - EC4MACS

Editors:
Markus Amann (IIASA)

March 2012

Table of Contents

Purpose of this document

This documentation provides background information to the reviewers of the GAINS 2009 peer review that will be conducted under the EC4MACS project (www.ec4macs.eu) of the EU LIFE programme.

Acknowledgements

The GAINS model brings together work from a large group of scientists from a wide range of disciplines. Thus, the development of the GAINS model would not have been possible without the constructive cooperation of so many colleagues.

The authors wish to express their sincere thanks to the large numbers of colleagues on whose contributions this works rests. In particular, we would like to thank

- Jürgen Schneider from the WHO European Office for Health, Bonn, for his critical review of the draft document and his constructive additions to this text,
- Leonor Tarrason, David Simpson and all their colleagues at EMEP/MSC-W at the Norwegian Meteorological Institute for their cooperation on regional-scale ozone modelling,
- Jean-Paul Hettelingh and Max Posch from RIVM, Netherlands, for their contributions to the modelling of ecosystems impacts,
- Kees Cuvelier and Philippe Thunis from the Joint Research Centre (JRC), Ispra, for providing material from the City-Delta and Euro-Delta model intercomparison projects, as well as all participants in these intercomparison exercises,
- Bernd Schärer (Umweltbundesamt Berlin), Mike Woodfield (AEAT, UK) and the colleagues from the Expert Groups on Techno-Economic Issues (EGTEI) at CITEPA, France, for assistance in the development of cost estimates for emission control options,
- Les White (Les White Associates) for his constructive review of the RAINS modelling approach,
- Marek Makowski (IIASA) for his involvement in the development and implementation of the RAINS optimization module.

In addition to core funds from IIASA, over time many institutions have made financial contributions towards the development of the RAINS and GAINS model. The authors would like to express their thanks to the following institutions:

- European Commission, LIFE programme
- European Commission, Directorate General for Environment, Nuclear Safety and Civil Protection, Brussels, Belgium
- European Environment Agency (EEA), Denmark
- United Nations, Economic Commission of Europe, Switzerland
- Finnish Environment Institute, Helsinki, Finland
- Ministry of Environment, Paris, France
- German Federal Environmental Agency, Berlin, Germany
- Italian Agency for New Technology, Energy and the Environment, Rome, Italy
- The Ministry of Housing, Spatial Planning and the Environment (VROM), The Hague, The Netherlands
- National Institute of Public Health and the Environment (RIVM), The Netherlands
- Norwegian Meteorological Institute (DNMI), Oslo, Norway
- The Royal Ministry of the Environment, Oslo, Norway
- Swiss Office of Environment, Forest and Landscape, Bern, Switzerland
- Department of the Environment, Food and Rural Affairs, London, United Kingdom
- Nordic Council of Ministers, Sweden
- The Oil Companies' European Organization for environment, health and safety (CONCAWE), Brussels, Belgium

Obviously, views and opinions expressed in this paper do not necessarily represent those of the funding institutions.

1 Introduction

For a number of historic reasons, response strategies to air pollution and climate change are often addressed by different policy institutions. However, there is growing recognition that a comprehensive and combined analysis of air pollution and climate change could reveal important synergies of emission control measures (Swart *et al.*, 2004), which could be of high policy relevance. Insight into the multiple benefits of control measures could make emission controls economically more viable, both in industrialized and developing countries. While scientific understanding on many individual aspects of air pollution and climate change has considerably increased in the last years, little attention has been paid to a holistic analysis of the interactions between both problems.

The Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model has been developed as a tool to identify emission control strategies that achieve given targets on air quality and greenhouse gas emissions at least costs. GAINS considers measures for the full range of precursor emissions that cause negative effects on human health via the exposure of fine particles and ground-level ozone, damage to vegetation via excess deposition of acidifying and eutrophying compounds, as well as the six greenhouse gases considered in the Kyoto protocol. In addition, it also considers how specific mitigation measures simultaneously influence different pollutants. Thereby, GAINS allows for a comprehensive and combined analysis of air pollution and climate change mitigation strategies, which reveals important synergies and trade-offs between these policy areas.

IIASA's Greenhouse gas – Air Pollution Interactions and Synergies (GAINS) model explores synergies and trade-offs between the control of local and regional air pollution and the mitigation of global greenhouse gas emissions. GAINS estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_x, PM, NH_3, VOC) and for the six greenhouse gases included in the Kyoto protocol. GAINS quantifies the technical and economic interactions between mitigation measures for the considered air pollutants and greenhouse gases. It assesses the simultaneous impacts of emission reductions on air pollution (i.e., shortening of statistical life expectancy due to the human exposure to PM2.5, premature mortality related to ground-level ozone, protection of vegetation against harmful effects of acidification and excess nitrogen deposition) as well as for selected metrics of greenhouse gases (e.g., the global warming potentials). Thereby GAINS explores the full effect of reducing air pollutants and/or greenhouse gases on all these endpoints. In addition, GAINS includes an optimization approach that allows the search for least-cost combination of mitigation measures for air pollutants and/or greenhouse gases that meet user-specified constraints (policy targets) for each of the environmental endpoints listed above. Thereby, GAINS can identify mitigation strategies that achieve air quality and greenhouse gas related targets simultaneously at least cost.

This report provides a documentation of the methodology that is applied for the GAINS model.

2 General approach

2.1 A multi-pollutant/multi-effect DPSIR approach

The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model quantifies the full DPSIR (demand-pressure-state-impact-response) chain for the emissions of air pollutants and greenhouse gases. Thereby it represents an extension – and a practical implementation - of the pressure-state-response model developed by the OECD. GAINS incorporates data and information on all the different elements in the DPSIR chain and specifies connections between these different aspects. In particular GAINS quantifies the DPSIR chain of air pollution from the driving forces (economic activities, energy combustion, agricultural production, etc.) to health and ecosystems effects (Figure 2.1).

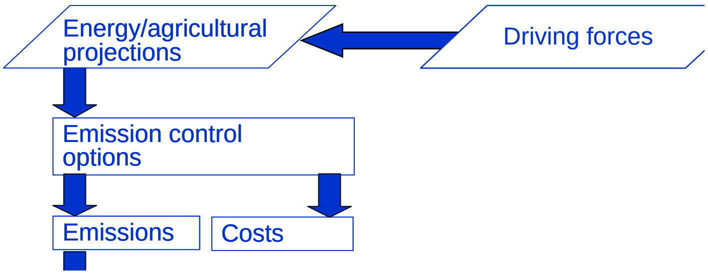

Figure 2.1: DPSIR chain of the GAINS model for the emissions of greenhouse gases and air pollutants

For each of the model compartments shown in Figure 2.1, GAINS quantifies the most relevant state variables using latest scientific understanding and best available data, and describes the interactions of these variables with those of other compartments. Thereby, GAINS describes the fate of pollution from the origin (anthropogenic driving forces) to the impacts.

GAINS captures the multi-pollutant/multi-effect nature of atmospheric pollution. It addresses impacts of air pollution on human health, vegetation and aquatic ecosystems, and considers the release of a emissions that exert radiative forcing. GAINS follows emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), various fractions of fine particulate matter (PM), ammonia (NH_3) and volatile organic compounds (VOC). In addition to these air pollutants, GAINS includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the F-gases HFC, PFC, SF_6 (Figure 2.2).

	PM	SO_2	NO_x	VOC	NH_3	CO_2	CH_4	N
Health impacts: PM	√	√	√	√	√			
O_3			√	√			√	
Vegetation damage: O			√	√			√	

Figure 2.2: The GAINS multi-pollutant/multi-effect framework

2.2 Scenario analysis and optimisation

The GAINS model framework makes it possible to estimate, for a given energy- and agricultural scenario, the costs and environmental effects of user-specified emission control policies (the "scenario analysis" mode), see Figure 2.3. Furthermore, an optimisation mode can be used to identify the cost-minimal combination of emission controls meeting user-supplied targets on air quality and/or greenhouse gas emissions, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. The optimisation capability of GAINS enables the development of multi-pollutant, multi-effect pollution control strategies. In particular, the optimisation can be used to search for cost-minimal balances of controls of the 12 pollutants (SO_2, NO_x, VOC, NH_3, primary $PM_{2,5}$, primary $PM_{10-2.5}$ (= PM coarse), CO_2, CH_4, N_2O, HFC, PFC, SF_6) over the various economic sectors in all European countries that simultaneously achieve user-specified targets for human health impacts (e.g., expressed in terms of reduced life expectancy), ecosystems protection (e.g., expressed in terms of excess acid and nitrogen deposition), maximum allowed violations of WHO guideline values for ground-level ozone, and a basket of greenhouse gas emissions (Figure 2.3).

While the scenario analysis mode can be used to illustrate the economic and environmental consequences of an exogenously assumed pattern of emission controls, the optimisation feature allows the systematic identification of the least-cost allocation of emission controls that meet exogenously determined environmental targets for air pollution and greenhouse gas emissions.

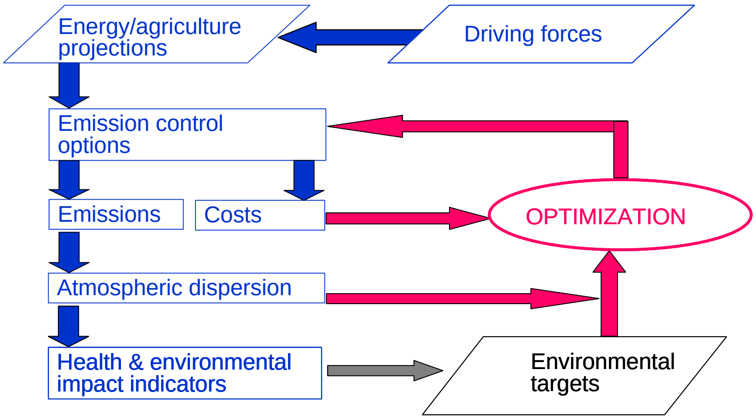

Figure 2.3: The iterative concept of the GAINS optimisation

With the scenario mode, the number of "what-if" scenarios that can be explored with the GAINS model is limited, which makes it impossible to fully explore the consequences of even the most important permutations of emission control measures in all economic sectors of several dozens of countries. Thus, in practice such scenarios address a limited number of technology-related emission control rationales, but cannot deliver a systematic analysis of environmentally driven emission control strategies.

The optimisation concept provides an important element of a "science based" rationale as a basis for emission reduction accords. By calculating country- and sector-specific reduction requirements for any exogenously specified environmental target, the GAINS optimisation can provide results that are of immediate relevance to negotiators because they meet the spatial and temporal scales that are relevant for decision makers. The optimisation is also attractive because, while striving for a common target (e.g., equal environmental improvement for all Parties), it considers environmental and economic differences between Parties that lead to objectively justifiable differences in abatement efforts. Resulting inequities in abatement burdens are based on scientifically determined differences in environmental sensitivities, atmospheric dispersion characteristics or emission source structures.

It is also important that the optimisation problem as set up in the GAINS model does not provide an absolute and unique answer to the pollution control problem. Actual results of an optimisation run depend on the environmental objectives (e.g., the acceptable environmental risk) as established by the negotiators, the goal function (minimization of total emission control costs), and the problem framing (e.g., the exclusion of changes in the energy systems, which cannot be directly influenced by environmental policies in Europe). All these settings are subject to negotiations, and the optimisation results are critically influenced by the policy choices on these issues. Thus, the GAINS model does not internalise policy choices, but deliberately leaves room for decisions of negotiators.

2.3 System boundaries

It is at the heart of integrated assessment models to achieve integration by including as many aspects as possible in order to gain comprehensive insights into the full range of issues related to the strategies under consideration. However, it is also crucial to keep integrated assessment models manageable in order to facilitate the direct interaction with decision makers in the analysis of a large number of alternatives in a timely manner. Thus, integrated assessment modelling must strike a balance between a larger range of integration on the one side and practical manageability (for modellers) and transparency (for users) on the other.

Over time, the predecessor of GAINS, i.e., the RAINS (Regional Air Pollution Information and Simulation) model has included a large number of aspects of air pollution, and has developed into a powerful tool for providing policy relevant insight into many facets of air pollution control. However, deliberate decisions were taken by the developers of GAINS to keep certain aspects outside the model, partly because they are of less relevance than other aspects, and partly because an appropriate treatment of these issues would dramatically increase the complexity of the overall GAINS model and thus seriously compromise its performance and transparency. Nevertheless, it is recognized that many aspects that are presently not hard-wired into GAINS are important.

This applies particularly to the assessment of ancillary benefits, to the monetary evaluation of benefits, to emission control options that imply substantial structural changes in the economy (or deviations from the baseline assumptions about economic development), and to the macro-economic feedbacks of emission control strategies. With the tightening stringency of emission control strategies over time, it becomes increasingly important to treat these issues properly in order to obtain a full picture of costs and benefits of possible policy action.

Compared to the earlier RAINS model, the GAINS model incorporates now aspects that constitute important interactions with greenhouse gas mitigation strategies. GAINS covers now a wider range of pollutants, and it includes structural changes in the energy systems such as energy efficiency improvements and fuel substitution as means for emission reductions. It models the impacts of emission control measures on multiple pollutants (co-control) for a wide range of mitigation options in the energy and agricultural sectors.

However, GAINS does not include the simulation of behavioural changes of consumers that influence demand for energy, transport and agriculture; also responses of the energy and agricultural markets towards higher emission control costs are outside its systems boundaries, and it does not address effects that higher pollution control costs might have on the transfer of production to third countries. The main rationale for excluding such effects from the immediate GAINS analysis is the interest to maintain transparency and manageability of the GAINS model.

Instead of incorporating all complex relations that are relevant for these aspects into one super-model, a network of specialized models that address these aspects in more detail has been created through the EC4MACS (European Consortium for the Modelling of Air pollution and Climate Strategies) project (www.ec4macs.eu). The EC4MACS model suite includes the GAINS integrated assessment model for air pollution, the PRIMES energy model, the TREMOVE transport model, the CAPRI agriculture model, the EMEP atmospheric dispersion model, the GAINS-Europe model for greenhouse gas mitigation, models for health and ecosystems impacts, the GEM-E3 macro-economic general equilibrium model and the Beta and Externe benefit assessment approaches (Figure 2.4). Furthermore, to embed the European-scale analyses into a global context, EC4MACS includes the global scale POLES energy model and the TM5 global chemistry and transport model.

