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The GAINS optimization module: Identifying cost-effective measures for improving air quality and short-term climate forcing

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Abstract

This document describes the optimization framework of the GAINS model as used for the development of cost-effective air pollution control scenarios for Europe. We put particular emphasis on the methodology for finding cost-effective control strategies that address both environmental impact indicators related to air pollution, and the radiative forcing of (some of) these pollutants. The GAINS multi-pollutant multi-effect framework lends itself for analysing synergies and trade-offs between different objectives and for quantifying cost implications.

In this document we describe various formal aspects of the optimization, including the dimension of the solution space, nature and use of decision variables and their relation to relevant functions, such as cost, emissions and environmental impact indicators. We illustrate standard optimization configurations that are used to calculate commonly used scenarios. We introduce the gap closure procedure that allows to set targets that are guaranteed to be feasible and which at the same time respect the need to distribute environmental benefits evenly, as far as possible, between countries.

We further illustrate, for selected ambition levels, the trade-off between reductions in environmental impact indicators and radiative forcings. Within certain ranges, these trade-offs in terms of physical effects can be compensated by changing to a more costly control strategy. The cost for compensation can systematically be calculated, and very specific recommendations can be made in terms of measures in different countries.

Unlike in multi-criteria optimization the current formulation of the GAINS optimization makes very explicit the distinction between environmental objectives and control costs. Thus, judgements about the relative value of various environmental benefits are not hidden in some model assumption but need to be made explicit and open in view of the results. In this way, GAINS can be used to aid policy makers to contemplate policy options with the required flexibility, without losing sight of cost-effectiveness considerations.

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1 Introduction

Emissions of air pollutants have adverse effects, both for ecosystems and human health. Some air pollutants also act as climate forcers in the atmosphere. Emissions can be reduced by using appropriate emission control technologies. Some of these technologies are costly. In several European policy processes of air pollution control a cost-effectiveness approach was chosen as a basis for identifying specific national obligations.

In this report we describe the methodology used in the GAINS model for finding cost-effective emission control strategies that address either air quality or short-term radiative forcing objectives (which are not covered by international agreements so far), or both. In particular, we focus here on emission control strategies that only affect the application of so-called end-of-pipe measures, i.e. measures that change the emission factors of one or more pollutants without affecting the underlying activities. Thus, fuel substitutions or energy saving measures are not considered in this approach.

The impact calculation in the GAINS model has recently been described by Amann et al. (2011*a*), while the GAINS methodology for calculating radiative forcing from the emissions of aerosol and precursors has not been published. Moreover, the the GAINS optimization methodology described by Wagner et al. (2007) has been revised to include both aspects. It the purpose of this document to provide a coherent and consistently notated documentation of environmental impact indicators and the GAINS optimization. We also provide further detail on the source-receptor matrices derived from the EMEP model and used assessment exercises under the LRTAP Convention and for the European Union.

In the following section we give a broad overview of the GAINS model in general, before describing formally the optimization problem, as well as the configuration procedure. In Section 6 we provide some example analysis of the relationship between strategies that address local and transboundary air pollution and those that address regional radiative forcing.

2 The GAINS model

2.1 Concept

The GAINS model describes the pathways of atmospheric pollution from anthropogenic driving forces to the most relevant environmental impacts (Amann et al. 2004). It brings together information on future economic, energy and agricultural development, emission control potentials and costs, atmospheric dispersion and environmental sensitivities toward air pollution. The model addresses threats to human health posed by fine particulates and ground-level ozone, risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated levels of ozone, as well as long-term radiative forcing. These impacts are considered in a multi-pollutant context, quantifying the contributions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (VOC), and primary emissions of fine ($PM_{2.5}$) and coarse ($PM_{2.5}$-PM_{10}) particles. GAINS also accounts for emissions of the six greenhouse gases that are included in the Kyoto protocol, i.e., carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and the three F-gases (cf. Figure 1). Many of the critical relationships in GAINS (e.g., those describing the dispersion of pollutants in the atmosphere and environmental impacts of pollution) are derived from various complex disciplinary models, which are represented in GAINS as reduced-form functional relationships. Input from key models is coordinated in the EC4MACS project.[1]

	PM (BC, OC)	SO_2	NO_x	VOC	NH_3	CO	CO_2	CH_4	N_2O	HFCs PFCs SF_6
Health impacts: PM (Loss in life expectancy)	√	√	√	√	√					
O_3 (Premature mortality)			√	√		√		√		
Vegetation damage: O_3 (AOT40/fluxes)			√	√		√		√		
Acidification (Excess of critical loads)		√	√		√					
Eutrophication (Excess of critical loads)			√		√					
Climate impacts: Long-term (GWP100)							√	√	√	√
Near-term forcing (in Europe and global mean forcing)	√	√	√	√	√	√				
Black carbon deposition to the arctic	√									

Figure 1: Interactions between pollutants and impacts considered in the GAINS model

GAINS holds the essential information on all aspects listed above for 162 world regions, an in particular 43 European countries, and links this data in such a way that the environmental implications of alternative assumptions on economic development and emission control strategies can be assessed. The GAINS model allows simulation of the

[1] http://www.ec4macs.eu

costs and environmental impacts of user-defined emission control scenarios. Its optimization mode, discussed in this document, balances emission control measures across countries, pollutants and economic sectors in such a way that user-defined target levels on the various environmental impacts are met at least costs.

The GAINS model is implemented as an interactive web-based software tool that communicates with an ORACLE database. Access is freely available over the Internet.[2] The interface allows the user to display all calculation results, such as emissions and costs (to various levels of aggregation) for alternative scenarios. Impacts can be displayed in tabular or graphical form (maps), and all results can be exported to Excel for further analysis. One may examine all input data, such as cost parameters, activity projections, technology characteristics and assumptions about future emission control policies as well as technology portfolios. It is also possible to download, modify and upload this information to generate new, user-defined and user-owned scenarios with alternative configurations of activity projections, assumptions about policies and emission characteristics. Data can be shared by predefined groups of users, e.g. within an organization. This flexibility allows us to effectively communicate with stakeholders, such as representatives of environmental agencies and ministries in European countries, and to grant them ownership over their own contributions. Ownership and a hierarchy of user privileges also allow users and stakeholders to study the implications of their own alternative scenarios in a non-public part of the database.

In addition to this simulation mode, GAINS also features a stand-alone optimization module, which we describe in detail in this report. This module can be used to identify cost-effective technology portfolios, for given sets of environmental objectives and subject to various constraints. The optimization is formulated as a linear programming (LP) problem in the GAMS programming language (Brooke et al. 1988).

2.2 Activity data, control strategies, emission and cost factors

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. The aggregation of emission sources and control options chosen for the GAINS model attempts to reflect these differences while considering the availability of high quality input data for all countries.

GAINS estimates emission control costs from the perspective of a social planner, with a focus on resource costs of emission controls to societies. While this perspective is different from that of private profit oriented actors, it is the appropriate approach for decisions on the optimal allocation of societal resources (Turner et al. 1993).

[2] http://gains.iiasa.ac.at

2.3 Policy applications of the GAINS model

Since 20 years, the RAINS (Regional Air Pollution Information and Simulation) model (Schöpp et al. 1999) has been used as a commonly shared tool in the key negotiation processes in Europe that led to international agreements on harmonized emission control strategies. Other models include the ASAM (Warren & ApSimon 2000, Oxley & ApSimon 2007) and the MERLIN models (Reis et al. 2005). Under the Convention on Long-range Transboundary Air Pollution, the RAINS model was used to guide negotiations on national emission ceilings for the 1994 Second Sulfur Protocol (Tuinstra et al. 1999, Farrell et al. 2001) and the Gothenburg Multi-pollutant Protocol in 1999 (Hordijk & Amann 2007, Eckley 2002). Whereas earlier protocols under the Convention used a flat-rate approach with a fixed percentage of emission reductions for all parties, these 'second generation' protocols employed cost-effectiveness as the rationale for differentiated obligations for individual parties. According to (Haas & McCabe 2001), the concept was virtually revolutionary in diplomacy because it assigned differential national obligations based on the carrying capacity of vulnerable ecosystems rather than a politically equitable (and arbitrary) emission cut. The European Commission used RAINS to quantify, inter alia, the obligations in its 1999 Directive on National Emission Ceilings (EC 2001, Amann & Lutz 2000) and in the Clean Air For Europe (CAFE) program that was adopted in 2005 (CEC 2005, Tuinstra 2007). In 2009 the Convention on Long-range Transboundary Air Pollution started negotiating a revision of its 1999 Gothenburg Protocol aiming at a Europe-wide harmonized strategy for further air quality improvements up to 2020. This time negotiations employ the GAINS (Greenhouse gas and Air Pollution Interactions and Synergies) model to provide a quantitative scientific basis for the deliberations. GAINS is a successor to the RAINS model, incorporating latest scientific understanding on the impacts of air pollution and extended to cover the mitigation of greenhouse gases.

3 A Formal Approach to Optimization: Dimensions, Variables, Functions

The GAINS optimization module answers the question: how can a given set of environmental targets across Europe be achieved most cost-effectively, and how much does it cost? A solution to the first question is given in the form of an energy mix and set of emission control measures for each country and sector involved. The answer to the second question is given by the total control and fuel substitution cost at appropriate levels of aggregations. The optimization is formulated as a Linear Programming (LP) problem, i.e., all equations, definitions and constraints are linear in the decision variables. This allows us to use very fast solvers (CPLEX) that are commercially available.

In principle, any LP problem can be written formulated as: minimize an objective function C, so that all constraints are met, i.e.

$$\min C(x), \quad \text{such that } A \cdot x \leq b \tag{1}$$

for some matrix A and some vector b, where x are the decision variables. The purpose of this section is to specify these elements, i.e. to flesh out the individual components. In the course of this specification we will also explain how these elements relate to the components of the GAINS model and motivate the approach taken in the GAINS model to identify cost-optimal scenarios.

3.1 Dimensions

In the following it will be useful to recall some of the structure of the GAINS model. The GAINS databases cover information in various dimensions: in time, space, sectors, activities, emission control technologies, pollutants. We discuss these briefly in turn and introduce useful notation.

3.1.1 Space

The GAINS model covers at the global level 162 land-based regions, most of them individual countries, but also subnational regions for large countries like China and India. In Europe, which is the focus of this document, GAINS covers more than 40 land-based regions and fifteen sea regions are represented. For simplicity only, in this document we may refer to all these regions as 'countries'. We use the index $i \in I$ to denote the set of emitter countries, and in circumstances in which it is necessary to draw the distinction between emitter/source and receptor countries, we denote the receptor countries by an index $k \in K$. Impacts are calculated on a grid (e.g. the 50 km $\times$ 50 km EMEP grid, currently refined to 28 km $\times$ 28 km), and then aggregated to the country level. City-scale concentrations are taken into account using the City-Delta methodology described in Section 3.4.1.

In GAINS it is possible to include all of the regions, or only subsets of regions in the optimization. For the optimization the flexibility is manifold:

- It is possible to select a subset $I_0 \subset I$ of emitter countries i on which the optimization operates, i.e., whose emissions can be changed by changing the country's control strategy and activity data.[3] For all other countries included in I but not in I_0 all activity data and control measures are fixed at the baseline level. This allows us to study the different implications of whether a policy is applied, e.g., only in EU27, or also beyond.