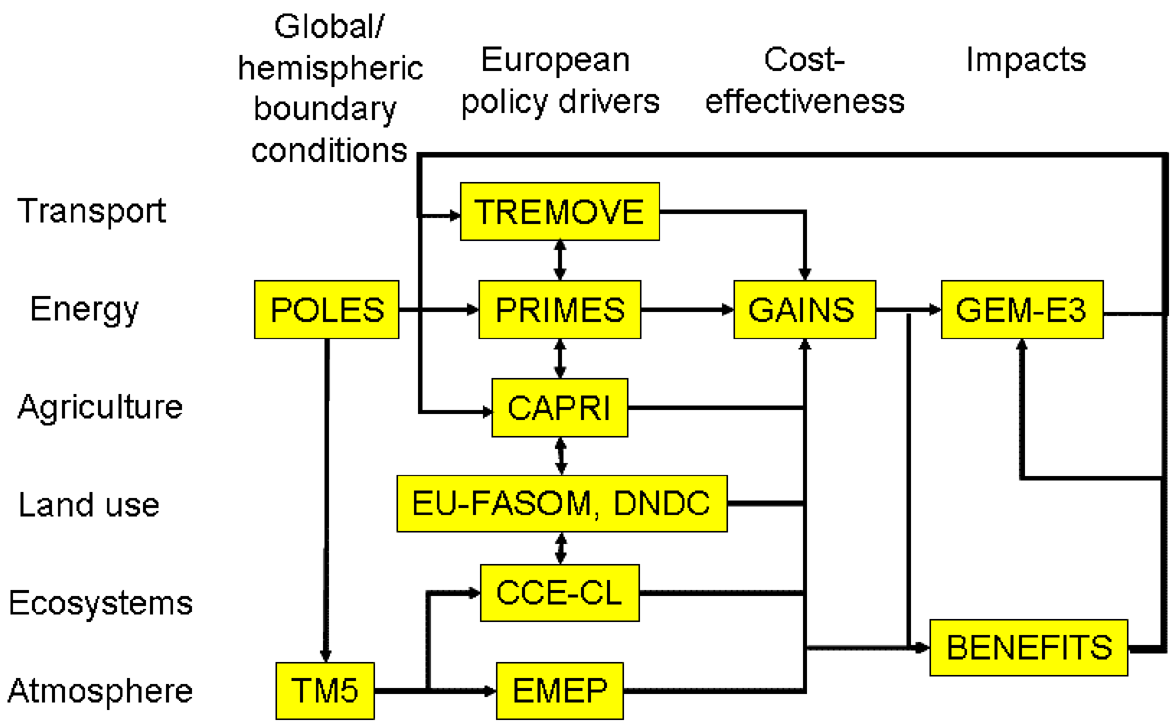

Figure 2.4: Linkages of the EC4MACS models

3 Emissions and mitigation potentials

3.1 Emission estimates

For each of the pollutants, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures and the extent to which such measures are applied:

$$E_{i,p} = \sum_k \sum_m A_{i,k} ef_{i,k,m,p} x_{i,k,m,p} \tag{1}$$

where:

i, k, m, p	Country, activity type, abatement measure, pollutant, respectively
$E_{i,p}$	Emissions of pollutant p (for SO_2, NO_x, VOC, NH_3, PM2.5, CO_2 , CH_4, N_2O, etc.) in country i
$A_{i,k}$	Activity level of type k (e.g., coal consumption in power plants) in country i
$ef_{i,k,m,p}$	Emission factor of pollutant p for activity k in country i after application of control measure m
$x_{i,k,m,p}$	Share of total activity of type k in country i to which a control measure m for pollutant p is applied.

This approach allows capturing critical differences across economic sectors and countries that could justify differentiated emission reduction requirements in a cost-effective strategy. It reflects structural differences in emission sources through country-specific activity levels. It represents major differences in emission characteristics of specific sources and fuels through source-specific emission factors, which account for the degrees at which emission control measures are applied. More detail is available in Cofala and Syri, 1998a, Cofala and Syri, 1998b, Klimont *et al.*, 2000, Klimont *et al.*, 2002, Klimont and Brink, 2006, Klaassen *et al.*, 2005, Höglund-Isaksson and Mechler, 2005, Winiwarter, 2005, Tohka, 2005. GAINS estimates future emissions according to Equation 1 by varying the activity levels along exogenous projections of anthropogenic driving forces and by adjusting the implementation rates of emission control measures.

3.2 Emission control measures and their costs

Basically, three groups of measures to reduce emissions can be distinguished:

- *Behavioral changes* reduce anthropogenic driving forces that generate pollution. Such changes in human activities can be autonomous (e.g., changes in life styles), they could be fostered by command-and-control approaches (e.g., legal traffic restrictions), or they can be triggered by economic incentives (e.g., pollution taxes, emission trading systems, etc.). The GAINS concept does not internalize such behavioral responses, but reflects such changes through alternative exogenous scenarios of the driving forces.
- *Structural measures* that supply the same level of (energy) services to the consumer but with less polluting activities. This group includes fuel substitution (e.g., switch from coal to natural

gas) and energy conservation/energy efficiency improvements. The GAINS model introduces such structural changes as explicit emission control options.

- A wide range of *technical measures* has been developed to capture emissions at their sources before they enter the atmosphere. Emission reductions achieved through these options neither modify the driving forces of emissions nor change the structural composition of energy systems or agricultural activities. GAINS considers about 1,500 pollutant-specific end-of-pipe measures for reducing SO_2, NO_x, VOC, NH_3 and PM emissions and several hundred options for greenhouse gases and assesses their application potentials and costs.

Any optimal allocation of emission control measures across countries and sectors is crucially influenced by differences in emission control costs across emission sources. It is therefore of utmost importance to systematically identify the factors leading to variations in emission control costs among countries, economic sectors and pollutants. Diversity is caused, i.a., by differences in the structural composition of existing emission sources (e.g., fuel use pattern, fleet composition, etc.), the state of technological development, and the extent to which emission control measures are already applied.

Assuming a free market for emission control technologies, the same technology will be available to all countries at the same costs. However, country- and sector-specific circumstances (e.g., size distributions of plants, plant utilization, fuel quality, energy and labor costs, etc.) lead to justifiable differences in the actual costs at which a given technology removes pollution at different sources. For each of the 1,500 emission control options, GAINS estimates their costs of local application considering annualized investments (I^{an}), fixed (OM^{fix}) and variable (OM^{var}) operating costs, and how they depend on technology *m*, country *i* and activity type *k*. Unit costs of abatement (*ca*), related to one unit of activity (*A*), add up to:

$$ca_{i,k,m} = \frac{I^{an}_{i,k,m} + OM^{fix}_{i,k,m}}{A_{i,k}} + OM^{var}_{i,k,m} . \qquad (2)$$

For the cost-effectiveness analysis, these costs can be related to the emission reductions achieved. The costs per unit of abated emissions (*cn*) of a pollutant p are calculated as:

$$cn_{i,k,m,p} = \frac{ca_{i,k,m}}{ef_{i,k,0,p} - ef_{i,k,m,p}} \qquad (3)$$

where $ef_{i,k,0,p}$ is the uncontrolled emission factor in absence of any emission control measure (m=0).

3.2.1 Cost curves for emission controls

For its optimization routine the RAINS model produces cost curves for emission control, which provide for each country a ranking of the available emission control measures according to their marginal costs. If, for a given activity *k*, more than one control option is available, marginal costs (*mc*) for control option *m* for pollutant *p* in country *i* are calculated as:

$$mc_{i,k,m,p} = \frac{cn_{i,k,m,p} ef_{i,k,m,p} - cn_{i,k,m-1,p} ef_{i,k,m-1,p}}{ef_{i,k,m,p} - ef_{i,k,m-1,p}} . \qquad (4)$$

Cost curves $f_{i,p}$ list for a country i for increasing levels of stringency the total costs $C_{i,p}^*$ of the least-cost combinations of the available abatement measures that reduce national total emissions of pollutant p to any technically feasible emission level $E_{i,p}^*$ $(E_{i,p\,min}<E_{i,p}^*<E_{i,p\,max})$:

$$C_{i,p}^* = f_{i,p}(E_{i,p}^*) = \sum_{s=1}^{S} \Delta E_{i,s,p} mc_{i,s,p} + \delta \cdot mc_{i,s+1,p} \tag{5}$$

where $mc_{i,s,p}$ are the marginal costs defined in Equation 4 and sorted over the activities k and measures m in such a way that $mc_{i,s,p} \leq mc_{i,s+1,p}$, $\Delta E_{i,s,p}$ are the corresponding emission reductions, and S is such that $E_{i,p\,max} - \sum_{s=1}^{S} \Delta E_{i,s,p} > E_{i,p}^*$, but $E_{i,p\,max} - \sum_{s=1}^{S+1} \Delta E_{i,s,p} \leq E_{i,p}^*$ and $\delta = E_{i,p\,max} - \sum_{s=1}^{S} \Delta E_{i,s,p} - E_{i,p}^*$. Details on the cost calculations are provided in Cofala and Syri, 1998a, Cofala and Syri, 1998b, Klimont *et al.*, 2000, Klimont *et al.*, 2002.

3.2.2 The use of cost data in GAINS

In contrast to the single-pollutant cost curve approach used in RAINS, the optimization module of GAINS uses an explicit representation of technologies. While in RAINS the decision variables in the cost optimization are the segments of (independent) cost curves based on a fixed energy projection, in GAINS the decision variables are the activity levels of individual technologies themselves.

The advantages of this approach are fourfold:

- Multi-pollutant technologies are represented adequately in this approach. Multi-pollutant emission control technologies, such as those meeting the various Euro-standards for road vehicles, can be cost-effective in a multi-pollutant multi-objective regulatory framework, even though as single pollutant control technologies they may be not. Thus, while in a cost curve approach multi-pollutant technologies often do not appear to be cost effective, in the GAINS optimization these technologies are appraised on the basis their efficiency to meet (potentially) several environmental objectives simultaneously.

- GAINS allows for (limited) changes in the underlying energy system, primarily as possible measures to reduce greenhouse gas emissions. With each change in the energy system, however, the potential for air pollution control technologies may change, and thus in RAINS the individual cost curve would need to be recalculated for each change in the energy system. Using an explicit technology representation in the GAINS optimization avoids such a cumbersome procedure, as the model "sees" the available technologies and their potentials for their application *at every stage*.

- The GAINS approach fully integrates air pollution control and greenhouse gas mitigation measures so that it not only possible to address the two issues *sequentially*, as has been done in the past: with this tool both aspects of emission control can be addressed *simultaneously* to increase economic efficiency and environmental effectiveness.

- Emission control costs are directly associated with technologies, rather than with pollutants. For single pollutant technologies this difference is spurious, but both for multi-pollutant technologies and activities changes commonly considered as greenhouse gas mitigation options it is often inappropriate to attribute costs to the reduction of a single pollutant or to allocate the costs to individual pollutants. With the technology approach of GAINS no such allocation is needed, nor is it always possible.

Another important consequence of the technology representation in GAINS is the extension of the concept of maximum technically feasible reductions (MTFR). While in the RAINS approach the point of MTFR on a single pollutant cost curve was determined by the maximum application of end-of-pipe technologies, in GAINS further reductions can be achieved by changing the underlying activities, e.g., the energy mix for a given sub-sector. Thus, for example, a switch from coal to gas or to a renewable fuel will reduce emissions of particles below a level that could be achieved with filter technologies. Though a particular fuel switch may not be cost-effective as a control measure for a single air pollutant, it is important to take this additional potential for reduction into account when air pollution targets are discussed, particularly in a carbon constrained setting.

It is important to take note of the fact that the GAINS optimization module can still be used to construct single pollutant cost curves for individual countries if so desired. In this mode the GAINS model is allowed to use all add-on technologies for air pollution control like in the RAINS model, but fuel substitutions or efficiency improvement options are suppressed, i.e., are not available. Ignoring multi-pollutant technologies for the time being, the GAINS model in RAINS mode exactly reproduces the results of the original RAINS optimization approach.

Figure 3.1 shows the validation of the "RAINS-mode" operation of GAINS for a RAINS SO_2 cost curve for a single country. The curve connects bold squares that represent individual control technologies in the RAINS model. The curve is generated by ordering the individual control measures according to their marginal cost, taking into account maximum application rates. Each bullet is generated with the GAINS model by imposing an emission ceiling and optimizing for costs. It can be seen that the points calculated by GAINS all lie on the RAINS cost curve.

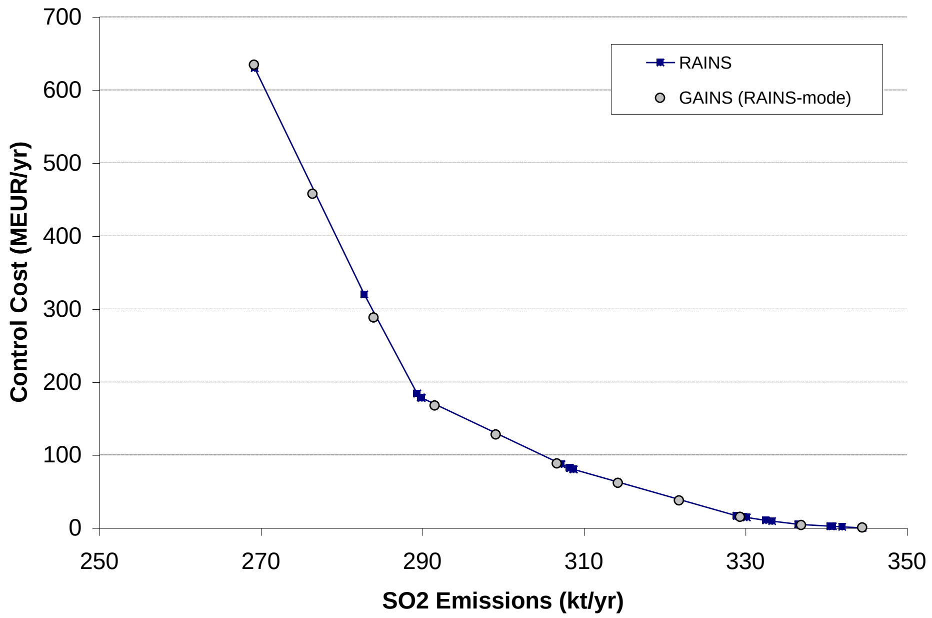

Figure 3.1: Validation of an original RAINS cost curve with the GAINS model operated in the "RAINS" mode

In contrast, when the restrictions on fuel substitutions and efficiency improvements are lifted and the GAINS model is allowed to use all available options, the “GAINS-mode” reveals a larger potential for emission reductions. In Figure 3.2, the thin line with bullets illustrates the single pollutant cost curve that is obtained with the GAINS model in RAINS mode. The curve begins at around 108 kt PM2.5 per year and ends at around 86 kt PM2.5 per year, which represents the maximum technically feasible reductions scenario generated with the RAINS model. Results emerging from the “GAINS mode” are indicated by the thin line with squares. This curve ends at around 79 kt PM2.5 per year with costs of around 7 billion €/yr (off the diagram). This cost estimate takes into account the change in the total system costs, i.e., costs of all fuel substitution options taken to achieve an emission level of 79 kt PM2.5 per year. If, however, only those costs are taken into account that are explicitly connected with PM2.5 end-of-pipe technologies, then the resulting costs in the MTFR scenario at 79 kt PM2.5 per year is lower than 1.6 billion €/yr, which is even below the level of the MTFR calculated in the RAINS mode (more than 1.6 billion €/yr). This is easily understood if one takes into account that the energy systems in the MTFR situations of the two cost curves are different: the bulleted line is constructed from a baseline scenario, whereas the endpoint of the second and third curves result from a scenario with less use of solid fuels – which means that there is less absolute amount of capacities that need to be controlled, which in turn implies smaller amounts of money spent on control equipment (dotted line with triangles).

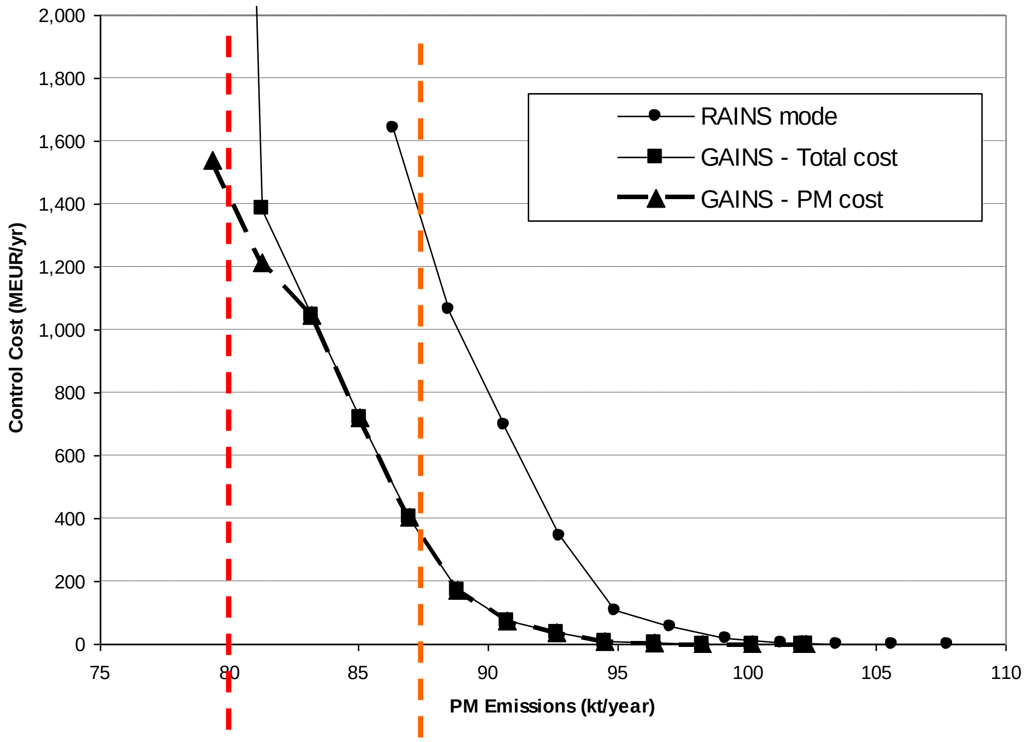

Figure 3.2: Single pollutant cost curves for PM2.5 in the year 2020. This illustrates the difference in maximum technically feasible reductions (MTFR) in the full GAINS model compared to the RAINS mode of GAINS. For details see text.

4 Atmospheric dispersion

An integrated assessment needs to link changes in the precursor emissions at the various sources to responses in impact-relevant air quality indicators *q* at a receptor grid cell *j*. Traditionally, this task is accomplished by comprehensive atmospheric chemistry and transport models, which simulate a complex range of chemical and physical reactions. The GAINS integrated assessment analysis relies on the Unified EMEP Eulerian model, which describes the fate of emissions in the atmosphere considering more than a hundred chemical reactions involving 70 chemical species with time steps down to 20 seconds including numerous non-linear mechanisms (Simpson *et al.*, 2003). This model was updated in August 2006. However, the joint analysis with economic and ecological aspects in the GAINS model, and especially the optimization task, calls for computationally efficient source-receptor relationships. For this purpose, an attempt has been made to describe the response surface of the impact-relevant air quality indicators through mathematically simple, preferably linear, formulations. Functional relationships have been developed for changes in annual mean PM2.5 concentrations, deposition of sulfur and nitrogen compounds as well as in long-term levels of ground-level ozone. The (grid- or country-specific) parameters of these relationships have been derived from a sample of several hundred runs of the full EMEP Eulerian model with systematically perturbed emissions of the individual sources. This "calibration sample" spans the policy-relevant range of emissions, i.e., taking the "current legislation" (CLE) emission projection as the upper limit and its "maximum technically feasible reduction" (MTFR) case as the lower end. While the optimization task in GAINS employs these fitted source-receptor relationships, policy-relevant scenario results are validated ex-post through runs of the full EMEP Eulerian model.

Source-receptor relationships have been developed for changes in emissions of SO_2, NO_x, NH_3, VOC and PM2.5 of the 25 Member States of the EU, Romania, Bulgaria, Croatia, Norway and Switzerland, and five sea areas, describing their impacts for the EU territory with the 50 km × 50 km grid resolution of the geographical projection of the EMEP model (see www.emep.int/grid/index.html).

4.1 Fine particulate matter – regional scale

The health impact assessment in GAINS relies on epidemiological studies that associate premature mortality with annual mean concentrations of PM2.5 monitored at urban background stations. Thus, the source-receptor relationships developed for GAINS describe, for a limited range around a reference emission level, the response in annual mean PM2.5 levels to changes in the precursor emissions SO_2, NO_x, NH_3 and primary PM2.5. The formulation reflects the interplay between SO_2, NO_x and NH_3 emissions in the formation of secondary sulfate and nitrate aerosols in winter. The almost linear response in annual mean PM2.5 produced by the EMEP Eulerian model towards changes in annual emissions of fine primary particulate matter (PM2.5) and of SO_2, as well as for changes in NO_x emissions during the summer, is represented as:

$$
\begin{aligned}
PM_j = {} & k_{0,j} + \sum_i pm_i PP_{ij}^A + \sum_i s_i S_{ij}^A + c_0 \left(\sum_i a_i A_{ij}^S + \sum_i n_i N_{ij}^S \right) + \\
& + (1-c_0) \min \left\{ \max \left\{ 0, k_{1,j} + c_1 \sum_i a_i A_{ij}^W - c_2 \sum_i s_i S_{ij}^W \right\}, k_{2,j} + c_3 \sum_i n_i N_{ij}^W \right\}
\end{aligned}
\tag{6}
$$

with

PM_j	**Annual mean concentration of PM2.5 at receptor point *j***
s_i, n_i, a_i, pm_i	Emissions of SO_2, NO_x, NH_3 and primary PM2.5 in country *i*
A^X_{ij}, N^X_{ij}, S^X_{ij}, PP^X_{ij}	Matrices with coefficients for reduced (*A*) and oxidized (*N*) nitrogen, sulfur (*S*) and primary PM2.5 (*PP*), for season *X*, where *X=W* (winter), *S* (summer) and *A* (annual)
c_0, c_1, c_2, c_3, $k_{0,j}$, $k_{1,j}$, $k_{2,j}$	Model parameters.

While the above formulation with a computationally complex min-max formulation is required to capture changes in chemical regimes when ratios between the abundances of sulfur, nitrogen and ammonia in the atmosphere are changing due to different emission reduction rates of the pollutants involved, a simpler formulation appears to be sufficient when only limited changes in emissions around a reference point are considered. For such optimization problems, Equation 6 can be turned into a linear form:

$$PM_j = \sum_i pm_i \cdot PP^A_{ij} + \sum_i s_i \cdot S^A_{ij} + \sum_i a_i \cdot A^A_{ij} + \sum_i n_i \cdot N^A_{ij} + k_{0,j} \qquad (7)$$

For the CAFE programme, where the European Commission explored a wide range of alternative environmental targets implying large differences in emission reductions, the RAINS optimization applied the formulation of Equation 6. For the NEC analysis, however, where the general ambition level has been settled in the Thematic Strategy, the GAINS optimization problem uses Equation 7 with transfer coefficients which have been derived from permutations of emissions around the indicative target emissions levels outlined in the Thematic Strategy. Taking these target levels as the reference point, the GAINS optimization using local derivatives at this point results in a significantly more accurate representation of the underlying EMEP Eulerian model despite the simpler mathematical formulation.

This formulation only describes the formation of PM from anthropogenic primary PM emissions and secondary inorganic aerosols. It excludes PM from natural sources and primary and secondary organic aerosols due to insufficient confidence in the current modeling ability. Thus, it does not reproduce the full mass of PM2.5 that is observed in ambient air. Consequently, results of this approach need to be compared against observations of the individual species that are modeled. The health impact assessment in GAINS is consequently only conducted for *changes* in the specified anthropogenic precursor emissions, and excludes the (largely) unknown role of secondary organic aerosols and natural sources.

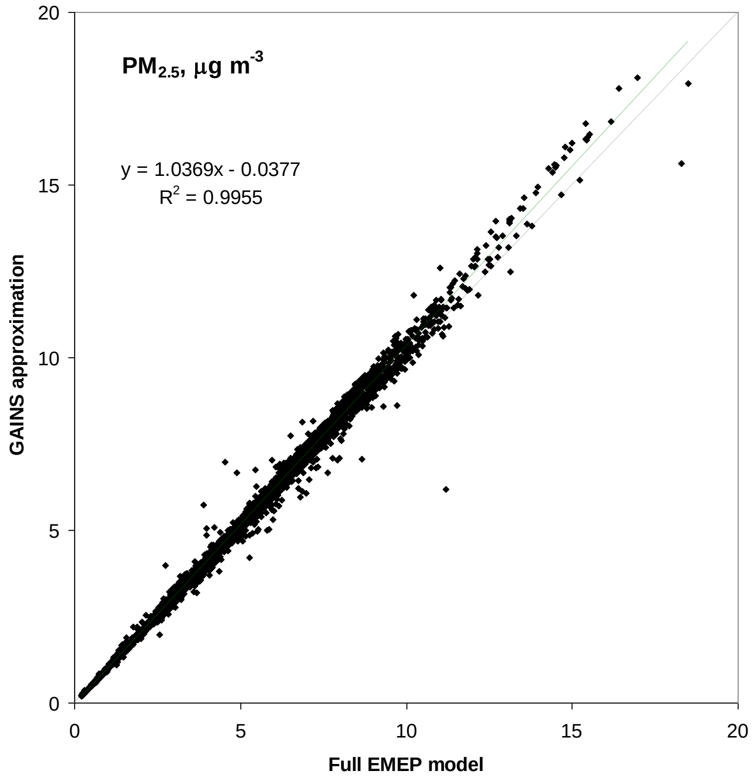

Figure 4.1: Validation of the GAINS approximations of the functional relationships against computations of the full EMEP model around the emission levels outlined in the Thematic Strategy for Air Pollution.

4.2 Fine particulate matter – urban scale

In GAINS the regional-scale assessment is performed for all of Europe with a spatial resolution of 50 km × 50 km. Health impacts are, however, most pertinent to urban areas where a major share of the European population lives. Any assessment with a 50 km resolution will systematically miss out higher pollution levels in European cities. Based on the results of the City-delta model intercomparison, which brought together the 17 major European urban and regional scale atmospheric dispersion models (Thunis *et al.*, 2006), a generalized methodology was developed to describe the increments in PM2.5 concentrations in urban background air that originate – on top of the long-range transport component – from local emission sources.

These relationships associate urban increments in PM levels, i.e., incremental (PM2.5) concentrations in a city originating from emissions of the same city with the spatial variations in emission densities of low-level sources in that city and city-specific meteorological and topographic factors. In a second step, urban background PM2.5 concentrations within cities are then computed by correcting the PM concentration value computed by a 50*50 km regional dispersion model with a “city-delta”, i.e., the local increase in concentration in the city due to emissions in the city itself. In the regional-scale calculations this contribution is smeared out over the whole 50*50 km grid element. In the City-delta approach the mass within the 50*50 km grid element is redistributed in such a way that the concentration in the city is increased by the “city-delta” increment, whereas the concentration in the country-side consequently is decreased. In this way mass is being conserved.

The GAINS/City-delta methodology starts from the hypothesis that urban increments in PM2.5 concentrations originate predominantly from primary PM emissions from low-level sources within the city. The formation of secondary inorganic aerosols, as well as the dispersion of primary PM2.5 emissions from high stacks, are reflected in the background computed by the regional-scale dispersion model.

Based on this hypothesis, urban increments have been derived with the following approach:

Step 1: Preparation of a data sample of model responses

Three urban dispersion models (Chimere, CAMx, REM3) have been used to generate a data sample with computed impacts of local emission control measures on urban PM2.5 concentrations for seven European cities with different characteristics (Berlin, Krakow, Lisbon, London, Milan, Paris, Prague). Scenarios have been computed for emissions in 2020 with and without urban emissions from low level sources, using the meteorological conditions of the year 2004.

Step 2: Hypothesis of local determinants and the functional forms for computing the urban increments

Based on atmospheric diffusion theory, potential determinants of urban increments and functional forms of their relationships have been hypothesized. Under neutral atmospheric conditions, the vertical diffusion of a non-reactive pollutant from a continuous point source can be described in general form through the following relationship (e.g., Seinfeld and Pandis, 1998):

$$\sigma_z^2 = \frac{2K_{zz}x}{U} \tag{8}$$

with σ_z^2 [m^2] indicating the variance of the vertical diffusion after a distance x [m] from the source, K as the Eddy diffusivity [$m^2\ s^{-1}$] and U [$m\ s^{-1}$] as the wind speed. For a homogenously distributed area source with source strength (emission rate) Q, the resulting concentration Δc of a pollutant due to emissions in the city can be derived from a spatial integration over the diameter of the city D [m] (Anton Eliassen, personal communication)

$$\Delta c = \frac{1}{2\sqrt{2}}\frac{1}{\sqrt{K_{zz}}}\left(\frac{D}{U}\right)^{1/2} Q \quad . \tag{9}$$

The diffusivity K_{zz} as well as wind speeds and city diameters along the wind directions show variations over the year. In Equation 8 K_{zz} and U are constant with height. In reality and under neutral atmospheric conditions, K_{zz} increases approximately linearly with height, whereas U increases with the logarithm of the height. Moreover, at a relative short distance from the low source the plume is reflected at the earth's surface. Therefore only the general relation between Δc and $(D/U)^{0.5}$ is used in Equation 9, whereas all other effects are described by the diffusion characteristics of the city given by the constant α. Equation 10 shows that the urban concentration increments Δc can be described as a function of city diameter D, wind speed U, emission rates Q:

$$\Delta c = \frac{1}{2\sqrt{2}}\frac{1}{\sqrt{K}}\left(\frac{D}{U}\right)^{1/2} Q = \alpha \cdot \left(\frac{D}{U}\right)^{1/2} Q \tag{10}$$

In principle, the same type of model could also describe the relation under stable atmospheric conditions. However, it will be difficult to describe the situation for wind speeds below 0.5 – 1 m s^{-1}, as the flow will no longer be determined by the external wind speed, but by other effects such as differences in heating of the earth's surface and differences in terrain height.

Low wind situations in summer are different from low wind situations in winter. In summertime in a high pressure area during day time there are unstable conditions leading to a well-mixed atmosphere. In such situations the increase in concentration due to the low wind speed (causing less dilution) is partly compensated by a decrease in concentration due to better vertical mixing. In these situations a large fraction of the airborne aerosol does not directly come from nearby PM2.5 sources, but is generated by photochemical reactions by which so called secondary aerosols are formed. However, as mentioned above, there is insufficient confidence in the abilities of current atmospheric chemistry models to deliver reliable quantitative estimates for secondary organic aerosols. As a consequence, the current GAINS analysis excludes secondary organic aerosols altogether.

In winter, low wind speed conditions are mostly related to shallow boundary layers, in which emissions from local sources accumulate over time. Since process modelling of such conditions would require detailed meteorological information on the situation within cities that is usually unavailable for most European cities, a statistical approach has been adopted that builds upon model computations carried out by the City-delta models for the seven cities. Figure 4.2 indicates that winter days with wind speeds below 1.5 m/s make a stronger contribution to annual mean PM2.5 concentrations than days with higher wind speeds.