[3] In GAINS policies are represented by application rates of (mixes) of technologies. The set of values of application rates for all technologies is called a 'control strategy' (cf. relation (9) below), which we denote by $q_{i,s,f,t}$ (the year index is understood and thus suppressed)

- It is also possible to select a subset $K_0 \subset K$ of receptor countries that are included in the impact calculation. By defining K_0 independently of I_0 we are able to calculate, e.g., the value of the YOLL function (see below) in EU27 only, but taking into account also emissions from non-EU regions. Sensitivity runs with different boundary conditions give useful insights in planning future policies.
- Radiative forcing and carbon deposition are calculated not at the country level but at relevant scales: radiative forcings are calculated over the EMEP domain, over the arctic Arctic region above 60° north, the Arctic region above 70° north, and all of Europe; carbon depositions are calculated over the Arctic region above 60° N, the Arctic region above 70° N, and the Alps). For simplicity, when there is no danger of confusion we consider and the label these receptor regions also as $k \in K$.

3.1.2 Time

The GAINS model in simulation mode operates in 5-year steps, starting from a base year and running into the future. The baseyear for air pollutant emissions is (currently) typically the year 2000 or 2005, depending on the context and the base year activity data and emissions are calibrated to international statistics. Different scenarios can have different time horizons, depending on the context. Currently the longest time horizon available within the GAINS model is the year 2050.

The optimization mode is applied only to a single year period. The objective of the optimization to identify cost-effective emission control strategies that meet a given set of environmental targets under constraints on technologies, etc, in that particular year. It is thus designed to (a) illustrate the costs for given targets, (b) provide an initial set of potential emission ceilings and hence a distribution of costs across countries and sectors, and thereby (c) provide policy processes with plausible scenarios of future controls and their costs. The optimization, however, does not provide trajectories leading from base year configurations to an optimal control strategy. Thus it is not prescriptive on the timing for the introduction of additional control measures.

As a consequence of this approach, in the following we can suppress the time index, understanding that a specific future year (e.g. 2020 or 2030) for which the optimization is carried out has been pre-selected.

3.1.3 Activities and Sectors

GAINS covers a large number of sectors, and each sector may be associated with a number of different activities. Hence, in GAINS activity data are structured by sector-activity combinations. For example, in the sector ‘industrial boilers’ the associated activities are the various fuels that are used in industrial boilers, i.e., coal, oil, etc. Activities may be further subdivided, e.g., hard coal (grade 1), hard coal (grade 2), etc. The sectors covered by GAINS are indexed by $s \in S$, and likewise the set of activities is indexed by $f \in F$. There are approximately 1,000 legitimate combinations of sectors and activities (s, f) in the GAINS model, each of which representing a source category for one or more pollutants. For the present purposes we restrict ourselves to the case in which the activity data are constant, i.e. they are not allowed to change relative to the baseline scenario. Thus emission reductions can only be achieved by changing the application rates of control technologies, but not by changes in the activity data (fuel switches, energy efficiency improvements, etc.).

In many circumstances it is useful to consider certain subsets of sectors or activities. For example, we define the subset $F_{i,s}$ as the set of activities in country i that are occurring in sector s. This set is clearly only a subset of F, the set of all activities, since not all activities are associated with each sector. Note that the activities actually occurring may be different in different countries. For example, in some countries heavy fuel oil is used as a fuel in the power plant sector, whereas in others it is not. Hence the sets $F_{i,s}$ can be different for different countries. Similarly, the set $S_{i,f}$ is set of sectors in country i in which a certain activity occurs. One may define such subsets for specific years or for a whole period.

3.1.4 Pollutants

The set of pollutants $p \in P$ in GAINS covers both the traditional air pollutants (SO_2, NO_x, $PM_{2.5}$, BC, OC, NH_3 and VOC) as well as the greenhouse gases CO_2, CH_4, N_2O and FGAS (a GWP-weighted average of HFCs, PFCs, SF_6). In this report we focus on identifying control strategies for the traditional air pollutants.

3.1.5 Emission control technologies

Recall that here we are focussing only on end-of-pipe measures and do not considered changes of the underlying activity data (e.g. fuel switches, energy savings).

Emissions of pollutants can be controlled with control technologies $t \in T$, but not every technology controls every pollutant. Rather, for a given pollutant p, the set of technologies that controls this pollutant is denoted by $T_p \subset T$, and conversely, for a given technology t it is useful to define the set of pollutants P_t that are controlled by that technology. In the set of technologies T we have also included pollutant-specific 'no-control' technologies NOC_p, for example 'NOC_NOX'. In this way any activity, whether controlled or uncontrolled is associated with a technology. The significance of this provision will become clearer in due course.

It is very useful to define the set of technologies that can be applied in sector s to activity f, and to denote it by $T_{s,f}$ (NB: this set does not depend on the country-index i). Also, we will make use of the set $T_{s,f,p}$, the set of technologies t that are applicable to the sector-activity combination (s, f) and that control pollutant p (NB: this set includes the 'technology' no-control, NOC_p). Finally, not every sector-activity combination is associated with each pollutant; hence it is helpful to define the set $P_{s,f}$ of pollutants that are associated with the activity-sector combination (s, f).

3.2 Decision variables

Note again that in this document we restrict ourselves to the GAINS optimization in which we assume the activity data to be constant and all emission control measures be implented as 'end-of-pipe' technologies. In this case GAINS uses essentially two sets of decision variables:

- **Technology-specific activity data.** These variables describe the level of the activity f in sector s and country i that is controlled by technology t. We denote these variables by $x_{i,s,f,t}$. Naturally, theses variables can only take non-negative values and the following has to hold: $f \in F_{i,s}$ and also $t \in T_{i,s,f}$. Thus,

$$0 \leq x_{i,s,f,t}, \quad \forall i \in I, \forall s \in S, f \in F_{i,s}, t \in T_{i,s,f} \tag{2}$$

  In the baseline scenario the $x_{i,s,f,t}$ are simply obtained by calculating the activity data in the baseline scenario $xa^{\mathrm{B}L}_{i,s,f}$ with the corrensponding control strategy values, which we denote by $q^{\mathrm{B}L}_{i,s,f,t}$

$$x^{\mathrm{B}L}_{i,s,f,t} = xa^{\mathrm{B}L}_{i,s,f} \cdot q^{\mathrm{B}L}_{i,s,f,t} \tag{3}$$

- **Subsectoral technology-specific activity data.** As will be discussed in some detail below in Section 4.3, a key element in the optimization are the technological constraints that specify to what extent technologies can be used beyond the baseline application rate, but also to what extent the baseline technologies can be replaced by other, better technologies. In order to implement such technology replacement constraints, it is useful to define permissible 'chains' of technologies, i.e. rules that control which technologies can replace a given technology. For example, a simple rule would be to require that a technology can only be replaced by a technology with a lower emission factor. However, such a simple rule may not be applicable for those multi-pollutant technologies for which the reduction of one pollutant is associated with the increase of the emission factor of another. For this reason we have decided to model this kind of constraint in a different way (cf. the following and also Section 4.3). Also, in principle further restrictions could apply, for example, a GAINS sector may represent an aggregation of heterogeneous sub-sectors for which not the same technology portfolio is available. Specifically for the case of VOC we have provided in Appendix B an overview of such technology chains.

  In order to control the consistent use of technologies we introduce variables $xx_{i,s,f,t,t',p}$. These are essentially technology-specific activity data that where subject to control by technology t in the baseline, and are subject to t' in the alternative scenario.

  The transition variables $xx_{i,s,f,t,t',p}$ are linked to the technology-specific activity data through the following relation:

$$x_{i,s,f,t'} = \sum_{t \in T_{t'}} xx_{i,s,f,t,t',p} \tag{4}$$

where the set $T_{t'}$ specifically refers to the technologies that have a lower (or equal) emission factor (for a given air pollutant p) than t'. Eq. (4) has to hold for each pollutant separately and for all valid combinations of (i, s, f, t) and (i, s, f, t').

The xx are then uniquely defined by the following link to the baseline values:

$$x^{\mathrm{BL}}_{i,s,f,t} = \sum_{t' \in T_t} xx_{i,s,f,t',t,p} \tag{5}$$

where $x^{\mathrm{B}L}$ refers to the technology-specific activity data in the baseline, which are constants in the optimization. Again Eq. (5) has to hold for each pollutant separately and for all valid combinations of (i, s, f, t) and (i, s, f, t').

A simple example will illustrate the point . Suppose for a given sector-activity combination the control strategy in the baseline is as given on the left hand side of Figure 2: 40 percent is subject to control by technology A and B, and 20 percent is subject to technology C. The value of x_A and x_B is equal to 40 percent of the total activity data each, etc. As we optimize and change the mix of technologies the variables $xx_{t,t'}$ trace exactly which technologies are replaced by which other technologies[4]

In our concrete example the final outcome of the optimization is the column in the right hand side of Figure 2. Now only 20 percent of the activity is subject to technology A, 15 percent to B and 65 percent to C. In previous versions of the GAINS optimization this was all the information available. In contrast, we have introduced the variables xx and can monitor and control the transitions: from the middle column, focussing on the 'bottom' 40 percent of activity, we can see that 20 of the original 40 percent remain under technology A ($xx_{A,A}$), while 10 percent previously under A are now under B and C each. Similarly, focussing on the area between 40 and 80 percent in the first 2 columns, most of the activity originally under B is now under C, etc. With no better technology available, whatever used to be under C (on the left) remains under C (middle column, top 20 percent).

Had we banned the transition from B to C (for example, because the share of activity covered by B in the baseline was not suitable for control by C), the area between 45 and 80 percent in the middle bar of Figure 2 would not be coloured green and the resulting/net colouring would not be dominantely green.

By constraining the variables $xx_{i,s,f,t,t',p}$ appropriately (cf. Section 4.3.4), we can ensure that only certain transitions in the use of a technology relative to the baseline can occur.

[4]Naturally one must not think that technologies really get replaced when comparing two scenarios: the baseline scenario is also just a hypothetical future.

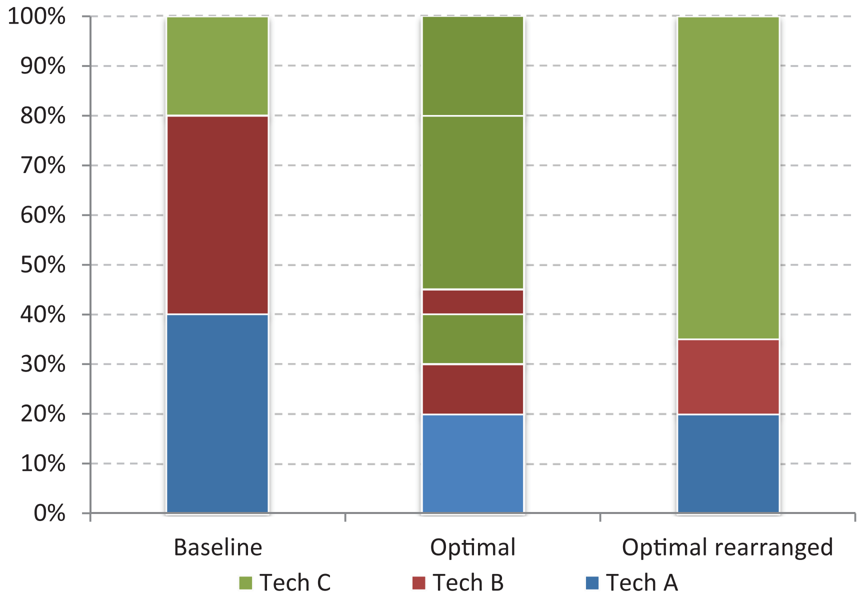

Figure 2: Example of the values and use of the transition variables $xx_{t,t'}$

3.3 Simple Functions: Emissions and Costs

There are a number of variables that can be derived from these two sets of decision variables x and xx. Among these are the activity data that can be linked to the activity data in the GAINS database, the application rates of technologies, the country emissions and the end-of-pipe control costs, as well as others. In the following we shall describe some of these derived variables.

3.3.1 Activity data

The technology-specific activity data $x_{i,s,f,t}$ describe the extent to which a certain control technology is applied in a given sector and country to a given activity, but it does not tell us what the total level of activity is. For, example the value for $x_{i,s,f,t}$ in a certain country may be 10 PJ for hard-coal fired power plants subject to advanced flue gas desulfurization, i.e. s = PP_NEW, and f = HC1 and t = RFGD. The total use of hard coal HC1 can only be inferred by summing over all 'appropriate' technologies. Since RFGD is an SO_2 control technologies we have to sum over all SO_2 control technologies (including the 'no-SO_2-control technology' NOC_SO2) in order to recover the total use of HC1 in PP_NEW. This can be generalized. We define:

$$xp_{i,s,f} = \sum_{t \in T_{s,f,p}} x_{i,s,f,t} \tag{6}$$

This is the pollutant p-specific activity data, which by itself may not be an intuitive concept. It significance becomes apparent shortly. Note that, mathematically for different pollutants the $xp_{i,s,f}$ are independent, i.e., they may be different. However, since $xp_{i,s,f}$

represents the total activity level, independently of the pollutant p under consideration, the $xp_{i,s,f}$ have to be the same for all pollutants:

$$xa_{i,s,f} = xp_{i,s,f} \quad , \quad \forall p \in P_{s,f}, i \in I, s \in S, f \in F_{i,s} \tag{7}$$

Eq. (7) defines the activity data for the sector-activity combination (s, f) in country i and it is used in GAINS as a constraint to ensure consistency of the activity data across pollutants. As mentioned above in this document we only consider end-of-pipe emission control measures which leave the activity unchanged at the baseline level:

$$xa_{i,s,f} = xa^{\mathrm{BL}}_{i,s,f} \tag{8}$$

i.e. these are constrained to be constants.

3.3.2 Application rates/Control strategies

. Starting from baseline activity data and a control strategy, the optimization routine may modify the decision variables x and xx, as decribed. Following the logic of the GAINS model, one can then separate these into (constant) activity data and a control strategy, i.e. the set of application rates of all relevant control technologies, which we denoted by $q_{i,s,f,t}$:

$$q_{i,s,f,t} = \frac{x_{i,s,f,t}}{xa_{i,s,f}}, \quad \forall i \in I, s \in S, f \in F_{i,s}, t \in T_{s,f} \tag{9}$$

so that $0\% \leq q_{i,s,f,t} \leq 100\%$. Eq. (9) is simply saying that the application rates are the ratios between technology-specific activity data and the total activity data for a given sector-activity combination.

3.3.3 Emissions of pollutant p.

Emissions can be calculated all levels of aggregations from the decision variables x and the emission factors. At the lowest level of aggregation, emissions steming from an activity f in sector s subject to control technology t is simply:

$$E_{i,s,f,t,p} = \mathrm{EF}^{\text{abated}}_{i,s,f,t,p} \cdot x_{i,s,f,t} \tag{10}$$

where the abated emission factor $\mathrm{EF}^{\text{abated}}_{i,s,f,t,p}$ is calculated in standard GAINS fashion as

$$\mathrm{EF}^{\text{abated}}_{i,s,f,t,p} = \mathrm{EF}_{i,s,f,p} \cdot (1 - \text{remeff}_{i,s,f,t,p}) \tag{11}$$

where in turn $\mathrm{EF}_{i,s,f,p}$ is the unabated emission factor of pollutant p associated with the sector-activity combination $(s, f,)$ in country i, and $\text{remeff}_{i,s,f,t,p}$ is the removal efficiency for pollutant p associated with technology t.

This can then easily be aggregated to the activity or sectoral level, in particular also to the level of SNAP1 sectors:

$$E^{\mathrm{SNAP1}=\gamma}_{i,p} = \sum_{(s,f)\in \mathrm{SNAP1}=\gamma} \sum_{T_{s,f,p}} w(s, f, \gamma) \cdot E_{i,s,f,t,p} \tag{12}$$

where $w(s,f,\gamma)$ denotes the share of the activity-sector values attributable to SNAP1 sector γ.[5]

Emissions of pollutant p in country i are thus calculated as:

$$E_{i,p} = \left(\sum_{s \in S} \sum_{f \in F_{i,s}} \sum_{t \in T_{s,f,p}} E_{i,s,f,t,p} \right) + E^0_{i,p} \tag{13}$$

where the second term, $E^0_{i,p}$, refers to emissions that are kept constant during the optimization because they are not modeled on the basis of the decision variables $x_{i,s,f,t}$. For land-based regions these emissions are zero, but for the sea regions these constants are a convenient method to represent ship emissions, for which no technical control options are modelled explicitly. Ship emissions stay constant during a GAINS optimization, the impact of different emissions from sea regions can, however, be analyzed on a scenario basis, i.e. by choosing different emission scenarios for these regions as a 'background' to the optimization.

3.3.4 Emission constrol costs.

Each emission control technology is associated with a unit cost, $uc_{i,s,f,t}$. Unit costs are calculated based on the assumption that, at a free market for emission control technologies, the same technology will be available to all countries at the same costs, at least within a world region. Also, technological progress is assumed in the performance and cost data, based on literature estimates. 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 3500 emission control options, GAINS estimates their costs of local application considering annualized investments (I_{an}), fixed ($\mathrm{OM}_{\mathrm{fix}}$) and variable ($\mathrm{OM}_{var}$) operating costs, and how they depend on technology t, country i and activity f in sector s (Cofala & Syri 1998*a*,*b*), (Klimont et al. 2000, 2002, Klimont & Winiwarter 2011), (Borken-Kleefeld et al. 2009), (Höglund-Isaksson et al. 2009).

With the given set of unit costs uc and the technology-specific activity data x, one calculates the cost for utilizing the technology as

$$C_{i,s,f,t} = uc_{i,s,f,t} \cdot x_{i,s,f,t} \tag{14}$$

which, again, can be aggregated to the activity-sector level, SNAP1 level, or the national level

$$C_i = \sum_{s \in S} \sum_{f \in F_s} \sum_{[t \in T_{s,f}]} C_{i,s,f,t} \tag{15}$$

[5]Typically (s,f) falls exactly into one of the SNAP1 sectors, i.e. $w = 1$. However, in individual cases GAINS activity-sector combinations do not match exactly the SNAP1 structure and are split.

Note that the sums do not run over the pollutants, ensuring that multi-pollutant technologies are only counted once. One can, however, indeed also calculate the cost for controlling a particular pollutant p:

$$C_{i,p} = \sum_{s \in S} \sum_{f \in F_s} \sum_{[t \in (T_{s,f} \cap T_p)]} C_{i,s,f,t} \tag{16}$$

where the sum over technologies only takes into account technologies that have an influence on the emission factor of pollutant p. The cost function defined in (16), however, has the disadvantage that it also includes costs for technologies that, though they affect multiple pollutants, even though they are not measures dedicated to the reduction of a particular pollutant. For example, the higher Euro vehicle standards affect NH_3 emissions, but cannot be considered NH_3 measures. Therefore it is useful that in GAINS we associate for each measure t a unique primary pollutant $\hat{p}(t)$ that is targeted by this measure. With the association of primary pollutants to measures we can then define the costs of all measures for which p is the primary pollutant:

$$\widehat{C}_{i,p} = \sum_{s \in S} \sum_{f \in F_s} \sum_{[t \in (T_{s,f} \cap T_p), p = \hat{p}(t)]} C_{i,s,f,t} \tag{17}$$

Since the association between measures and primary pollutant is one-to-one the total emission control cost Eq. (15) is also equal to the sum of the costs in Eq. (17) over all pollutants:

$$C_i = \sum_{p \in P} \widehat{C}_{i,p} \tag{18}$$

Naturally, other cost-aggregations can easily be formulated in GAINS for sundry purposes.

3.4 Atmospheric dispersion

An integrated assessment of air pollution needs to link marginal changes in precursor emissions at the various sources to responses in impact-relevant air quality indicators I_q at a receptor grid cell j, or aggregated to a receptor region k. 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 one hundred chemical reactions involving 70 chemical species with time steps down to 20 seconds including numerous nonlinear mechanisms (Simpson et al. 2012, Fagerli & Aas 2008). 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, reduced-form representations of the full models in form of response surfaces have been developed that describe the response of impact-relevant air quality indicators through mathematically simple formulations. Functional relationships describe changes in annual mean $PM_{2.5}$ 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 (15 %) emissions of the individual sources around a reference level (the baseline projection of the Thematic Strategy on Air Pollution for 2020). As indicated above, the GAINS model identifies cost-effective emission control scenarios based on these fitted source-receptor relationships. Subsequently, policy-relevant scenario results determined by GAINS are validated 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 $PM_{2.5}$ for 43 countries in Europe and fifteen sea areas, describing their impacts for the European territory with a 50 km $\times$ 50 km grid resolution. The following sections introduce the source-receptor relationships for the various substances that are used in GAINS to calculate the impacts of additional emission reductions beyond the baseline projection.

3.4.1 Fine particulate matter

The health impact assessment in GAINS relies on epidemiological studies that associate premature mortality with annual mean concentrations of $PM_{2.5}$ 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 $PM_{2.5}$ levels to changes in the precursor emissions of SO_2, NO_x, NH_3 and primary $PM_{2.5}$. 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. For the GAINS model it has been found that the almost linear response in annual mean $PM_{2.5}$ concentration produced by the EMEP Eulerian model toward changes in annual emissions of fine primary particulate matter ($PM_{2.5}$) and of SO_2, as well as for changes in seasonal NO_x and NH_3emissions, can be represented as:

$$\begin{aligned}
\rho_j(\mathrm{PM}_{2.5}) \quad = \quad & \sum_i T_{ij}^{\pi,A} \cdot E_{i,\mathrm{PM}_{2.5}} + \sum_i T_{ij}^{\sigma,A} \cdot E_{i,\mathrm{SO}_2} + k_{0,j} \\
+ \quad & c_0 \left(\sum_i T_{ij}^{\nu,S} \cdot E_{i,\mathrm{NO}_x} + \sum_i T_{ij}^{\alpha,S} \cdot E_{i,\mathrm{NH}_3} \right) \\
+ \quad & (1-c_0)\min\left\{ \max\left\{ 0, c_1 \sum_i T_{ij}^{\alpha,W} \cdot E_{i,\mathrm{NH}_3} - c_2 \sum_i T_{ij}^{\sigma,W} \cdot E_{i,\mathrm{SO}_2} + k_{1,j} \right\}, \right. \\
& \left. k_2 + c_3 \sum_i T_{ij}^{\alpha,W} E_{i,\mathrm{NO}_x} \right\}
\end{aligned} \tag{19}$$

where $\rho_j(\mathrm{PM}_{2.5})$ is the annual mean concentration of $PM_{2.5}$ at receptor point j; $E_{i,p}$ is the emissions of pollutant p in country i. (cf. Eq. (13) above); $T_{ij}^{X,Y}$ are the source receptor matrices with coefficients for reduced ($X = \alpha$), and oxidized (ν) nitrogen, sulfur (σ), and primary $PM_{2.5}$(π), for season Y, where $Y = W$(winter), $Y = S$(summer),

$Y = A$(average); c_0, c_1, c_2, c_3 are model parameters derived by regression analyses; and $k_{0,j}, k_{1,j}, k_{2,j}$ are constants to take into account background concentrations.