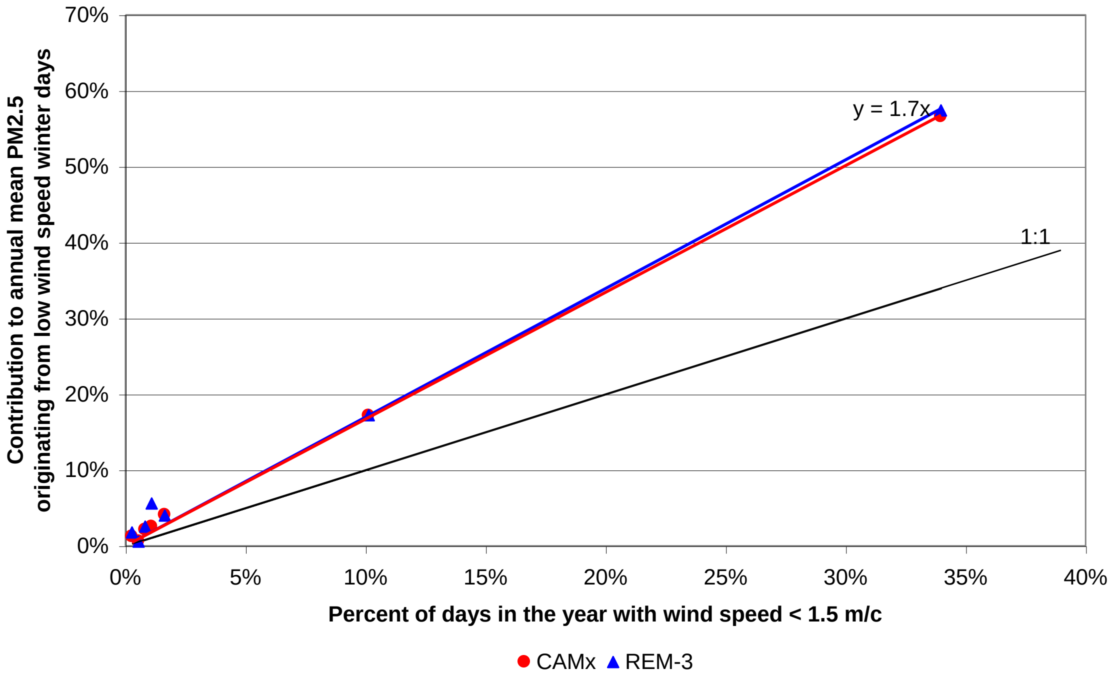

Figure 4.2: Contribution to annual mean PM2.5 concentrations originating from low wind speed days in winter, as computed by the CAMx and REM-3 models for the seven City-delta cities

As a pragmatic approach for determining the urban increments, the City-delta approach considers a second term that is related to the number of low wind speed days in winter (*d*):

$$\Delta c = \alpha \cdot \left(\frac{D}{U}\right)^{1/2} Q + \beta \cdot \left(\frac{D}{U}\right)^{1/2} Q \cdot \frac{d}{365} \tag{11}$$

Step 3: Regression analysis for the seven cities

In a further step, a regression analysis estimated the regression coefficients α and β in Equation 11 from the data sample on *Δc* computed by the three urban dispersion models for the seven City-delta cities, with city-specific diameters *D*, wind speeds *U*, low wind speed days *d*, and changes in emission fluxes *ΔQ*. For concentration changes averaged over 10*10 km domains in the city centers, the regression analysis renders statistically significant values for α of 0.22 and for β of 0.48 with an R^2 of 0.89. With these coefficients, the functional relationships according to Equation 11 deliver for the seven sample cities urban increments that lie within the range produced by the three detailed urban dispersion models (Figure 4.3).

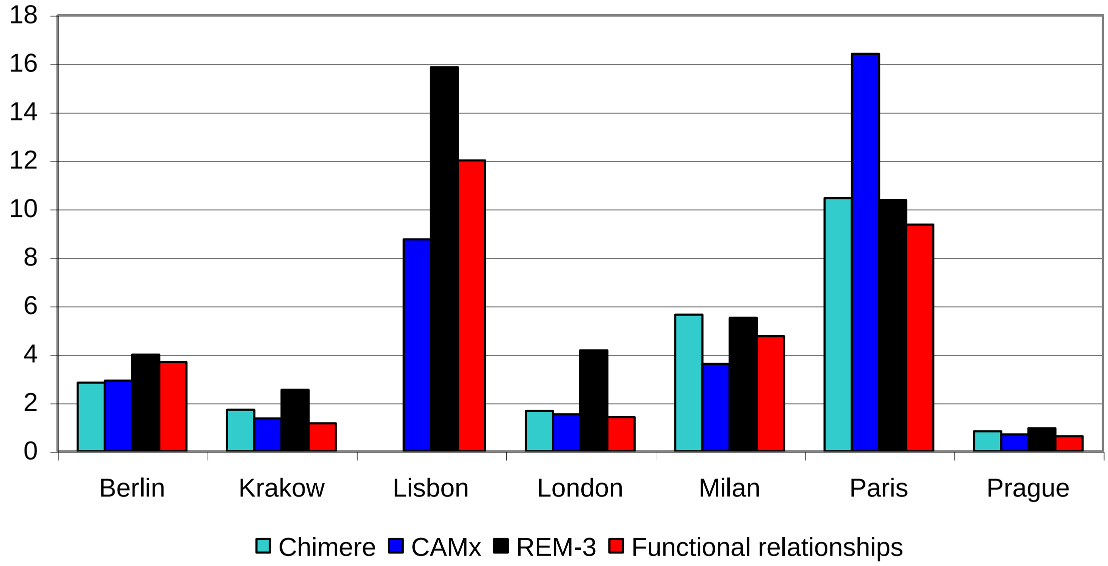

Figure 4.3: Urban increments of PM2.5 (in µg/m^3) computed by the three detailed urban dispersion models and the City-delta functional relationships for the seven City-delta cities, for the CAFE baseline emissions for 2020

Step 4: Extrapolation to all European cities

To estimate urban increments for all European cities based on the functional relationship identified in Equation 11, a database has been prepared with city-specific information on city area, city diameters, wind speeds, number of low wind days in winter for the 473 cities with more than 100,000 inhabitants.

Urban areas and diameters were derived from the JRC European population density data set and the *www.citypopulation.de* database using a special algorithm that associates populated areas with the individual urban agglomerations under consideration. Wind speed data have been extracted from the MARS meteorological database of JRC, which provides interpolated meteorological information derived from 2000 weather stations in Europe. Furthermore, local observations on wind speeds from a European database provided by the Free University Berlin have been used for German cities and other countries, when these data are more representative for city-centers than the interpolated MARS data (Figure 4.4, Figure 4.5).

With these data, the term $(D/U)^{1/2}$ in Equation 11 that reflects the influence of topography and meteorological conditions of a specific city on the dispersion characteristics of local emissions can be derived (Figure 4.6). This indicator displays a strong influence of the city size (shown by declining factors for the cities in each country, which are ranked by population) with the modifications of meteorological conditions.

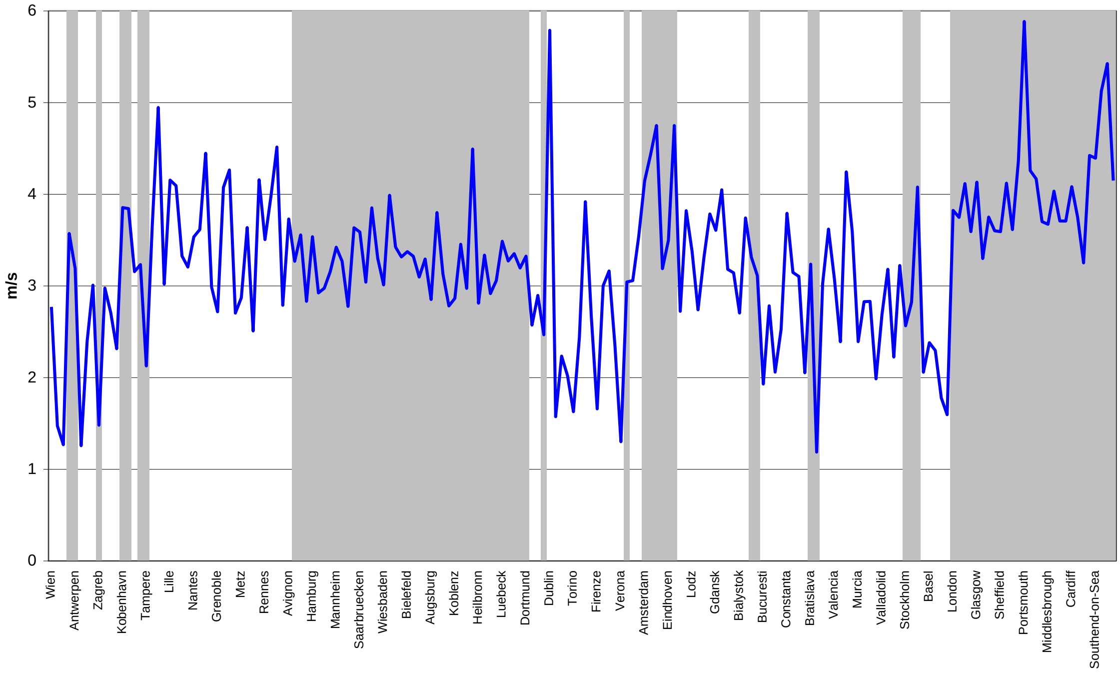

Figure 4.4: Mean annual wind speeds for the European cities with more than 250.000 inhabitants

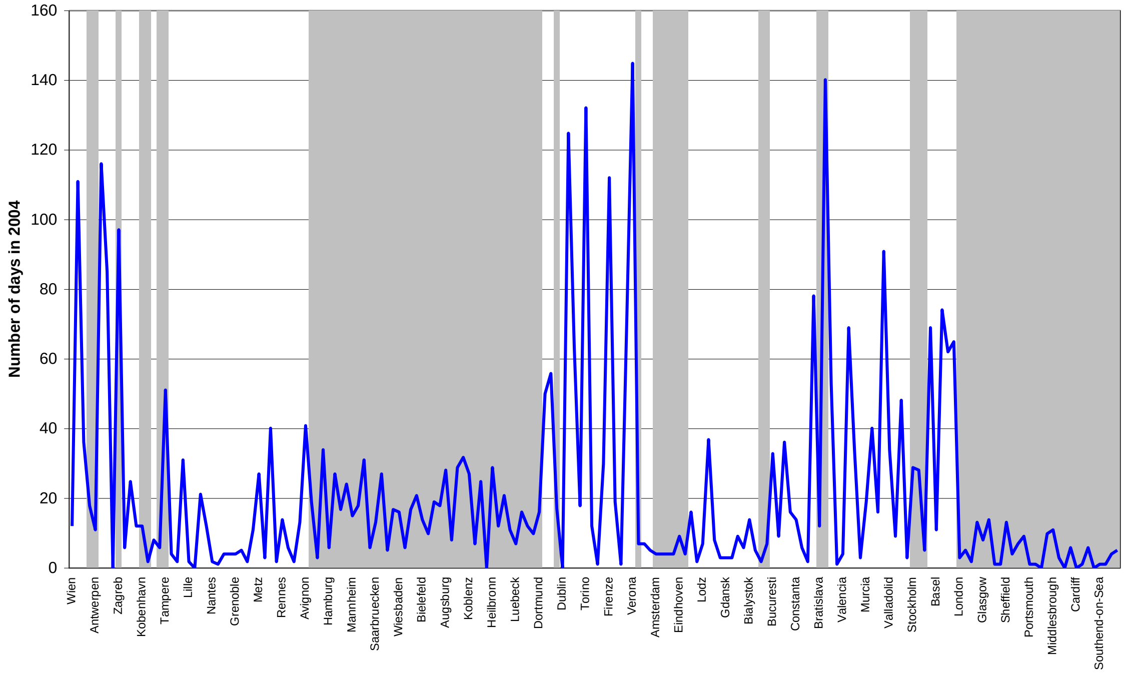

Figure 4.5: Number of days in winter with wind speeds below 1.5 m/s for cities with more than 250.000 inhabitants

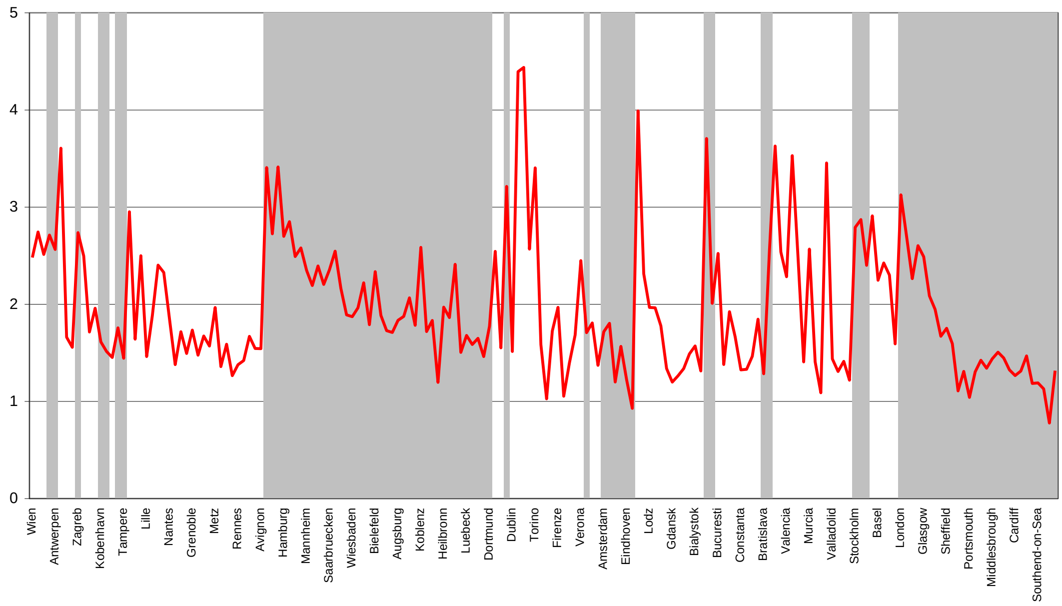

Figure 4.6: Topographic factors $(D/U)^{1/2}$ in Equation 11 that are proportional to the concentration increment (in $\mu g/m^3$) per ton PM2.5 emissions under neutral atmospheric conditions for the cities with more than 250.000 inhabitants

Special emphasis has been devoted to estimating urban emissions of low level sources. In the absence of city-specific emission inventories available at the European scale, urban emissions have been estimated on a sectoral basis (distinguishing the SNAP sectors) from the gridded emission inventory compiled for the calculations of the EMEP model. First, for each country, sectoral emissions reported in the EMEP database have been scaled to the estimates of the GAINS model, which have been recently agreed upon with national experts in the bilateral consultations with IIASA. In a second step, for each city, the sectoral emissions reported in the EMEP inventory for the specific grid cell (adjusted for the GAINS estimates) have been allocated to cities based on the distribution of urban and rural population within the grid cell. For splitting total emissions into low and high-level sources, the assumptions listed in Table 4.1 have been made. Essentially, it is assumed that all emissions of SNAP sector 2 (domestic and service sector), SNAP sector 4 (non-combustion related emissions from industrial processes, usually cold processes), SNAP sector 7 (traffic) and SNAP sector 8 (off-road sources, such as construction machinery, etc.) are emitted at low heights. Emissions from power stations (SNAP 1) and waste incineration plants (SNAP 9) are assumed to be high level, while in the absence of more city-specific information 50 percent of the PM2.5 emissions reported under SNAP 3 (industrial combustion and manufacturing) are assumed to be released into the surface layer.

It has to be mentioned that in the course of the bilateral consultations with national experts the RAINS estimates of sectoral PM2.5 emissions have been adjusted to match as far as possible the national inventories with plausible data on emission factors, removal efficiencies, activity rates and application rates of control measures.

Table 4.1: Assumptions about emission height for the SNAP sectors

SNAP sector		**Assumption about emission height**
1	Combustion in energy and transformation industries	0 % of emissions low level
2	Non-industrial combustion plants (domestic and service sector)	100 % of emissions low level
3	Combustion in the manufacturing industry	50 % of emissions low level
4	Production processes (e.g., diffusive emissions in industry, etc.)	100 % of emissions low level
5	Extraction and distribution of fossil fuels and geothermal energy	0 % of emissions low level
6	Solvent and other product use	Not relevant for PM2.5
7	Road transport	100 % of emissions low level
8	Other mobile sources and machinery	100 % of emissions low level
9	Waste treatment and disposal	0 % of emissions low level
10	Agriculture	Not relevant for urban PM2.5
11	Other sources and sinks including nature	Not relevant for urban PM2.5

However, it has to be mentioned that the information contained in the gridded EMEP emission inventory is burdened with uncertainties, since only few countries (Austria, Denmark, Spain, Finland, France and Lithuania) have provided information for PM2.5 and UK for PM10. For all other countries the spatial allocation of national PM2.5 emissions has been performed by EMEP based on surrogate indicators such as population densities.

A particular relevant source of uncertainties is related to emissions from wood burning. While a number of countries report rather high emissions from these activities, it is not always clear to what extent wood burning occurs within cities. There are indications that practices are different across countries, and gridded inventories that are not built upon bottom-up estimates but employ generic assumptions (like population-weighted spatial distributions) might results in serious over- or underestimates of urban PM2.5 emissions. However, there is little solid information on this subject available at this time at the European level that could allow further refinement of the current GAINS estimates.

There are striking differences in per-capita emissions and emission densities from urban low-level sources across the European cities. Differences in industrial emissions could be explained by the existence of specific plants in a given city, whose exact locations (i.e., within or outside the city boundaries) however would need to be validated on a case-by-case basis (Figure 4.8). Certain differences in the per-capita emissions from the domestic and service sector could potentially be related to different levels of wood burning, although the question to what extent wood burning takes place within cities needs further attention (Figure 4.7). Most strikingly, however, are variations in per-capita emissions from the transport sector across European countries (Figure 4.9). As a consequence, there are striking differences also in the spatial emission densities across European cities (Figure 4.10).

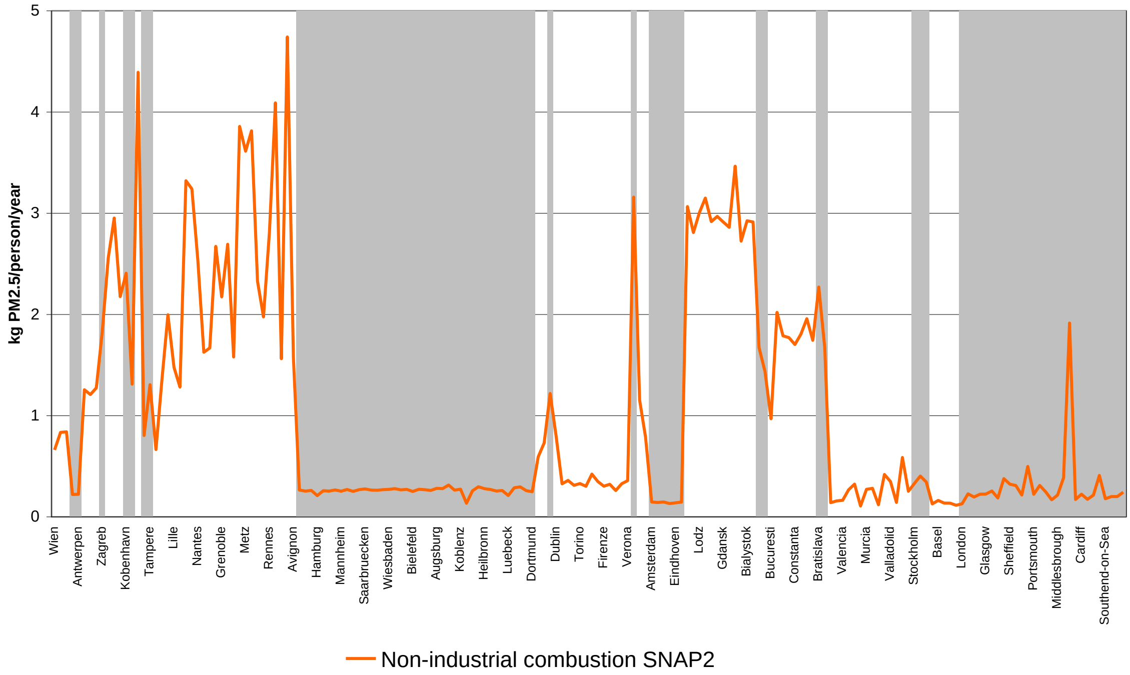

Figure 4.7: Urban per-capita emissions from non-industrial combustion (domestic and service sectors) – SNAP2 from the RAINS database for the year 2000, for the European cities with more than 250.000 inhabitants

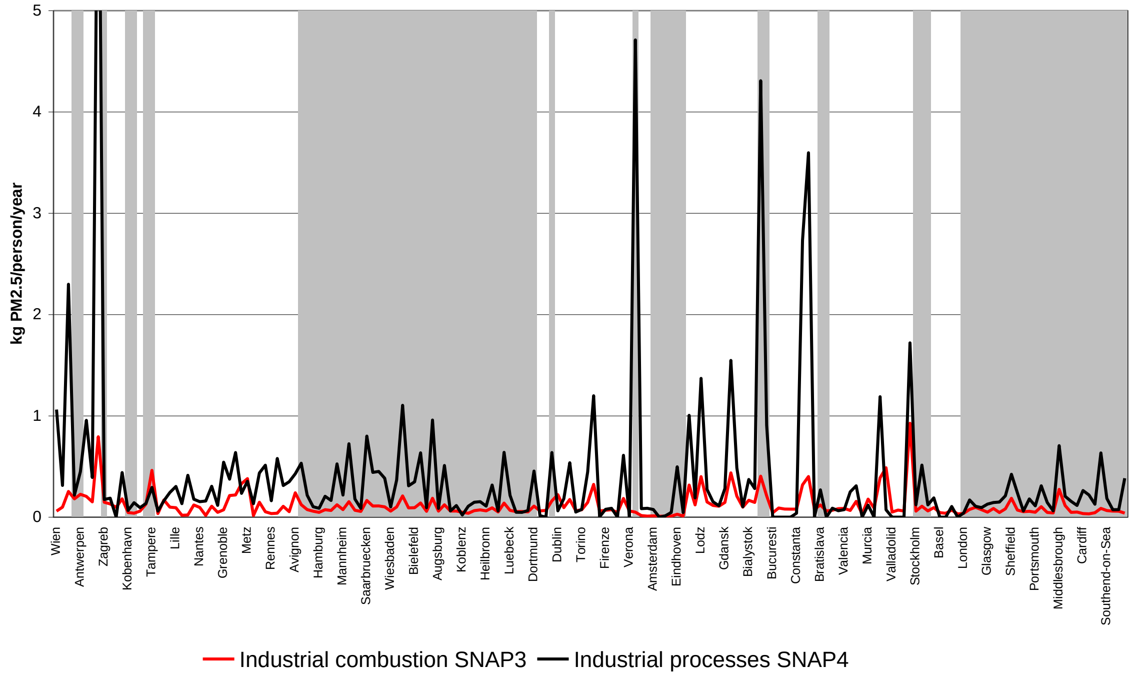

Figure 4.8: Urban per-capita emissions from industrial combustion (SNAP 3) and industrial processes (SNAP4) from the RAINS database for the year 2000, for the European cities with more than 250.000 inhabitants

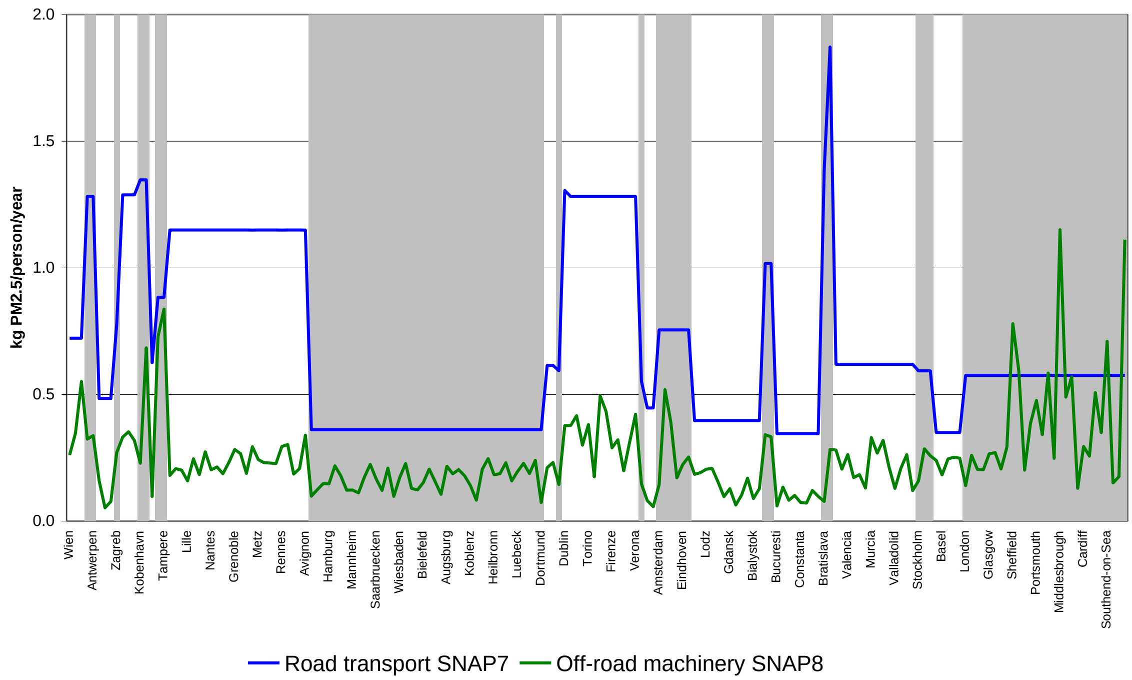

Figure 4.9: Urban per-capita emissions from road transport (SNAP 7) and off-road machinery (SNAP 8) from the RAINS database for the year 2000, for the European cities with more than 250.000 inhabitants

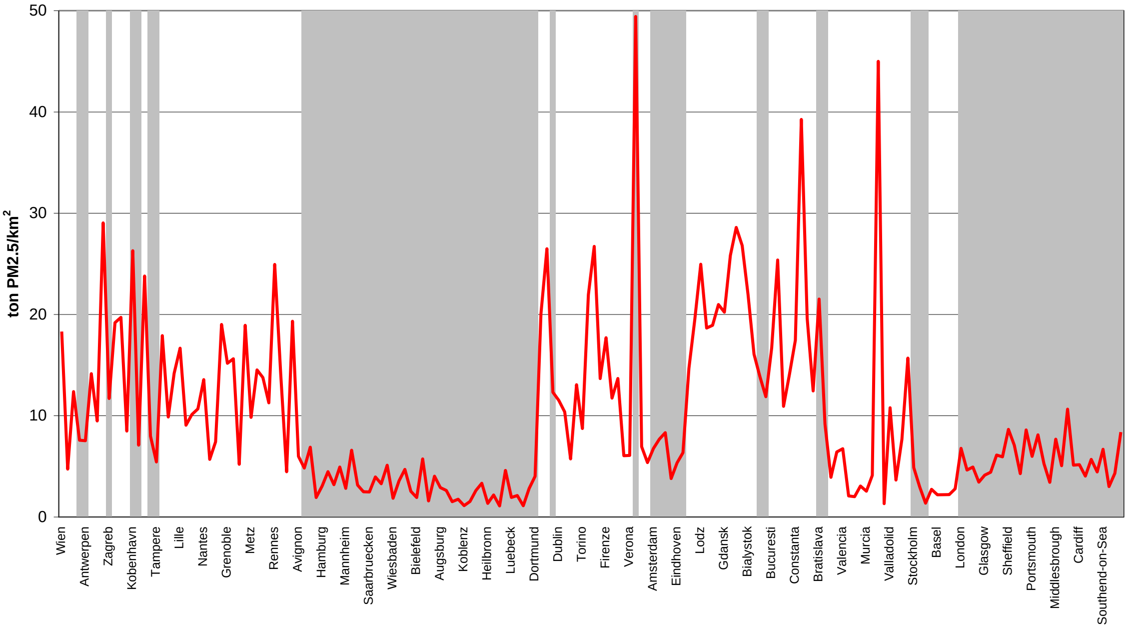

Figure 4.10: Emission densities of PM2.5 from urban low level sources (all sectors) for the European cities with more than 250.000 inhabitants

With all this information, urban increments have been estimated according to Equation 11 for the 473 European cities that have more than 100.000 inhabitants. Calculations show a wide spread across Europe, with peaks reaching between 15 and 19 µg/m^3 (Riga, Sofia, Milano, Athens, Katowice). Low emission densities in the UK and Germany (see Figure 4.10) result in comparably lower increments (e.g., London 4.8 µg/m^3, Sheffield 3.6 µg/m^3; Berlin 4.2 µg/m^3, Essen 4.1µg/m^3)

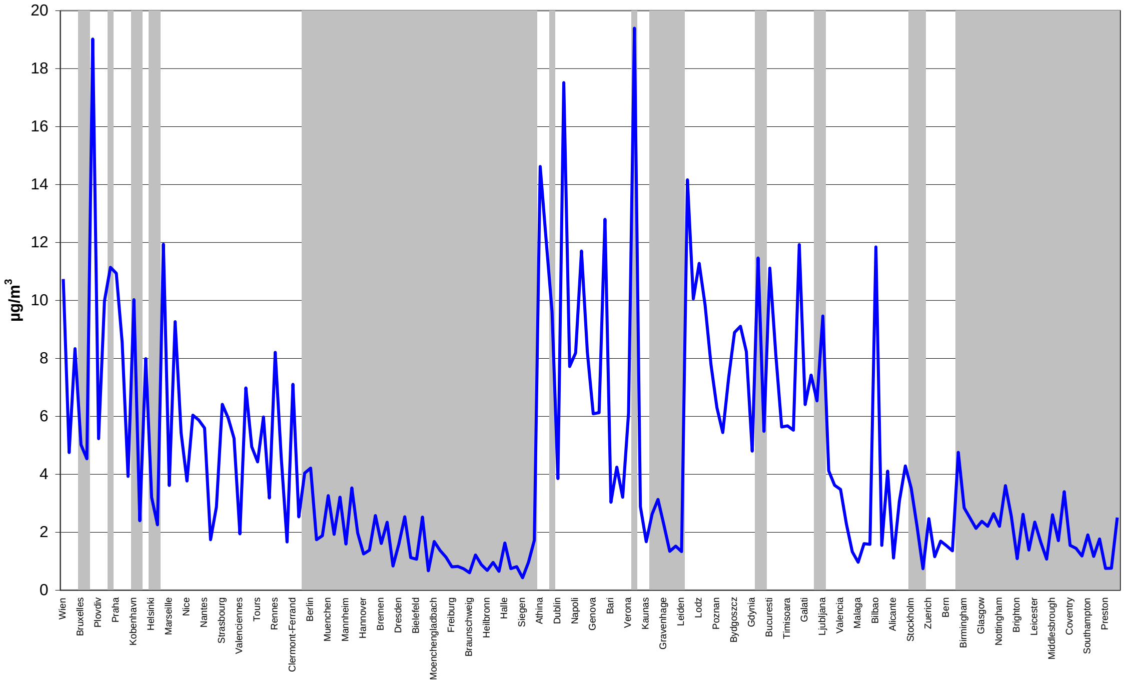

Figure 4.11: Computed urban increments for the year 2000 for the European cities with more than 250.000 inhabitants

Step 5: Calculations of the "city-deltas"

In a final step, the "city-deltas", i.e., the correction factors that have to be applied to the results of the EMEP regional scale model calculations in order to derive estimates of urban air quality, have been developed. As a pragmatic solution double-counting of the urban emissions (i.e., in the regional scale EMEP calculations and the urban increments) has been avoided by estimating the PM increase from the urban emissions that is applied in the EMEP model. With some simplifying assumptions, the city-deltas CD compute as:

$$CD = \alpha \cdot \Delta Q.\frac{1}{\sqrt{U}} \cdot \left((1 + \beta \frac{d}{365}) \cdot \frac{\sqrt{D}}{A_C} - \frac{\sqrt[4]{A_E}}{A_E} \right) \tag{12}$$

with the index C indicating city-related data and the index E values for the entire 50*50 km EMEP grid cell, and A relating to the respective areas .