While the above equation 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 has been found to perform reasonably well when only marginal changes in emis- sions around a reference point are considered. For such optimization problems, Eq. (19) has been transformed to a linear form, which is then used in GAINS:

$$\rho_j(\mathrm{PM}_{2.5}) = \sum_i T_{ij}^{\pi,A} \cdot E_{i,\mathrm{PM}_{2.5}} + \sum_i T_{ij}^{\sigma,A} \cdot E_{i,\mathrm{SO}_2} + \sum_i T_{ij}^{\nu,A} \cdot E_{i,\mathrm{NO}_x} + \sum_i T_{ij}^{\alpha,A} \cdot E_{i,\mathrm{NH}_3} + k_{0,j} \quad (20)$$

The grid-specific concentration $\rho_j(\mathrm{PM}_{2.5})$ can be converted into a population-weighted country average concentration $\rho_k(\mathrm{PM}_{2.5})$

$$\rho_k(\mathrm{PM}_{2.5}) = \sum_{j \in k} \frac{\mathrm{Pop}_j}{\mathrm{Pop}_k} \rho_j(\mathrm{PM}_{2.5}) \quad (21)$$

where Pop_j is the population of grid cell living in country k and Pop_k is the total population of country k. Similarly, the transfer coeffients can be expressed as country-to-country coefficients. Figure 3 shows the histograms of the country-to-country transfer coefficients for each of the four pollutants in Eq. (20), where the coefficients $T_{ik}^{X,Y}$ are scaled to the corresponding coefficient $T_{i,k=i}^{X,Y}$, so that Figure 3 illustrates the relative size of the downwind or transboundary effect (transfer into countries other than the emitting country i).

The formulation in Eq. (20) and Eq. (21) 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, the approach does not reproduce the full mass of $\mathrm{PM}_{2.5}$ that is observed in ambient air. 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.

The regional scale assessment is performed for all of Europe with a spatial resolution of 50 km $\times$ 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 underestimate higher pollution levels in European cities. To link the European-scale analysis with exposure levels in urban areas, GAINS employs a downscaling approach that has been developed based on the results of the City-Delta model intercomparison. City-Delta brought together the 17 major European urban and regional scale atmospheric dispersion models (Thunis et al. 2007) and developed a generalized methodology to describe the increments in $\mathrm{PM}_{2.5}$ concentrations in urban background air that originate e on top of the long- range transport component e from local emission sources. These relationships associate the difference in the annual mean

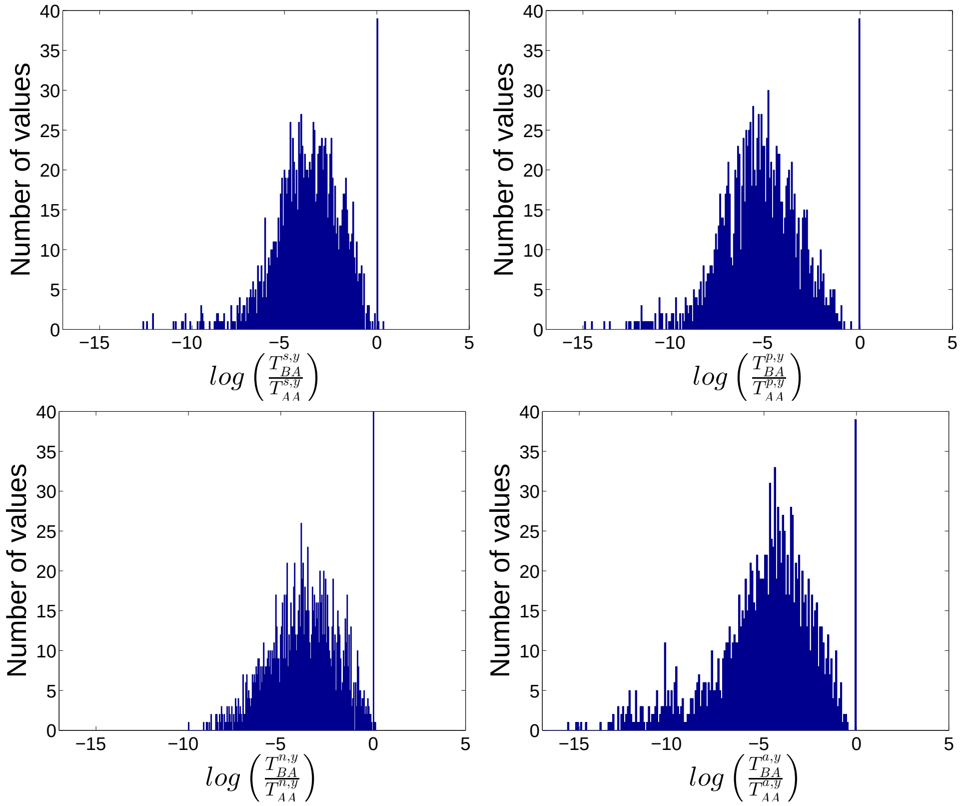

Figure 3: Histograms of the relative size of the transfer coefficients T^X_{ik} relative to the local coefficient $T^X_{i,k=i}$ in the calculation of the $PM_{2.5}$ concentration. (top left: SO_2, top right: primary $PM_{2.5}$, bottom left: NO_x, bottom right: NH_3)

$PM_{2.5}$ concentrations between an urban area and the average concentrations calculated over the 50 km × 50 km grid cell surrounding the city with spatial variations in emission densities of low-level sources and city-specific meteorological and topographic factors.

The GAINS/City-Delta methodology starts from the hypothesis that urban increments in $PM_{2.5}$ 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 $PM_{2.5}$ emissions from high stacks, is reflected in the background computed by the regional-scale dispersion model. Consistent with atmospheric diffusion theory, a functional form has been developed that includes wind speed and city diameter as important parameters that determine the incremental $PM_{2.5}$concentration within a city:

$$\Delta(\rho_{\text{PM,urban}}) = \frac{1}{2\sqrt{2}} \cdot \frac{1}{\sqrt{k}} \cdot \frac{Q}{A} \cdot \left(\frac{D}{U}\right)^{1/2} \tag{22}$$

where $\Delta(\rho_{\text{PM,urban}})$ is the difference in $PM_{2.5}$ concentration between the urban area and the $PM_{2.5}$ concentration averaged for a 50 km × 50 km grid cell; Q/A is the primary

$\text{PM}_{2.5}$ emission density from low-level sources within the city; D is the city diameter, U the mean wind speed in the city, and K the eddy diffusivity.

Two terms λ, μ representing $\frac{1}{2\sqrt{2}} \cdot \frac{1}{\sqrt{K}}$ for high and low wind speed days, respectively, have been determined through regression analyses from a sample of model results with four different urban dispersion models for six European cities (see (Amann et al. 2007)):

$$\Delta(\rho_{\text{PM,urban}}) = \frac{Q}{A} \cdot \left(\frac{D}{U}\right)^{1/2} \cdot \left(\lambda \cdot \frac{365-d}{365} + \mu \cdot \frac{d}{365}\right) \tag{23}$$

with d is the number of days with low wind speed (less than 1 m/s); λ, μ are regression coefficients based on the City Delta results, including the conversion factors for the different dimensions.

Urban areas and diameters were derived from the JRC European population density data set and the City Population database[6] 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[7], which provides interpolated meteorological information derived from 2000 weather stations in Europe. In the absence of city-specific emission inventories available at the European scale, urban emissions have been estimated on a sectoral basis from the gridded emission inventory compiled for the EMEP model [8].

To avoid double-counting of the urban emissions (i.e., in the regional scale calculation and the urban increment), the 'City-Delta' correction, ΔPM_{CD}, that has to be applied to the regional value in order to derive estimates of urban air quality is calculated as

$$\Delta(\rho_{\text{PM,urban}}) = Q_C \cdot \frac{1}{\sqrt{U}} \left(\left(\lambda \cdot \frac{365-d}{365} + \mu \cdot \frac{d}{365}\right) \cdot \frac{D_C}{A_C} - \lambda \cdot \frac{365-d}{365} \cdot \frac{\sqrt[4]{A_E}}{A_E}\right) \tag{24}$$

with the index C indicating city-related data and the index E values for the entire 50 km $\times$ 50 km EMEP grid cell, and A relating to the respective areas (for more details see (Amann et al. 2007).

In practice, the urban increment ΔPM_{CD} is a linear function in the emissions of $\text{PM}_{2.5}$ aggregated to the SNAP1 level

$$\Delta\text{PM}_{CD,k} = \sum_i \sum_\gamma \delta_{ik} \cdot T_{ik}^{\pi,CD,\gamma} \cdot E_{i,\text{PM}_{2.5}}^{\text{SNAP1}=\gamma} \tag{25}$$

where δ_{ik} is the Kronecker symbol that is equal to 1 if $i = k$ and zero otherwise. The transfer coefficients are non-zero only for the low-level sources (SNAP1 sectors 2,3,7 and 8). The total population-weighted $\text{PM}_{2.5}$ concentration in country k is thus (from Eq. (21) and Eq. (25))

$$\rho_{\text{PM},k}^{\text{total}} = \rho_k(\text{PM}_{2.5}) + \chi_k \cdot \Delta\text{PM}_{CD,k} \tag{26}$$

[6] http://www.citypopulation.de
[7] http://www.marsop.info
[8] http://webdab.emep.int/

where χ_k is the urban ratio of country k, i.e. the share of the country's population living in urban areas and thus being affected by the urban increment.

3.4.2 Deposition of sulfur and nitrogen compounds

For quantifying ecosystems risks from acidification and eutrophication the GAINS models employs the critical loads approach. Critical loads have been defined as âĂŸquantitative estimates of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge' (Nilsson & Grennfelt 1988). Thereby, the impact-relevant air quality indicator compares (ecosystem-specific) annual mean deposition of acidifying compounds (i.e., sulfur, oxidized and reduced nitrogen) against the critical loads. Significant non-linearities in the spatial source-receptor relationships due to co-deposition of sulfur 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 model suggests e for the technically feasible range of further emissions reductions beyond the baseline projection e nearly linear responses in annual mean deposition of sulfur and nitrogen compounds toward changes in SO_2, NO_x and NH_3 emissions:

$$\mathrm{Dep}_{p,j} = \mathrm{Dep}_{p,j,0} - \sum_i D_{ij}^p \cdot (E_{i,p}^0 - E_{i,p}) \tag{27}$$

with $\mathrm{Dep}_{p,j}$ the annual deposition of pollutant p at receptor point j; $\mathrm{Dep}_{p,j,0}$ the reference deposition of pollutant p at receptor point j; $E_{i,p}$ the annual emission of pollutant p (SO_2, NO_x, NH_3) in country i; $E_{i,p,0}$ the reference emissions of pollutant p (SO_2, NO_x, NH_3) in country i; and D_{ij}^p Transfer matrix for pollutant p for emission changes around the reference emissions

3.4.3 Formation of ground level ozone

The 2003 WHO systematic review of health aspects of air quality in Europe (WHO 2003) emphasized that new scientific studies have strengthened the evidence for health impacts from ozone not only from peak episodes, but also from lower ozone concentrations as they occur throughout the year. Subsequently, the UNECE/WHO Task Force on Health recommended for health impact assessments the so-called SOMO35 as the relevant ozone indicator (UNECE/WHO 2003). SOMO35 is calculated as the sum over the year of the daily 8-h 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 (e.g., (Seinfeld & Pandis 1998)). 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 protocol in 1999, the GAINS 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 (AOT60) in form of quadratic polynomials (Heyes et al. 1996). A re-analysis of the Eulerian model results with a focus on the likely emission levels for the year 2020 (Amann & Lutz 2000) 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 (e.g., AOT60), and

(iii) such non-linearities diminish even further when population-weighted country-means of SOMO35 (that represent total population exposure) are considered.