The resulting city-delta CD_C can then be added to the EMEP regional scale results PM_{EMEP} to attain total PM concentrations in urban areas PM_C:

$$PM_c = PM_{EMEP} + CD_c \tag{13}$$

Step 6: Validation

Finally, the total PM2.5 concentrations computed along Equation 13 together with generic assumptions on the PM contribution from mineral dust and sea salt have been compared against available monitoring data. However, such a comparison is inherently difficult for two major reasons:

- First, the computed urban increment that reflects PM concentrations in urban background air is rather sensitive towards the target domain for which it is computed. Sensitivity analyses show that urban increments computed with the detailed urban dispersion models for 5*5 km, 10*10 km and 15*15 km domains differ typically by a factor of two to three. While the impact assessment in GAINS should ideally use a population-weighted change in concentrations to connect to the relative risk functions provided by epidemiological studies, it is not always clear for which domain size a given observation can be considered as representative.
- Second, there are significant uncertainties in the reported monitoring data for PM2.5, both about their representativeness within a given city as well as on monitoring techniques and applied correction factors in an international context. While it seems difficult to quantify the uncertainties around the available monitoring data, they establish a serious obstacle for a solid intercomparison between monitoring data and model results.

Figure 4.12 Figure 4.16 compare the contributions of mineral dust, the long-range component and the estimated city-delta to urban background PM2.5 with available measurements. For mineral dust, it has been assumed that concentrations range between 1 and 3 µg/m^3 as a function of geographical latitude. The long-range component represents the PM2.5 concentration computed by the EMEP Eulerian model (for primary PM and secondary inorganic aerosols) for the meteorology of the year 2004, while the city-deltas have been calculated according to the methodology outlined above. Furthermore, the graphs provide measurement data extracted from the AIRBASE database and from other sources. Measurement data are displayed as contained in AIRBASE. They include, inter alia, different assumptions on correction factors or are uncorrected values, and the description of the station characteristics (urban background/traffic/etc.) is not always unambiguous.

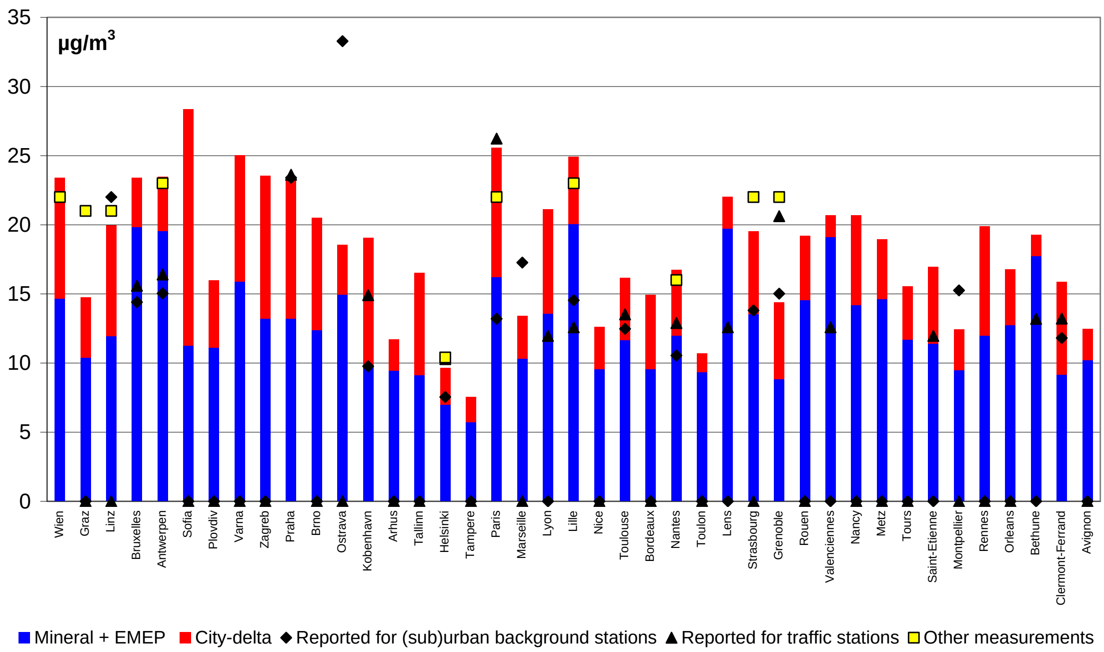

Figure 4.12: Contributions to urban background PM2.5 concentrations from mineral dust the long-range component computed by the EMEP model for the year 2004 and the estimated city-delta, compared to 2004 measurements reported in AIRBASE for urban background and traffic stations and from other sources, for Austria, Belgium, Bulgaria, Czech Republic, Denmark, Estonia, Finland, France.

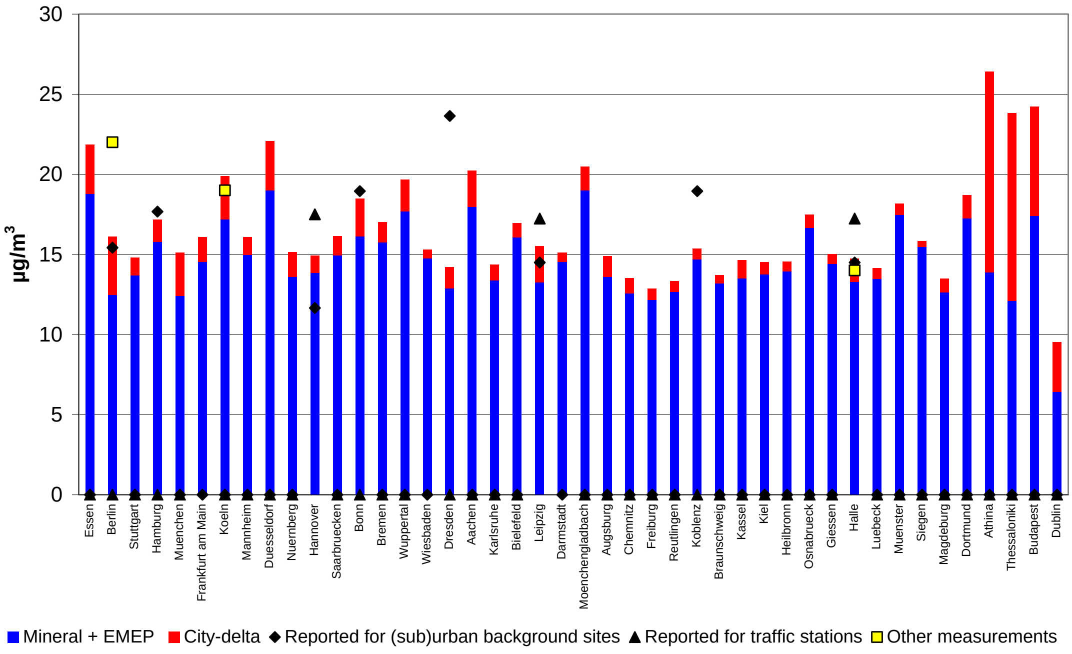

Figure 4.13: Contributions to urban background PM2.5 concentrations from mineral dust, the long-range component computed by the EMEP model for the year 2004 and the estimated city-delta, compared to 2004 measurements reported in AIRBASE for urban background and traffic stations and from other sources, for Germany, Hungary and Ireland.

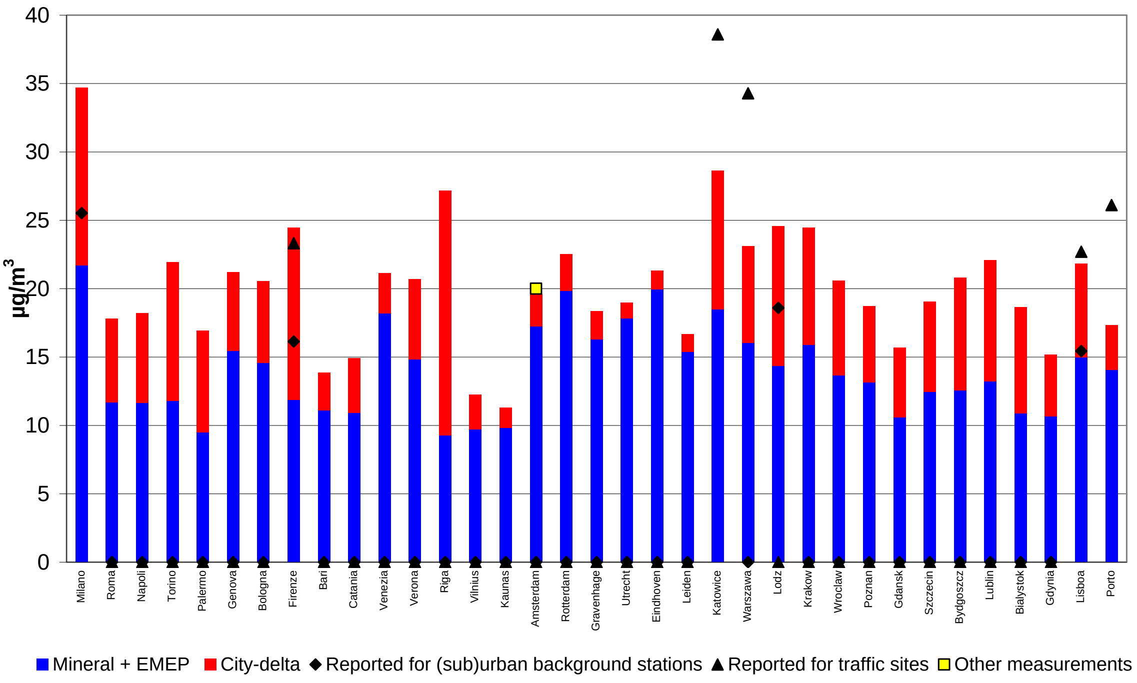

Figure 4.14: Contributions to urban background PM2.5 concentrations from mineral dust, the long-range component computed by the EMEP model for the year 2004 and the estimated city-delta, compared to 2004 measurements reported in AIRBASE for urban background and traffic stations and from other sources, for Italy, Latvia, Lithuania, Netherlands, Poland and Portugal.

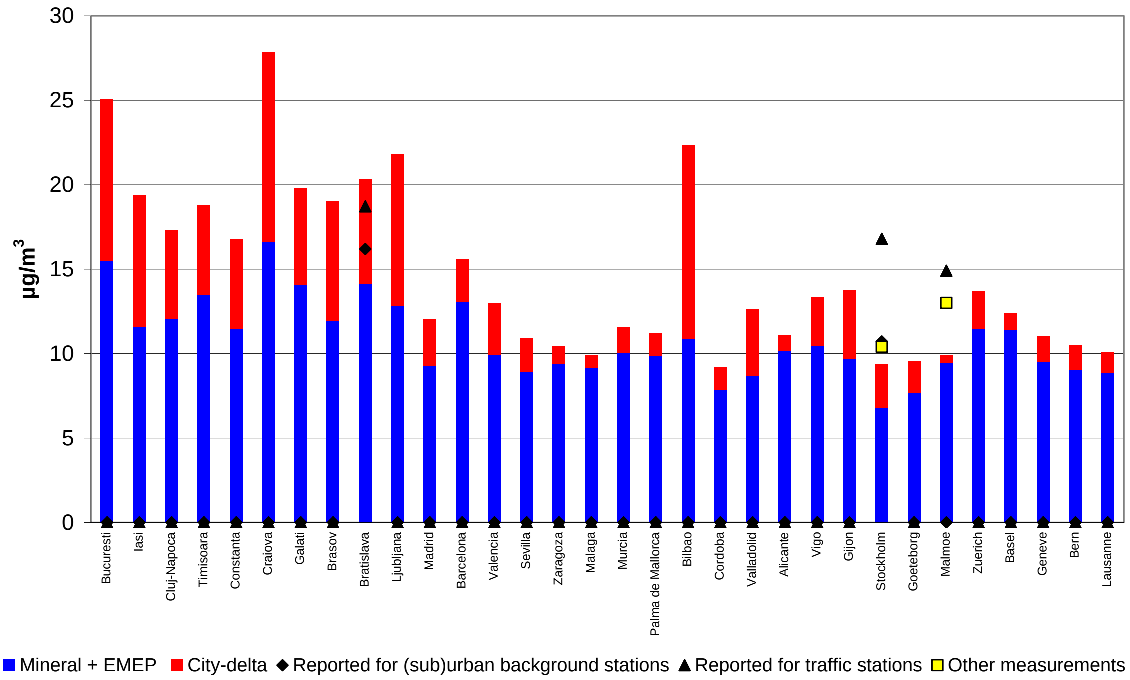

Figure 4.15: Contributions to urban background PM2.5 concentrations from mineral dust, the long-range component computed by the EMEP model for the year 2004 and the estimated city-delta, compared to 2004 measurements reported in AIRBASE for urban background and traffic stations and from other sources, for Romania, Slovakia, Slovenia, Spain, Sweden and Switzerland.