It was found that within the policy-relevant range of emissions (i.e., between the baseline and the maximum technically feasible emissions reductions in 2020), changes in the SOMO35 indicator could be described with sufficient accuracy by a linear formulation:

$$O3_k = O3_{k,0} - \sum_i N_{ik} \cdot (E^0_{i,\mathrm{NO}_x} - E_{i,\mathrm{NO}_x}) - \sum_i V_{ik} \cdot (E^0_{i,\mathrm{VOC}} - E_{i,\mathrm{VOC}}) \tag{28}$$

where $O3_k$ is the health-relevant long-term ozone indicator measured as the population-weighted SOMO35 in receptor country k; $O3_{k,0}$ is the population-weighted SOMO35 in receptor country k due to reference emissions E^0_{i,NO_x}, $E^0_{i,\mathrm{VOC}}$; E_{i,NO_x}, $E_{i,\mathrm{VOC}}$ are the emissions of NO_x and VOC in source country i; N_{ik}, V_{ik} are coefficients describing the changes in population-weighted SOMO35 in receptor country k due to emissions of NO_x and VOC in source country i.

Figure 4 shows the histograms of the country-to-country transfer coefficients for NO_x and VOC in Eq. (28), where the coefficients T^X_{ik} are scaled to the corresponding coefficient $T^X_{i,k=i}$ so that Figure 4 illustrates the relative size of the downwind effect (transfer into countries other than the emitting country i).

Validations of the reduced-form formulations described above against results of the full EMEP model, e.g., for the final policy scenario of the Clean Air For Europe (CAFE) program, show good agreement (Amann et al. 2011*a*).

3.5 Air Quality Impact Functions

3.5.1 Health impacts from PM

Based on the findings of the WHO review on health impacts of air pollution (WHO 2003, 2007), the GAINS model quantifies for different emission scenarios premature mortality that can be attributed to long-term exposure to $PM_{2.5}$, following the outcomes of the American Cancer Society cohort study (Pope et al. 2002) and its re-analysis (Pope et al. 2009). Cohort- and country-specific mortality data extracted from life table statistics are

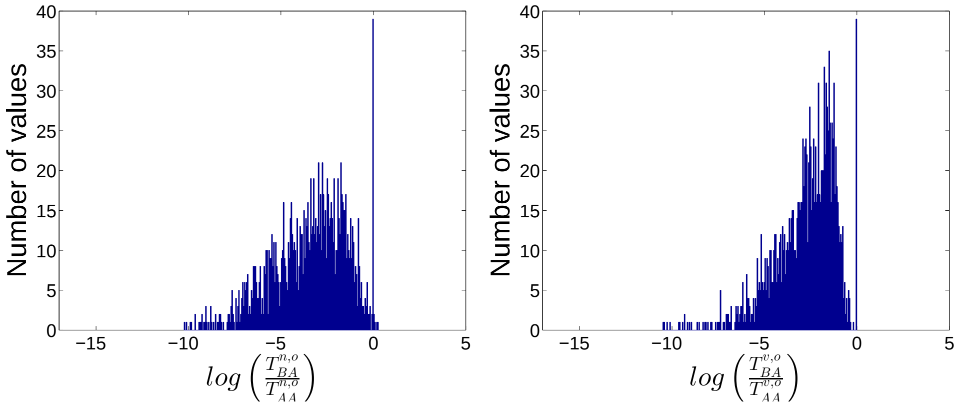

Figure 4: Histograms of the relative size of the transfer coefficients T_{ik}^X relative to the local coefficient $T_{i,k=i}^X$ in the calculation of SOMO35. (left: NO_x, right: VOC)

used to calculate for each cohort the baseline survival function over time. The survival function $l_c(\tau)$ indicates the percentage of a cohort c alive after time t elapsed since starting time w_0. $l_c(\tau)$ is an exponential function of the sum of the reference 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, the reference survival function $l_c^0(\tau)$ is (Mechler et al. 2002):

$$l_c^0(\tau) = \exp\left(-\sum_{z=c}^{\tau} \mu_{z,z-c+w_0}^0\right) \tag{29}$$

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 $PM_{2.5}$(PM), the life expectancy l_c is calculated as the integral over the remaining life time:

$$e_c = \int_c^{w_1} l_c(\tau)d\tau = \int_c^{w_1} \exp\left(-\sum_{z=c}^{\tau} \mu_{z,z-c+w_0}\right) d\tau \tag{30}$$

where w_1 is the maximum age considered and

$$\mu = \mu^0 \cdot \exp(\beta \cdot \rho(\mathrm{PM}_{2.5})) = \mu^0 \cdot \mathrm{RR}(PM) \tag{31}$$

$\mathrm{RR}(PM)$ is the relative risk for a given concentration $\rho(\mathrm{PM}_{2.5})$. With some simplifying assumptions and approximations (Vaupel & Yashin 1985), the change in life expectancy per person ($\Delta(e_c)$) of a cohort c can be expressed as:

$$\Delta e_c = \beta \cdot \rho(\mathrm{PM}_{2.5}) \int_c^{w_1} l_c(\tau) log(l_c(\tau)) d\tau \tag{32}$$

where – within the studied exposure range – $\mathrm{RR}_{\mathrm{PM}}$ has been approximated as $\mathrm{RR}_{\mathrm{PM}} = 1 + \beta \cdot \rho(\mathrm{PM}_{2.5})$ with $\beta = 0.006$, as given in (Pope et al. 2002) . For all cohorts in a country

k the change in life years ΔL_k is then calculated in GAINS as the sum of the change in life years for the cohorts living in the grid cells j of the country k:

$$\text{YOLL}_k = \Delta L_k = \sum_{c=w_0}^{w_1} \Delta L_{c,k} = \beta \cdot \sum_{j \in k} \rho(\text{PM}_{2.5})_j \frac{\text{Pop}_j}{\text{Pop}_k} \sum_{c=w_0}^{w_1} \text{Pop}_{c,k} \int_c^{w_1} l_c(\tau) log(l_c(\tau)) d\tau \quad (33)$$

where $\Delta L_{c,k}$ is the change in life years lived for cohort c in country k; $\text{Pop}_{c,k}$ population in cohort c in country k; Pop_j is the total population in grid cell j (at least of age $w_0 = 30$); Pop_k total population in country k (at least of age $w_0 = 30$).

For the health impact assessment of policy scenarios, GAINS calculates the loss in statistical life expectancy according to Eq. (32) as well as the total amount of life years lost (YOLL) for the entire population over 30 years. Health impacts for people younger than 30 years, and in particular the impacts on infant mortality, are presently not considered in GAINS.

3.5.2 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 2003), the GAINS model quantifies premature mortality through an association with the SOMO35 indicator for long-term ozone concentrations in ambient air (see Section 3.4.3). The GAINS calculation estimates for the full year daily changes in mortality as a function of daily 8-h maximum ozone concentrations, employing the concentration-response curves derived in the meta-analysis (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

$$\text{Mort}_k = \frac{1}{365} \text{Deaths}_k \cdot \text{RR}_{O3} \cdot O3_k \quad (34)$$

where Mort_k are the number of cases of premature mortality per year in country k; Deaths_k is the baseline mortality (number of deaths per year) in country k; RR_{O3} is the relative risk for one percent increase in daily mortality per ppb 8-hour maximum ozone concentration per day; and $O3_k$ is the population-weighted SOMO35 in country

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 are quantified ex-post in associated benefit assessments (Holland et al. 2005, 2008).

3.5.3 Protection of ecosystems against acidification and eutrophication

The GAINS model uses the critical loads concept as a quantitative indicator for sustainable levels of sulfur and nitrogen deposition. The GAINS analysis makes use of 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 internationally agreed methodologies (UBA 2004) and the current database contains details about 1.1 million ecosystems in Europe (Hettelingh et al. 2007, 2008).

To evaluate the ecological impacts of emission control scenarios, GAINS compares computed depositions with these critical loads employing the average accumulated exceedance (AAE) concept as a quantitative summary indicator for the excess of critical loads of all ecosystems in a region (country). For effect ϵ and country k the AAE is defined as (Posch et al. 2001):

$$\mathrm{AAE}_{\epsilon,k} = \sum_{j \in k} \sum_{u} A_{\epsilon,j,u} \cdot \max\{\mathrm{Dep}_{p,j} - \mathrm{CL}_{\epsilon,j,u}, 0\} / \sum_{j \in k} \sum_{u} A_{\epsilon,j,u} \tag{35}$$

where $\mathrm{CL}_{\epsilon,j,u}$ is the critical load for effect ϵ for ecosystem u in grid cell j onto that ecosystem. The summation runs over all types of ecosystems and all grid cells j within country k. 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.

For the optimization mode of GAINS, the AAE for effect ϵ in country k has been related to emissions by a linear model:

$$\mathrm{AAE}_{\epsilon,k} = \mathrm{AAE}_{\epsilon,k,0} - \sum_{p} \sum_{i} T_{ij}^{p,\epsilon} \cdot (E_{i,p}^{0} - E_{i,p}) \tag{36}$$

where the sum is over all emitter regions i and all pollutants p contributing to critical load excess (sulfur and nitrogen species for acidification, nitrogen species for eutrophication); as earlier, the index 0 refers to reference emission levels for which the approximation was carried out. The so-called 'impact coefficients' $T_{ij}^{p,\epsilon}$ are derived at the CCE by first computing, via Eq. (27), the depositions in country k from the emissions $E_{i,p}$ in country i with the emissions in all other countries equal to $E_{i',p}^{0}$ ($i' \neq i$) and then the AAE according to Eq. (35). This procedure is carried out for all country source-receptor combinations, resulting in a total of about 9000 coefficients for acidification and eutrophication, of which, however, a large number is (close to) zero (Posch et al. 2001). Eq. (36) 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). To derive exact estimates of policy-relevant scenarios, the AAE and protection percentages of optimized scenarios are validated in an ex-post analysis through direct calculations from the individual critical load values for each country (Hettelingh et al. 2007).

In order to capture some of the non-linear nature of the AAE function, we define the AAE as a piece-wise linear function of the emissions and it is useful to define this in terms of the maximum of linear functions. For example, for acidification:

$$\mathrm{AAE}_k^{\mathrm{acid}} = max_\xi(\mathrm{AAE}_k^{\mathrm{acid},\xi}) \tag{37}$$

where $\{T_{i,k}^\xi\}$, $\xi \in \{1, 2\}$, are two sets of transfer matrices derived from two separate base scenarios. The corresponding histograms are shown in Figure 5.

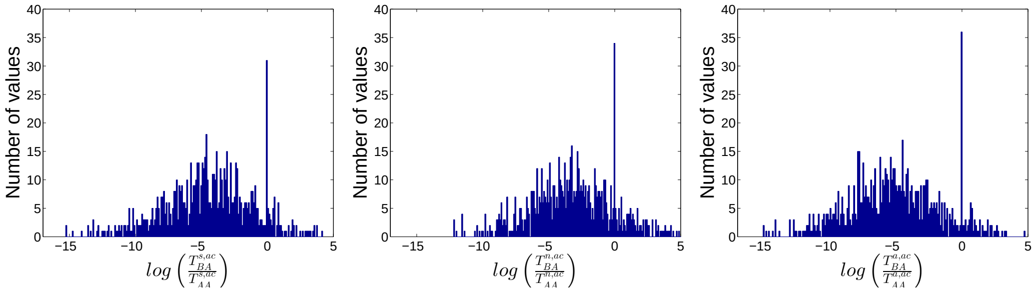

Figure 5: Histograms of the relative size of the transfer coefficients T_{ik}^X relative to the local coefficient $T_{i,k=i}^X$ in the calculation of the AAEs for acidification. (left: SO_2, middle: NO_x, right: NH_3)

Similarly, for eutrophication we use also transfer coefficients derived from two base cases to construct a piece-wise linear function. The corresponding histograms are shown in Figure 6.

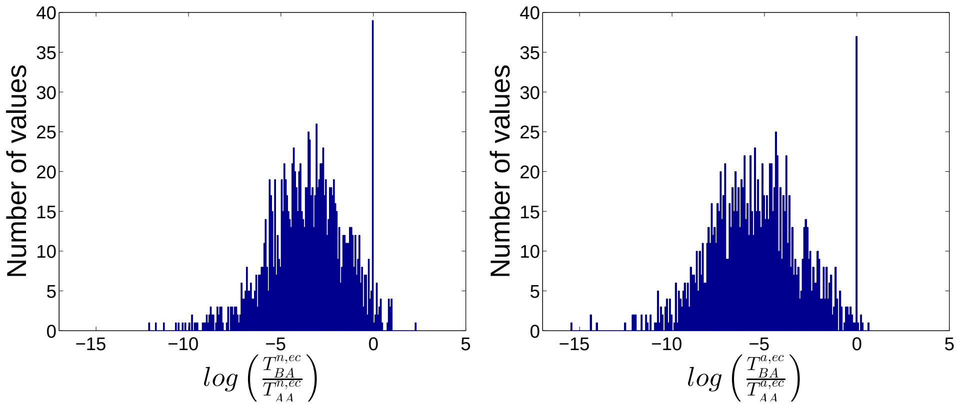

Figure 6: Histograms of the relative size of the transfer coefficients T_{ik}^X relative to the local coefficient $T_{i,k=i}^X$ in the calculation of the AAEs for eutrophication. (left: NO_x, right: NH_3)

3.5.4 Vegetation impacts from ground-level ozone

Elevated levels of ozone have been shown to cause widespread damage to vege- tation. In earlier policy analyses for the NEC Directive of the EU and the Gothenburg Protocol in 1999, GAINS applied the concept of critical levels to quantify progress toward the environmental long-term target of full protection of vegetation from ozone damage, using a formulation similar to Equation 11. Critical levels are defined as 'concentrations of pollutants in the atmosphere above which direct adverse effects on receptors, such as human beings, plants, ecosystems or materials, may occur according to present knowledge'.[9] Excess of critical levels for vegetation is measured with the AOT metric, which quantifies the 'accumulated ozone exposure over a threshold of 40 ppb' (UBA 2004). 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 AOT40 approach (Karlsson et al. 2004). As quantifications of all parameters that are necessary to compute ozone fluxes for the relevant vegetation types have just recently been developed, after 1999 ozone damage to vegetation has been determined with the flux approach outside the GAINS model in an ex-post analysis (e.g.(Holland et al. 2005, Mills et al. 2011).

3.6 Climate-relevant impact functions

3.6.1 Radiative forcing

Short-lived climate forcers (SLCFs) are greenhouse gases with a relatively short lifetime (not longer than a few years), and aerosols. SLCFs affect the Earth's radiative balance either directly through their radiative properties or indirectly through their interaction with clouds. Since reductions in those SLCFs that have a warming effect may offer possibilities to mitigate climate change on a short time horizon, there has been increasing interest in research on their emissions, distributions and effects.

Inclusion the effect of SLCFs allows us to analyse synergies and trade-offs between health effects from $PM_{2.5}$ exposure and primary particles with a warming effect (e.g. black carbon) as well as precursors of particles with a cooling effect (e.g. SO_2).

In this work we use near-term radiative forcing as the metric for climate forcing. Radiative forcing is defined as the change in the net, downward minus upward, irradiance (expressed in W/m^2) at the tropopause due to a change in an external driver of climate change (IPCC 2007). Radiative forcing is in this study calculated for the new steady-state condition of the atmosphere following a sustained emission change in a given EMEP country, calculated globally and for an extended region covering the CLRTAP region.

BC is an efficient absorber of solar radiation and contributes to global warming (IPCC 2007). By contrast, sulphate, nitrate and OC aerosols contribute to atmospheric cooling through reflecting solar radiation and modifying cloud properties. Aerosols with optically different properties (and thus different effects on climate) are often emitted from the same sources. Hence the net effect on climate following a reduction of particle emissions from one specific source is ambiguous until at least the relative amounts of BC and OC

[9]http://www.unece.org/env/lrtap/WorkingGroups/wge/definitions.htm

emissions from that source are known. Two new components have been implemented in the Unified EMEP model, namely black carbon (BC) and primary organic carbon (POC).

Source-receptor (SR) calculations have been performed to assess the effect of emissions from individual EMEP countries on global aerosol loading. In each SR run one of the following species was reduced by 15% in one country: SO_2, NH_3, VOC, NO_x, BC and POC.

Normalised radiative forcing is defined as the radiative forcing (units of W/m^2) divided by the total burden of a species (units of gram $/m^2$), i.e. NRF has units of Watts per gram. Conversely, RF can be calculated by multiplying NRF with burden. Normalised radiative forcing factors were provided to GAINS by CICERO. They were calculated by the global chemical transport model OsloCTM2 for BC, POC, SO_4 and NO_3 components. The forcing due to secondary organic aerosols, however, has not yet been considered. Indirect effects of aerosols, which are associated with significant uncertainties, are excluded and the influence of atmospheric ozone burdens on radiative forcing- related to NO_x and VOC emissions - is also ignored. A comprehensive description of the estimation of the radiative forcing due to the direct aerosol effect, including comparison with multiple aerosol observations, is provided by (Myhre et al. 2009).

Initially, the whole Northern Hemisphere, the EMEP region and the Arctic are being considered as receptor regions. By means of the transfer coefficients it is possible in a straightforward way to estimate the influence of each EMEP country on the RF in these regions (for those aspects of RF included in this assessment) for any particular emissions scenario. Radiative forcing of the short-lived aerosol forcers is calculated - as all other environmental impacts - as linear functions of the relevant pollutants, using matrix source-receptor relationships derived from a set of full EMEP model runs. The relevant precursor emissions for the radiative forcing calculation are SO_2 , NO_x , BC and OC. Emissions from all regions in the EMEP domain are used as input to the forcing calculation, contributions from other source regions are absorbed into constants. The relative magnitude of these constants can be significant, owing to the fact that the background contribution can be dominant. We thus write:

$$\mathrm{RF}_k = \sum_i \sum_p T_{ik}^{\mathrm{RF},p} \cdot E_{i,p} + k_k^{\mathrm{RF}} \tag{38}$$

where i are the source regions, k is the receptor region and p are the relevant pollutants. The constant k_k^{RF} represents the forcing resulting from emissions from outside the EMEP modeling domain. It is calibrated to ensure consistency between the EMEP model and the GAINS model for the base scenerio from which the transfer matrices are derived. Equation (38) shows how emissions from counties i and radiative forcing over receptor region k are related in the GAINS model

This initial implementation of source-receptor relationships for instantaneous radiative forcing within GAINS takes into account the emissions of BC, OC, SO_2 , and NO_x , as precursors but neglects the effects on sulphate and nitrate aerosol concentrations caused by changes in NH_3 emissions. The EMEP global model predicts that reductions in NH_3

emissions will result in an increased column burden of sulphate aerosol but the size of the overall effect over Europe is small (<5%) in comparison with the change - in the opposite direction - caused by corresponding reductions in SO_2 emissions.

Reductions in NH_3 emissions have a relatively more significant impact in decreasing nitrate aerosol column concentrations, broadly comparable to that of NO_x emission changes in the EMEP model results. However, the contribution of the nitrate aerosol to the calculated radiative forcing is minor compared to that from sulphate aerosol, and, indeed, BC. In these circumstances, excluding ammonia from this preliminary implementation is unlikely to have a major influence on the outcome. This approach is, in addition, consistent with that adopted within the current version of GAINS to estimate the deposition of acidifying and eutrophying species, where 'cross-terms', for example the change in deposition of oxidised nitrogen as a result of changes in NH_3 emissions, are also neglected.

Naturally the transfer matrices T vary by source regions and pollutant. Figure 7 shows the values of the transfer matrices for SO_2 and NO_x, the top left panel for all EMEP countries, the other panel provide more detail for the three clusters identified in the top left panel.

Similarly, Figure 8 shows the values of the transfer matrices for BC and OC, the top left panel for all EMEP countries, the other panel provide more detail for the three clusters identified in the top left panel.

In absolute terms, the BC coefficients are half an order of magnitude larger than the those of OC and SO_2, while the NO_xcoefficients are again one order of magnitude smaller. In general, however, the potential for reducing these pollutants also differs significantly. For example, we estimate that for the UNECE or EU27 region as a whole the absolute potential for reducing SO_2 is between 10 and 25 times larger than the potential for reducing BC, and 5 to 10 times larger than that of OC, while it has the same order of magnitude as the potential for reducing NO_x. It is understood that measures that target $PM_{2.5}$ emissions also reduce the subspecies BC and OC, and vice versa. However, the extent of the co-control depends on the exact technology, and this is reflected in the GAINS model.

3.6.2 Carbon deposition

Input data and optimization routines have also been developed for carbon deposition on the Arctic and on Alpine glaciers.

$$\mathrm{CDep}_k = \sum_i \sum_p T_{ik}^{\mathrm{CDep},p} \cdot E_{i,p} + k_k^{\mathrm{CDep}} \tag{39}$$

where as before i are the source regions, k is the receptor region and p are the relevant pollutants. The transfer matrices were actually calculated separately for dry and wet deposition. Figure 9 shows the values of the transfer matrices for BC and OC, for dry and wet carbon deposition in the Arctic region north of 70 degrees.