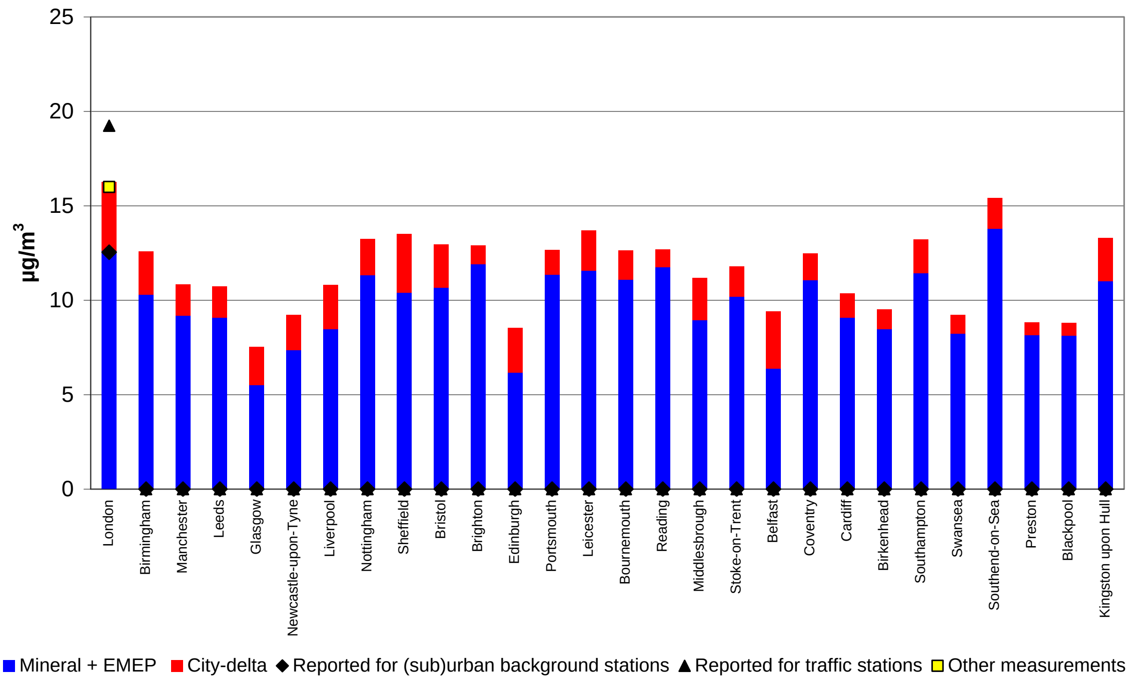

Figure 4.16: Contributions to urban background PM2.5 concentrations from mineral dust, the long-range component computed by the EMEP model for the year 2004 and the estimated city-delta, compared to 2004 measurements reported in AIRBASE for urban background and traffic stations and from other sources, for the United Kingdom.

Discussion

The urban increments derived with the methodology outlined above aim, for the purposes of a Europe-wide health impact assessment, at the quantification of the influence of urban emissions on health-relevant metrics of urban air quality. Since, from a health perspective, the endpoint of interest lies on a population-weighted long-term exposure of fine particles, the chosen metric (annual mean PM2.5 concentration in urban background air) cannot be directly compared with observations that are usually conducted to judge compliance with air quality limit values. Thus, the methodology is unable to provide meaningful information about PM concentrations over short time periods, for specific locations (e.g., hot spots, street canyons), and for other PM size fractions than PM2.5. Furthermore, measurements taken at such locations or taken for other size fractions (such as PM10) can be used for validation of the methodology to a limited extent.

Based on basic laws of atmospheric diffusion theory, the size of urban agglomerations, local wind speeds and the frequency of winter days with low ventilation, in addition to the emission densities of urban low-level emission sources, have been identified as critical factors that contribute to the "urban increments" in a given city. This information has been compiled from available sources for 473 European cities in Europe with more than 100.000 inhabitants. However, serious uncertainties that have critical influence on the estimated urban increments are associated with all these data. Most importantly, at the European level only limited information about the meteorological conditions within cities is available. Comparisons of local data with the information extracted from the Europe-wide databases reveals sometimes significant discrepancies. Furthermore, the available emission inventories for several source categories (e.g., road transport) exhibit substantial differences across countries which cannot always be explained to a satisfactory extent. Of particular relevance is the amount of fuel wood burned within cities, where the Europe-wide emission inventories provide only insufficient information.

Compared to the CAFE analysis, the revised methodology and data that are used for the NEC assessment result in higher urban increments of PM2.5. While a robust validation against the available measurements is burdened with high uncertainties, the comparably low increments computed, e.g., for Germany and the UK are mainly associated with the low densities of urban PM2.5 emissions that are used for the calculations, which are, however, in line with the nationally reported emission inventories. On the other hand, the uncertainties surrounding the issue of wood burning in cities might lead to potential overestimates of urban increments in countries with a high share of national total PM2.5 emissions from wood combustion (e.g., Austria, France). Furthermore, the lack of plant-specific specific information about the exact location and release height of industrial process emission sources might cause inaccuracies of the Europe-wide assessment for individual industrial cities.

More accurate information on city-specific meteorological data and information on the characteristics of local emission sources as well as improved monitoring data are important prerequisites for a further refinement of the methodology.

4.3 Deposition of sulphur and nitrogen compounds

The critical loads approach employed by the GAINS model for the quantification of ecosystems risks from acidification and eutrophication uses (ecosystem-specific) annual mean deposition of acidifying compounds (i.e., sulphur, oxidized and reduced nitrogen) as the impact-relevant air quality indicator. Significant non-linearities in the spatial source-receptor relationships due to co-deposition with ammonia have been found for the substantial emission reductions that have occurred over the last two decades (Fowler *et al.*, 2005). However, the EMEP Eulerian models suggests – for the technically feasible range of further emission reductions beyond the baseline projection considered by CAFE – nearly linear responses in annual mean deposition of sulfur and nitrogen compounds towards changes in SO_2, NO_x and NH_3 emissions:

$$Dep_{p,j} = Dep_{p,j,0} - \sum_i P_{i,j,p,0}(E_{i,p,0} - E_{i,p}) \tag{14}$$

with

$Dep_{p,j}$	***Annual deposition of pollutant* p *at receptor point* j**
$Dep_{p,j,,0}$	Reference deposition of pollutant *p* at receptor point *j*
$E_{i,p}$	Annual emission of pollutant *p* (SO_2, NO_x, NH_3) in country *i*
$E_{i,p,0}$	Reference emissions of pollutant *p* in country *i*
$\boldsymbol{P_{i,j,p,0}}$	Transfer matrix for pollutant *p* for emission changes around the reference emissions.

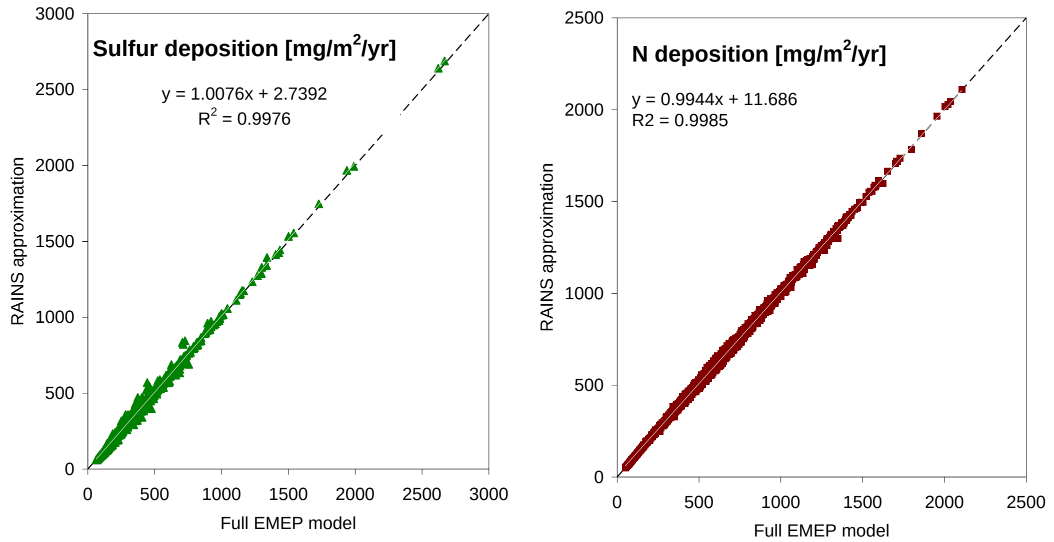

Figure 4.17: Comparison of the impact indicators calculated from the reduced-form approximations of the GAINS model with the results from the full EMEP Eulerian model, for the final CAFE scenario.

4.4 Formation of ground-level ozone – regional scale

The 2003 WHO systematic review of health aspects of air quality in Europe (WHO, 2003) emphasized that recent scientific studies have strengthened the evidence for health impacts from ozone not only from ozone peak episodes, but also from lower ozone concentrations as they occur throughout the year. The UNECE/WHO Task Force on Health recommended for health impact assessments the so-called SOMO35 as a relevant ozone indicator (UNECE/WHO, 2004). SOMO35 is calculated as the sum over the year of the daily eight-hour maximum ozone concentrations in excess of a 35 ppb threshold.

A wide body of scientific literature has highlighted important non-linearities in the response of ozone concentrations to changes in the precursor emissions, most notably with respect to the levels of NO_x emissions. It has been shown that, at sufficiently high ambient concentrations of NO and NO_2, lower NO_x emissions could lead to increased levels of ozone peaks. In earlier analyses for the negotiations of the Gothenburg multi-pollutant/multi-effect protocol in 1999, the RAINS model reflected this non-linear response through source-receptor relationships that describe the effect of NO_x emission reductions on accumulated ozone concentrations above 60 ppb in form of quadratic polynomials (Heyes *et al.*, 1996). A re-analysis of the latest Eulerian model results for the CAFE programme with a focus on the likely emission levels for the year 2020 suggests that such non-linearities will become less important for three reasons: (i) In 2020 "current legislation" baseline NO_x emissions are expected to be 50 percent lower than in the year 2000. (ii) The chemical processes that cause these non-linearities show less effect on the new long-term impact indicator (SOMO35) than for ozone peak concentrations; and (iii) such non-linearities diminish even further when population-weighted country-means of SOMO35 are considered. It was found that within the policy-relevant range of emissions (i.e., between the "CLE" and the "MTFR" levels anticipated for 2020), changes in the SOMO35 indicator could be described sufficiently accurate by a linear formulation:

$$O3_l = O3_{l,0} - \sum_i N_{i,l}(n_{i,0} - n_i) - \sum_i V_{i,l}(v_{i,0} - v_i) \qquad (15)$$

where

$O3_l$	***Health-relevant long-term ozone indicator measured as the population-weighted SOMO35 in receptor country* l**
$O3_{l,0}$	Population-weighted SOMO35 in receptor country *l* due to reference emissions n_0, v_0
n_i, v_i	Emissions of NO_x and VOC in source country *i*
$\boldsymbol{N_{i,l}}$, $\boldsymbol{V_{i,l}}$	Coefficients describing the changes in population-weighted SOMO35 in receptor country *l* due to emissions of NO_x and VOC in source country *i*.

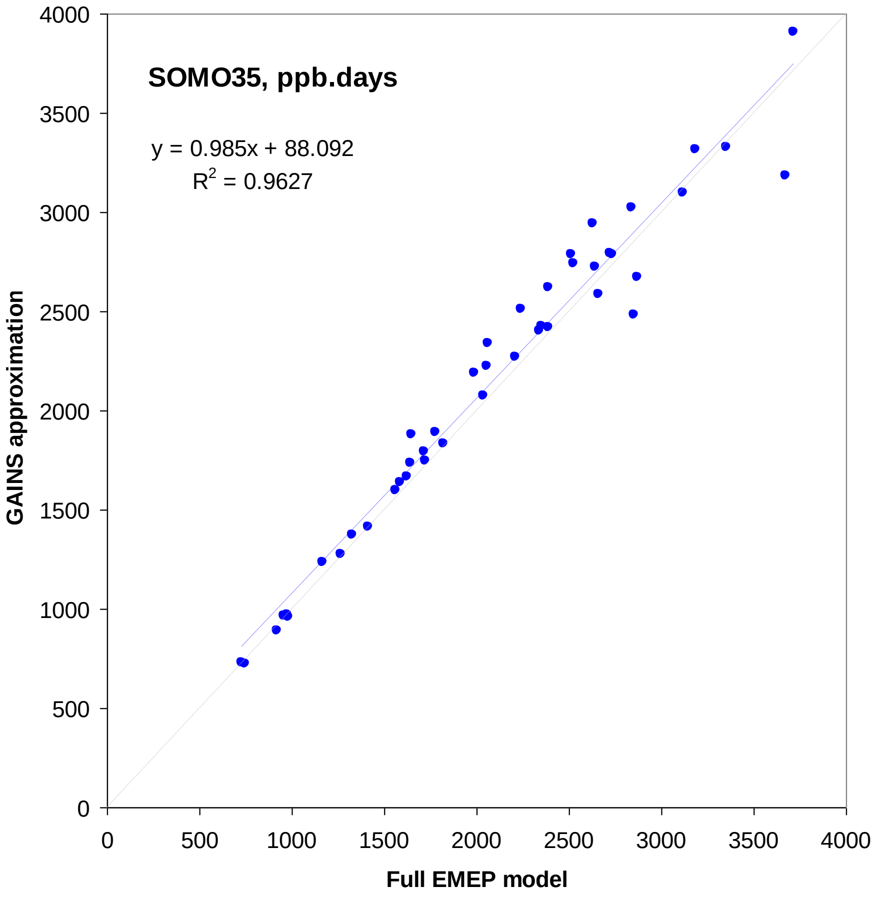

Figure 4.18: Comparison of the impact indicators calculated from the reduced-form approximations of the GAINS model with the results from the full EMEP Eulerian model, for the final CAFE scenario.

4.5 Formation of ground-level ozone – urban scale

As for fine particles, the GAINS analysis employs the EMEP regional scale Eulerian dispersion model with a 50*50 km resolution to compute regional scale changes in ozone that are thought to be representative for rural ozone levels. However, it is well understood that ozone within cities shows distinctive and systematic differences to rural levels, inter alia to the availability of local NO emissions in cities that cause a disappearance of ozone in urban areas. Analysis conducted within the City-delta project indicates in general that for reductions of urban NO_x emissions ozone concentration in cities increases because there is less NO released in the cities to react with ozone. This is e.g. reflected in the SOMO35 exposure measure (Figure 4.19). Within cities, these increases counteract reductions in ozone resulting from regional scale reductions of NO_x emissions.

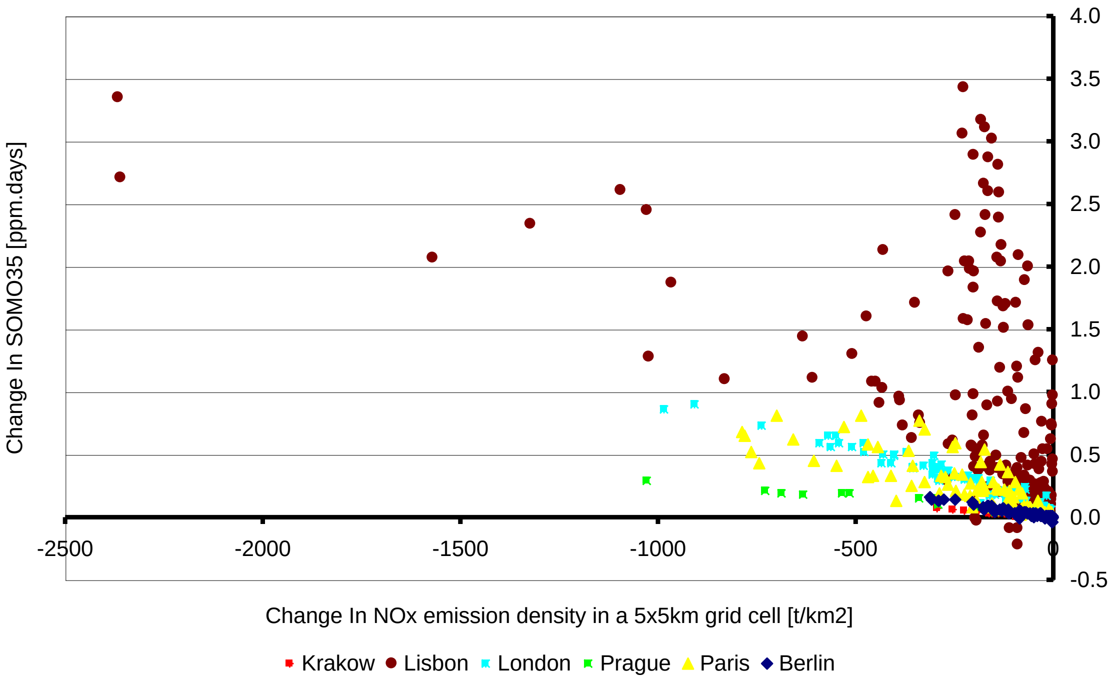

Figure 4.19: Change in the SOMO35 indicator in response to reductions of urban NO_x emissions as computed by the CAMx model for six European cities participating in the City-delta project.

While the existence of this inverse relation between the reductions of NO_x emissions and of urban ozone levels is widely acknowledged, the magnitude of this effect has not been quantified in a systematic ways for cities in different parts in Europe. It is clear from Figure 4.19 that ozone responds at different rates to emission reductions in the six cities analyzed, but the influence of the determining factors (such as meteorological conditions, emission densities, NO_x/VOC ratios, etc.) in a Europe-wide context has not been developed as yet.

In order to avoid that European emission control strategies focusing on health impacts are unduly driven by inaccurate representations of ozone formation for urban areas (e.g., by simply using results from regional scale dispersion models), a zero-order assumption has been made for the GAINS computations that reductions in urban NO_x emissions would not lead to decreased ozone within cities.

In practice, based on the source-receptor relationships of Equation 15 derived from the regional scale model, for each country the changes of a population-weighted SOMO35 metric (which is proportional to the health impacts computed by GAINS) have been computed. Calculations have been done for the urban, rural and total populations, respectively, and for changes in NO_x and VOC emissions, respectively. In a second step, all improvements in the ozone indicator computed for the urban population in response to NO_x emission reductions have been set to zero, as a conservative reflection of the ozone chemistry within cities.

Furthermore, as indicated in Equation 15, the GAINS model applies a linear representation of ozone formation that is valid for limited variations from the reference (target) emission level. Obviously, such a formulation does not convey the important information of full ozone formation models to the optimizer that – at places with sufficiently high NO_x concentrations – larger reductions of NO_x emissions will lead to declining ozone, while smaller reductions will increase ozone. Without the information that larger reductions (beyond the analyzed emission range) will lead to declining ozone, a cost-minimizing optimization would tend to increase NO_x emissions in order to reduce ozone concentrations. Obviously, although such a solution constitutes a valid reaction on formal grounds, it is contrary to the objectives of European clean air policy. To avoid the GAINS optimization to be misled by incomplete information about ozone formation characteristics, all source-receptor relationships that indicate for the analyzed range of emission changes increases in the ozone health metric for the rural population due to reduced NO_x emissions have been set to zero.

In a third step, the resulting changes for urban and rural populations have been combined into single coefficients that reflect the collective response of total population to changes in NO_x and VOC emissions, respectively.

5 Air quality impacts

5.1 Health impacts from PM

Based on the findings of the WHO review on the health impacts of air pollution (WHO, 2003), the GAINS model quantifies for different emission scenarios premature mortality that can be attributed to long-term exposure to PM2.5, following the outcomes of the American Cancer Society cohort study (Pope *et al.*, 2002).

Cohort- and country-specific mortality data extracted from life table statistics are used to calculate for each cohort the baseline survival function over time. The survival function $l_c(t)$ indicates the percentage of a cohort c alive after time t elapsed since starting time w_0. $l_c(t)$ is an exponential function of the sum of the mortality rates $\mu_{a,b}$, which are derived from life tables with a as age and b as calendar time. As the relative risk function taken from Pope *et al.*, 2002 applies only to cohorts that are at least w_0=30 years old, younger cohorts were excluded from this analysis. Accordingly, for a cohort aged c, $l_c(t)$ is:

$$l_c(t) = \exp\left(-\sum_{z=c}^{t} \mu_{z,z-c+w_0} \right). \tag{16}$$

The survival function is modified by the exposure to PM pollution, which changes the mortality rate and consequently the remaining life expectancy (e_c). For a given exposure to PM2.5 (PM), life expectancy $\bar{l}_c$ is calculated as the integral over the remaining life time:

$$e_c = \int_c^{w_1} \bar{l}_c(t)dt = \int_c^{w_1} \exp\left(-RR_{PM} \sum_{z=c}^{t} \mu_{z,z-c+w_0} \right) dt \tag{17}$$

where w_1 is the maximum age considered and RR_{PM} the relative risk for a given concentration of PM2.5. With some simplifying assumptions and approximations (Vaupel and Yashin, 1985), the change in life expectancy per person (Δe_c) of a cohort c can be expressed as:

$$\Delta e_c = \beta PM \int_c^{w_1} l_c(t) \log l_c(t) dt \tag{18}$$

where – within the studied exposure range – RR_{PM} has been approximated as $RR_{PM} = \beta \cdot PM + 1$ with β = 0.006 as given in Pope *et al.*, 2002. For all cohorts in a country l the change in life years ΔL_l is then calculated as the sum of the change in life years for the cohorts living in the grid cells j of the country l:

$$\Delta L_l = \sum_{c=w_0}^{w_1} \Delta L_{c,i} = \beta \sum_{j \in l} PM_j \frac{Pop_j}{Pop_l} \sum_{c=w_0}^{w_1} Pop_{c,l} \int_c^{w_1} l_c(t) \log l_c(t) dt \tag{19}$$

where

$\Delta L_{c,l}$	***Change in life years lived for cohort* c *in country* l**
$Pop_{c,l}$	Population in cohort c in country l
Pop_j	Total population in grid cell j (at least of age w_0=30)
$\boldsymbol{Pop_l}$	Total population in country l (at least of age w_0=30).

5.2 Protection of ecosystems against acidification and eutrophication

The GAINS model applies the critical loads concept as a quantitative indicator for sustainable levels of sulfur and nitrogen deposition. Critical loads have been defined as the maximum input of deposition of sulfur and nitrogen compounds that does not, according to current scientific understanding, cause harmful effects in sensitive ecosystems in the long run (Nilsson and Grennfelt, 1988). The GAINS analysis employs the critical loads databases compiled by the Coordination Centre for Effects (CCE) of the UNECE Working Group on Effects. These critical loads have been computed by national focal centers using an internationally agreed methodology (Hettelingh *et al.*, 2004; UBA, 2004).

To evaluate the ecological impacts of emission control scenarios, GAINS compares computed deposition with these critical loads. GAINS uses the average accumulated exceedance (AAE) as a quantitative summary indicator for the excess of critical loads considering all ecosystems in a region. For the optimization mode of GAINS, the AAE for effect q in country l has been related to emissions by a linear model:

$$AAE_{q,l} = AAE_{q,l,0} - \sum_p \sum_i a_{i,l,p,q} (E_{i,p,0} - E_{i,p}) \tag{20}$$

where the sum is over all emitter regions i and all pollutants p contributing to critical load excess (sulfur and nitrogen species); as earlier, the index 0 refers to reference emissions. The so-called impact coefficients $a_{i,l,p,q}$ are derived at the CCE by first computing the depositions in one country from the emissions in another country via Equation (20) and then AAE from the individual critical loads according to:

$$AAE_{q,l} = \sum_{j \in l} \sum_u A_{q,j,u} \cdot \max\{Dep_{p,j} - CL_{q,j,u}, 0\} \Big/ \sum_{j \in l} \sum_u A_{q,j,u} \tag{21}$$

where $CL_{q,j,u}$ is the critical load of effect q for ecosystem u in grid j which has area $A_{q,j,u}$ and $Dep_{p,j}$ is the ecosystem-specific deposition onto that ecosystem of the relevant pollutant. The summation runs over all ecosystems within a grid cell j in country l. The ‘maximum’ in the equation makes sure that an ecosystem contributes zero to the AAE if the deposition is smaller than the critical load, i.e., if there is non-exceedance. This procedure is carried out for all country source-receptor combinations, resulting in a total of about 9,000 coefficients for acidification and eutrophication, of which, however, a large number is (close to) zero (Posch *et al.*, 2005). Equation 21 describes the AAE calculation for a single pollutant, such as total nitrogen for eutrophication. For acidification, the AAE calculations are more complicated since they include the effects of sulfur and nitrogen deposition (for technical details see Posch *et al.*, 2001, UBA, 2004). In the ex-post analysis of an optimization result, the AAE and protection percentages for the individual countries are directly and exactly computed from the individual critical load values.

5.3 Health impacts from ozone

Based on a comprehensive meta-analysis of time series studies conducted for the World Health Organization (Anderson *et al.*, 2004) and on advice received from the UNECE/WHO Task Force on Health (UNECE/WHO, 2004), the GAINS model quantifies premature mortality through an association with the so-called SOMO35 indicator for long-term ozone concentrations in ambient air. SOMO35 is calculated as the daily eight-hour maximum ozone concentrations in excess of a 35 ppb threshold, summed over the full year. In essence, the GAINS calculation estimates for the full year daily changes in mortality as a function of daily eight-hour maximum ozone concentrations, employing the concentration-response curves derived in the meta-analysis of Anderson *et al.*, 2004. The threshold was introduced (i) to acknowledge uncertainties about the validity of the linear concentration-response function for lower ozone concentrations, and (ii) in order not to overestimate the health effects. The annual cases of premature mortality attributable to ozone are then calculated as

$$Mort_l = \tfrac{2}{365} Deaths_l \cdot RR_{O3} \cdot O3_l \qquad (22)$$

where

$Mort_l$	***Cases of premature mortality per year in country* l**
$Deaths_l$	Baseline mortality (number of deaths per year) in country l
$\boldsymbol{RR_{O3}}$	Relative risk for one percent increase in daily mortality per µg/m^3 eight-hour maximum ozone concentration per day.

In addition to the mortality effects, there is clear evidence about acute morbidity impacts of ozone (e.g., various types of respiratory diseases). However, the GAINS model quantifies only mortality impacts of ozone, as they emerge as the dominant factor in any economic benefit assessment. Morbidity impacts will be quantified ex-post in the benefit assessment.

5.4 Vegetation impacts from ground-level ozone

Elevated levels of ozone have been shown to cause wide-spread damage to vegetation. In earlier policy analyses for the NEC Directive of the EU and the Gothenburg Protocol in 1999, RAINS applied the concept of critical levels to quantify progress towards the environmental long-term target of full protection of vegetation from ozone damage. The UNECE Working Group on Effects lists in its Mapping Manual critical levels for crops, forests and semi-natural vegetation in terms of different levels of AOT40 (UBA, 2004). This indicator is defined as the sum of hourly ozone concentrations above a threshold of 40 ppb, accumulated over the most sensitive vegetation period. After 1999, several important limitations and uncertainties of the AOT approach have been pointed out, inter alia a potential mismatch with critical features of important physiological processes. Alternative concepts, including the ozone flux concept, were developed and suggested as superior alternatives to the former AOT40 approach (Karlsson *et al.*, 2004).

While the theoretical advantage of the flux concept is widely accepted, the quantification of its critical parameters and their validation for economically and ecologically important vegetation types and plant species could not be completed in time for this analysis. Thus, for describing vegetation impacts of ozone the GAINS model cannot yet rely on a generally accepted methodology. It was found that the SOMO35 indicator as it is used by GAINS for quantifying health impacts is generally more sensitive than both the AOT40 and the currently available ozone flux indicators. Thus, it was concluded that progress on the SOMO35 scale will lead to at least equivalent progress on both scales that are currently discussed for vegetation impacts. Ozone vegetation impacts will be quantified ex-post in the benefit assessment.

6 The GAINS optimization

THE optimization model of GAINS uses two types of decision variables: (i) activity variables $x_{i,k,m}$ for all countries i, activities k, and control technologies m, and (ii) the substitution variables $y_{i,k,k'}$ that represent fuel substitutions and efficiency improvements (replacing activity k by activity k'). The objective function that is minimized is the sum

$$C = \sum_{i,k} \left(\sum_{m} c^{x}_{i,k,m} \cdot x_{i,k,m} + \sum_{k'} c^{y}_{i,k,k'} y_{i,k,k'} \right) \tag{23}$$

where the first term represents the total end of pipe technologies cost, and the second term represents the total substitution/energy efficiency cost term. In order to avoid double counting the substitution cost coefficients $c^{y}_{ikk'}$ in the second term are calculated for uncontrolled activities, the difference in cost for control equipment for a fuel substitution is accounted for in the first term.

It is convenient to consider the activity data $x_{i,k}$, which are obtained from the variables $x_{i,k,m}$ by performing the appropriate sum over control technologies m. Activity data as well as the substitution variables may be constrained:

$$x^{\min}_{i,k,m} \leq x_{i,k,m} \leq x^{\max}_{i,k,m}, \; x^{\min}_{i,k} \leq x_{i,k} \leq x^{\max}_{i,k}, \quad y^{\min}_{i,k,k'} \leq y_{i,k,k'} \leq y^{\max}_{i,k,k'} \tag{24}$$

due to limitations in applicability or availability of technologies or fuel types.

The applicability of add-on technologies may be constrained by a maximum value:

$$x_{i,k,m} \leq appl^{\max}_{i,k,m} x_{i,k}, \quad appl^{CLE}_{i,k,m} \leq appl^{\max}_{i,k,m} \tag{25}$$

where the maximum application rate is at least as high as the application rate in the current legislation scenario. For ammonia (NH_3), technologies in the agricultural (livestock) sector are subdivided into technologies applying to different stages of manure treatment. For these technologies, application constraints are applied at a more aggregated level.

Emissions of pollutant p are calculated from the technology-specific activity data $x_{i,k,m}$ and their associated emission factors $ef_{i,k,m,p}$:

$$E_{i,p} = \sum_{k} \sum_{m} ef_{i,k,m,p} \cdot x_{i,k,m} \tag{26}$$

Since for no individual activity k emissions should increase above the current legislation level, it is further imposed that

$$\sum_{m} ef_{i,k,m,p} \cdot x_{i,k,m} \leq IEF^{CLE}_{i,k,p} \cdot x_{i,k} \tag{27}$$

where $ef_{i,k,m,p}$ is the emission factor for pollutant p stemming from activity k being controlled by technology m, and $IEF_{i,k,p}^{CLE}$ is the implied, i.e., average emission factor for that pollutant from activity k in country i in the current legislation scenario.

Activity variables $x_{i,k,m}$ are linked to the substitution variables $y_{i,k,k'}$ via the balance equations

$$x_{i,k} + \sum_{k'} y_{i,k,k'} - \sum_{k'} \eta_{i,k',k} \cdot y_{i,k',k} = x^{CLE}_{i,k} \tag{28}$$

where $x^{CLE}_{i,k}$ is the activity k in country i in the current legislation scenario and $\eta_{i,k,k'}$ is the substitution coefficient that describes the relative efficiency change in the transition from activity k' to activity k. For example, in the energy sector this last equation is balancing the energy supply before and after a fuel substitution. There are also a number of constraints which ensure consistency across various levels of aggregations of sub-sectors and sub-activities.