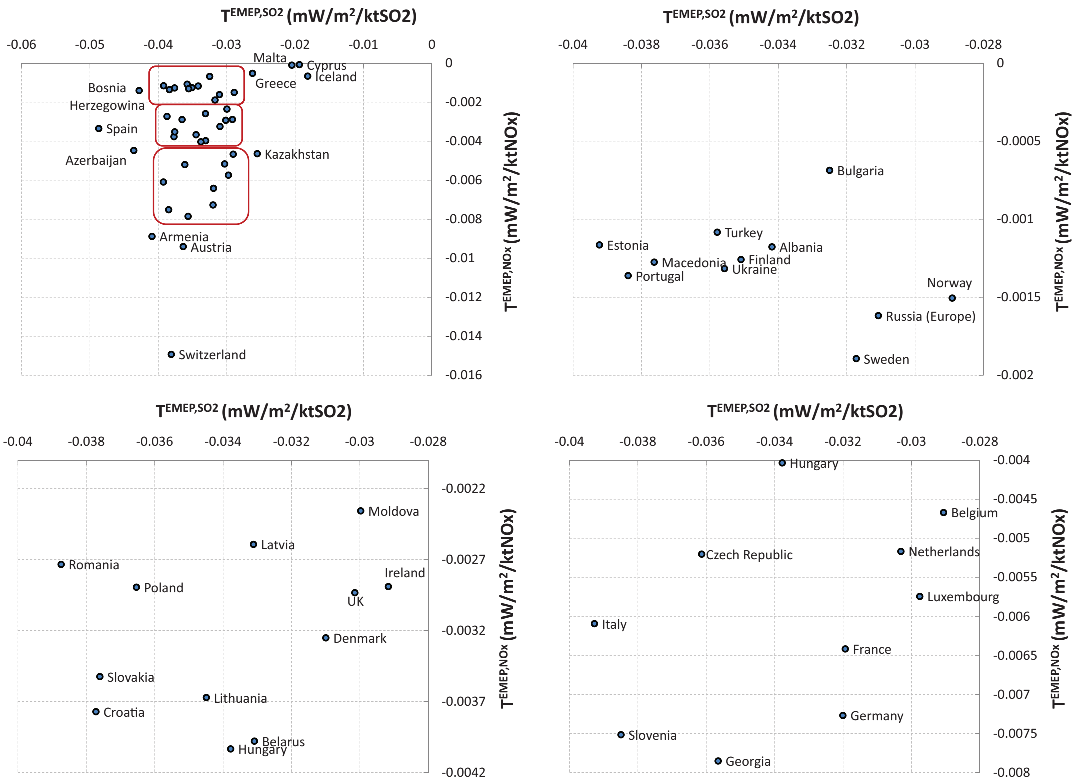

Figure 7: Size distribution and relation between source-receptor matrices T for SO_2 and NO_x (in NO_3 calculation) from European countries to the EMEP region. Top left: all countries. Other panels: countries falling into one of the three clusters identified in the top left panel.

4 Formalizing Objectives and Constraints

Above we have described the optimization problem as

$$\min C, \quad \text{such that } A \cdot x \leq b \tag{40}$$

for some matrix A and some vector b, where x are the decision variables. We have also describe the specific economic, technological and environmental functional relationships in GAINS that describe the system. In this section we further specify the objective function and constraints. In Section 5 we will discuss several alternative standard configurations in some of which the objectives and constraints change their roles.

4.1 Objective function

The function that is (here) minimized in the optimization procedure is called the *objective function* (OF). Typically (and we will qualify this in the next section), the objective in the GAINS optimization is to minimize the emission control costs across a given domain, e.g.

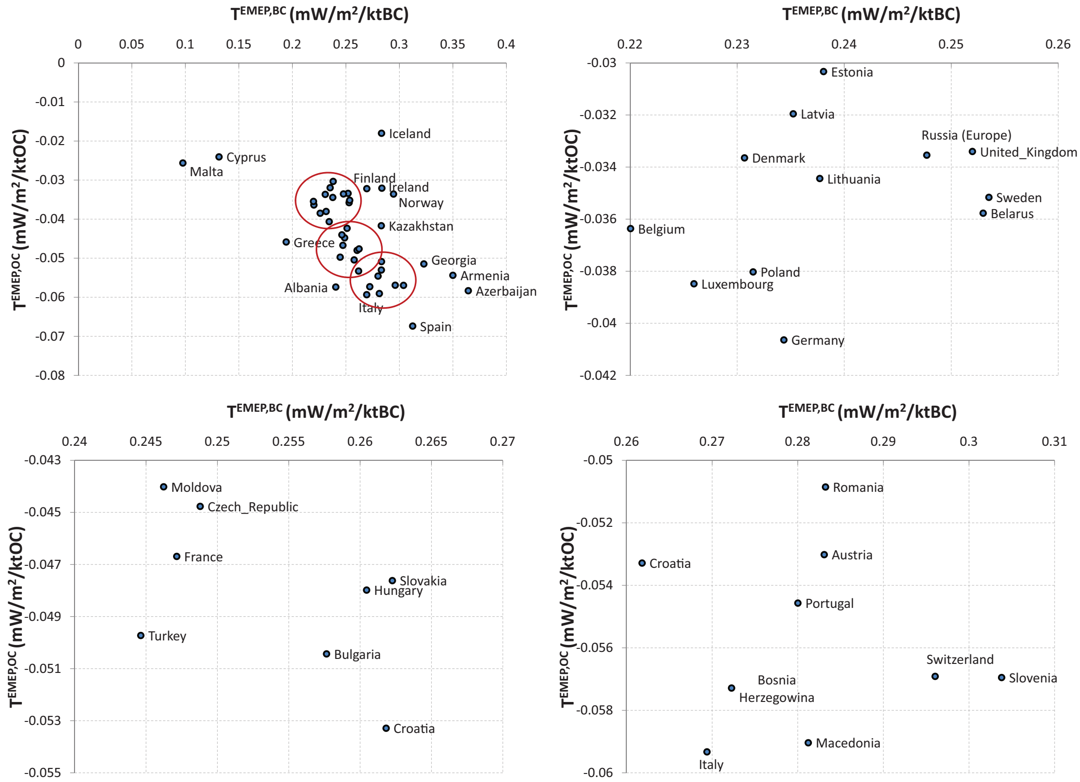

Figure 8: Size distribution and relation between source-receptor matrices T for BC and OC from European countries to the EMEP region. Top left: all countries. Other panels: countries falling into one of the three clusters identified in the top left panel.

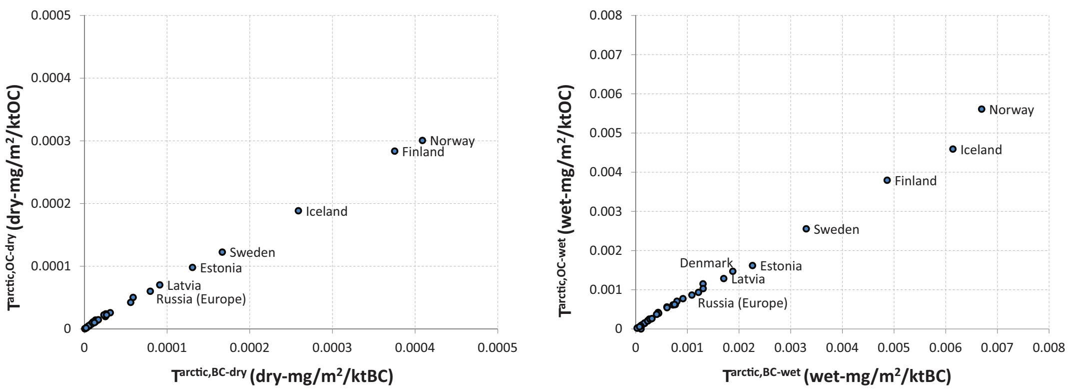

Figure 9: Transfer matrices for dry (left panel) and wet (right panel) carbon deposition to the arctic 70 $\circ$ N region. In general the wet deposition coefficients are larger than the dry ones, and the rates are higher for BC than those for OC.

the European Union or the Europe as a whole, etc.:

$$\mathrm{OF} = C = \sum_{i \in I} C_i \tag{41}$$

where C_i was defined in Eq. (18) as the emission control cost across all relevant pollutants in source country i.

Note that all source regions i carry the same weight in Eq. (41), thus in particular neither larger or smaller regions are given priority or are discounted.

4.2 Environmental targets

The GAINS optimization procedure aims to identify cost-effective responses to given environmental objectives. These objectives, or targets, have to be related to the environmental impact functions discussed in Section 3.5. Thus, for example, targets could be set on the change in life years (years of life lost - YOLL) in Eq. (33), the AAE functions (Eqs.(35), (36)), and the ozone mortality indicator Eq. (34), either individually or jointly, as discussed in Section 5.

In joint optimizations targets are set simultaneously, and many alternative approaches to systematically explore targets and to identify plausible combinations of targets exists, and will be discussed below in Section 5.3.

However, some aspects of the target setting procedure need to be addressed here already.

- Targets are typically defined for each relevant receptor region k, i.e. typically for each country. For a given impact indicator, these targets can be chosen independently for each k; however, in an international context where questions of burden sharing and benefit sharing are important, it is often useful to provide a general rule for setting targets for all relevant k simultaneously in a transparent manner. One such approach is the 'gap closure' procedure to be discussed in Section 5.3.

- Some environmental indicators could be aggregated across receptor regions. For example, the total YOLLs over a domain K, YOLL^K is obtained by summing over the corresponding YOLL function in the individual receptor regions within the domain:

$$\text{YOLL}^K = \sum_{k \in K} \text{YOLL}_k \tag{42}$$

  In contrast, the linearized AAE indicators cannot be aggregated.

- In the GAINS optimization the environmental targets are always made explicit by defining upper limits as constraints on the indicators $\text{EnvImp}_{\Omega,k}$ of the environmental impacts Ω (typically we consider several different indicators simultaneously):

$$\text{EnvImp}_{\Omega,k} \leq \text{Target}_{\Omega,k} \quad , \tag{43}$$

  in this case for each receptor k. In contrast, multi-criteria optimization internalizes environmental impact indicators into the objective function with the help of Lagrangian multipliers, Λ_Ω, symbolically,

$$\min \left(C + \sum_{\Omega} \Lambda_\Omega \cdot \text{EnvImp}_\Omega \right) \tag{44}$$

For a given value of the Lagrangian multipliers the optimization balances costs and impact indicators, identifying an optimal mix of environmental ambition and budgetary prudence.

While mathematically equivalent via duality theorems, the disadvantage of the multi-criteria approach requires that the values for the Λ_Ω be given. This means that the relative values of the impact indicators (in monetary terms) need to be defined by the modeller. This, however, is a value-judgement that should be left to the decision makers Amann et al. (2011*a*).

In contrast, in GAINS environmental ambition levels are defined initially independently of budgetary considerations. The optimization is only used to identify the cost-optimal mix to reach the predefined ambition levels. The calculated costs are then reported to stakeholder groups who then have to consult with each other whether the ambition levels are adequate and the costs acceptable. The process is then iterated until an agreement is reached. This approach lends itself much better for supporting international policy processes.

- Targets need to be feasible, i.e. within reach. A zero-impact goal is laudable, but often cannot be reached. There are technological constraints of various types (see Section 4.3), so that anthropogenic emissions cannot be reduced to zero. Moreover, even with zero anthropogenic emissions the environmental impact indicators would not necessarily be zero. Thus, in order to ensure to estimate the lowest possible values and that only feasible targets are considered, it is useful to first generate the maximum technically feasible reduction (MTFR) scenario (cf. Section 5.2), which represents the lowest achievable emission level under the given constraints.

  In general, target values between the baseline (current legislation) and MTFR level are feasible for any combination of target values on indicators whose transfer matrices have the same sign. For example, the AAE functions are linear functions in the emissions of NO_x, and the coefficients of NO_x in these functions is positive. However, in the calculation of radiative forcing the NO_x coefficient is negative (NO_x through nitrate is cooling), hence there is a trade-off between targets on the AAEs and on radiative forcing. This will be explored further in Section 6.3.

4.3 Constraints on technologies

Having set environmental targets, minimizing the cost of control measures will identify an optimal control strategy for achieving these targets. This control strategy represents a mix of technologies, each of which is characterized by costs and emission factors.

However, for some technologies the application may be restricted, either in the sense that further application potential is limited, or that (a shre of) existing technology cannot be replaced.

This constraints are discussed in the following. We distinguish between generic constraints that apply generally, sector-specific constraints that need to be discussed in detail, and context-related constraints that allow us to focus on specific regions and pollutants of interest.

4.3.1 Generic Technology Constraints

1. **Maximum application rates.** The extent to which some technologies can be applied to the whole activity data may be restricted for a number of reasons. For example, a certain technology may only be available for installations of a certain size, so the maximum application rate is less than 100 percent. These technology-specific maximum application rates are stored in the GAINS database as part of the set of technology characteristics. The maximum application rates are also country-specific and may change over time, reflecting changes in the substructure of the activity data. The maximum application rates may be zero in individual countries if local conditions are not suitable.

2. **Shares not suitable for control.** There may be activities that (partially) cannot be subject to any control technology modeled in GAINS. As an example, consider historic vehicles ('oldtimers') which represent a certain share of the vehcile fleet in industrialized countries, but do not meet any of the modern emission standards. The GAINS database contains information on these shares for selected sector-activity combinations.

3. **Vintage structure and no-regret investments.** Certain technologies require significant upfront investment that makes economic sense if the technology is operated over its full technical lifetime. GAINS respects this technical lifetime, i.e. past investments into such technologies are reflected in a vintage structure of equipment. This means that at a given moment in the future only for a certain share of future activity data an alternative control equipment can be employed. This share ('share of class 2') is growing over time, reaching 100 percent as soon as all of today's existing capacities are expected to be replaced or taken offline.

4. **Fixed application rates.** A small class of technologies (so-called 'N'-technologies in the GAINS database) is considered so stable/inert that no changes in the application rate can conceivably occur in any policy scenario relative to the baseline. For example, the central collection of domestic wastewater and subsequent secondary/tertiary treatment is considered not to be a flexible item in the context of air pollution or GHG mitigation policies, even though it influences the level of methane emissions. Whatever implementation rate is assumed in the baseline cannot be changed in a corresponding alternative policy scenario.

5. **Going beyond baseline controls.** It is understood that baseline scenarios are used in policy development as a point of departure. Going beyond the baseline scenario means that stricter, not more lenient policies are considered (cf. Section 4.4).

Therefore, GAINS assumes that, all else being equal, for any given sector-activity-pollutant combination in a particular year the overall level of control can only increase, i.e. the uncontrolled share can only decrease relative to the baseline level in the same year.

4.3.2 Sector-specific Technology Constraints

1. **Europe-wide vehicle Euro standards.** Over the past two decades in Europe vehicle emission standards have been introduced not at the country level but Europe-wide. The assessment of impacts and costs of alternative schedules for introducing new standards are typically performed with GAINS in simulation mode, i.e. without explicitly modeling an optimal control strategy. Thus, within the optimization we typically assume that the application rate of all measures for vehicles (and off-road machinery) remain at baseline level (exception are all those SO_2technologies modeled in GAINS at the vehicle/entity level, such as low sulphur gasoline).

2. **Engines.** Only recently a new emission category 'Power & district heat plants with internal combustion engines' was introduced into the GAINS model. As relatively little is currently known about emission control technologies on these and costs, in GAINS currently no further controls are assumed to be possible beyond baseline levels.

3. **High and low efficiency options in Agriculture.** For technical reasons the measures 'covered storage (CS)' and 'low nitrogen application (LNA)' are included as feasible technologies in the GAINS optimization, although in practice they will occur only a high or low efficiency flavour (e.g. 'CS_high'). To suppress an invalid use of the unspecified version, the maximum application rate for CS and LNA is set to zero. This does not affect the flavoured versions, nor the combination of CS and LNA in combinations of measures at different stages (because in these combinations 'high' or 'low' is always understood.)

4.3.3 Context-providing Technology Constraints

1. **Emissions outside the domain of interest.** Emissions of source countries outside the policy domain are not subject to optimization. For example, in the analysis of EU air pollution policy, the emissions of non-EU countries are assumed to remain at baseline level or at an predefined alternative scenario level. Even so, these emissions are not just entered as constant but are still calculated within the GAINS model using the same methodology as for the policy relevant countries.

2. **Pollutants not addressed.** The optimization addresses a specific set of pollutants, for example $PM_{2.5}$, NO_x, SO_2, NH_3, and VOC. Technologies that do not influence the emissions of these pollutants are kept at baseline levels. Measures that influence the emissions of more than one pollutant are flexible within the bounds discussed

above, if they influence at least one of the relevant pollutants. The co-benefits of such measures can be quantified.

4.3.4 Constraints on technology transitions

Finally, we discuss briefly the constraints applied to the transition variables $xx_{i,s,f,t,t',p}$ we introduced in Section 3.2. For these we require that $xx_{i,s,f,t,t',p} = 0$ if t has a lower emission factor for pollutant p than t' or if the two technologies are not connected by an arrow in the appropriate graph in Appendix B). This means that a technology that is present in the baseline scenario cannot be replaced by a 'worse' technology.

For multi-pollutant technologies this needs to be further clarified. In fact, for these we require only that $xx_{i,s,f,t,t',p} = 0$ if p is indeed the primary pollutant affected by t'. Thus, a multi-pollutant technology may increase the emission factor of one pollutant if, at the same time, it reduces the emission factor of the primary pollutant it addresses.

4.4 Emission standards

Each activity-sector combination is associated with a control strategy. In the baseline this control strategy implies baseline emission levels for each relevant pollutant for every activity sector combination. In GAINS it is required that for each sector-activity combination the emissions of any pollutant can only decrease, but not increase:

$$\sum_{[t \in T_{i,s,f}]} \mathrm{EF}^{\text{abated}}_{i,s,f,t,p} \cdot x_{i,s,f,t} \leq \mathrm{IEF}^{\mathrm{B}L}_{i,s,f,p} \cdot xa_{i,s,f} \tag{45}$$

where $\mathrm{IEF}^{\mathrm{B}L}_{i,s,f,p}$ is the âĂŸimplied emission factorâĂŹ of pollutant p for the sector-activity combination (s, f) in country i in the baseline (BL), i.e.

$$\mathrm{IEF}^{\mathrm{B}L}_{i,s,f,p} = \frac{\sum_{[t \in T_{i,s,f}]} \mathrm{EF}^{\text{abated}}_{i,s,f,t,p} \cdot x^{\mathrm{B}L}_{i,s,f,t}}{xa^{\mathrm{BL}}_{i,s,f}} \tag{46}$$

There are few exceptions for which Eq. (45) does not apply. For example, if a NO_x control technology increases emissions of N_2Oor NH_3(e.g., catalytic converter), the constraint is not applied to N_2Oor NH_3.

5 Applications: common configurations

Thus far we have clarified the objective function and constraints that are used in the GAINS optimization. Actually, the system is much more flexible than suggested, in fact cost and impact functions can change their roles in the optimization for exploration purposes, and this can be very useful in policy application.

In this section we discuss some common configurations of the framework, illustrating the general scope.

5.1 The cost-optimal baseline scenario

As has been discussed elsewhere, the starting point of the optimization is a baseline scenario which represents a future activity pathway (e.g. energy systems scenario data plus an agricultural activity scenario), and a 'current legislation' (CLE) control strategy.

This CLE control strategy is a set of application rates of technologies and is the GAINS representation of the existing air pollution legislation. This legislation is the result of some process, for example an international or EU-wide agreement, following by detailed national allocation, resulting in specific guidelines, mandatory technological specifications, standards, etc. Implementing this current legislation results in baseline emissions for each of the relevant pollutants.

However, despite all intentions, the CLE is not necessarily the most cost effective way to achieve the baseline emission level for each source category (activity-sector combination). One may ask: what is the most cost-effective control strategy to reach (at least) the baseline emission level *for each source category*? To answer this question, one can use the GAINS optimization in the following way:

- Use the total cost function Eq. (41) as the objective function to be minimized
- remove all environmental constraints by setting the targets to Infinity (or some very high but finite number)
- use all other constraints, in particular, Eq. (45) will guarantee that the emission standards of the baseline will at least be kept, if not improved.

The resulting scenario is what can be called the 'cost-optimal baseline' (COB) scenario, which is the starting point for other optimizations with non-trivial environmental targets.

In practice, when all constraints are considered, it will typically turn out that the COB scenario differs from the CLE scenario only for very few source categories. For example, for recent scenario exercises in Europe the overall difference in emissions was around or less than 0.1 % for SO_2, NO_x and $PM_{2.5}$, while 0.5 % to 1 % for NH_3 and VOC. Most of these residual differences can be explained by the fact that the interest rate typically used in GAINS (4 percent per annum) is lower than what industrial stakeholder use internally for investment planning, hence the actual control strategy may turn out to be different from what GAINS considers optimal.

5.2 The Maximum Technically Feasible Reduction (MTFR) Scenario

In Section 4.2, in the context of feasible environmental targets we have already mentioned the uses of the maximum technically feasible reduction (MTFR) scenario. Here we briefly describe how it is calculated using the optimization routine.

The purpose of the MTFR scenario is to identify a bound on the space of all feasible solutions: it represents the 'lowest' scenario, i.e. the scenario of lowest emissions, and for single pollutants this is well-defined. However, we have already seen that for at least two reasons, the 'lowest' is not well-defined when several pollutants and impact functions are considered:

- Some multipollutant technologies reduce the emissions of one pollutant, but increase the emissions of another. Considering that different combinations enter different impact indicator functions, there is not a unique scenario in which all environmental indicators are at their lowest possible value simultaneously.
- We have also seen that the signs of the coefficients for the same pollutant can be different in different impact functions. Therefore we cannot expect that different impact functions take their minimum in the same scenario.

Since there generally is thus no unique definition of the MTFR scenario we find it useful to define the MTFR scenario as the one in which the *sum* of all emissions is at a minimum. This at least makes use of the fact that though a multi-pollutant technology may increase the emissions of some (non-primary) pollutants somewhat, this increase is dominated by a reduction in the primary pollutant. Thus, the MTFR scenario is obtained by using the total emission function

$$E^{tot} = \sum_i \sum_{p \in P_1} E_{i,p} \tag{47}$$

as the objective, using the constraints described in Sections 4.3 and 4.4, while imposing no targets on the environmental impact indicators. Here the set of pollutants P_1 only includes SO_2, NO_x, $PM_{2.5}$, NH_3 and VOC, but not BC and OC (in order to avoid double counting).

The emissions decompose naturally into regions, because the emissions in one region are considered to be independent of the emissions in another. Hence one can write:

$$\min E^{tot} = \sum_i \left(\min \sum_{p \in P_1} E_{i,p} \right) \tag{48}$$

i.e. the MTFR scenario can be calculated in all emitting regions i simultaneously.

Since we are not minimizing cost the optimization routine is free to select the best technologies, which are often also the most costly ones. Thus, it is to be expected that the costs of the MTFR scenario are very high. However, since the MTFR scenario is not a realistic policy scenario but only a bounding scenario, this does not need to be of concern.

5.3 The gap closure procedure

In Section 4.2 we have explained that, given the technological constraints and the objective function (costs), environmental targets can be set independently for each indicator and each receptor region. We have also mentioned that in multi-region settings, whether they are international or national, issues of burden and benefit sharing are important and need to be addressed. In particular, in the European context it is understood that any additional emission control policy will have to be designed so that they all ratifying parties have a share in the benefit of the policy, but also so that they participate in the overall effort and to prevent any free riding. Moreover, it is desirable to also strike a balance across all economic sectors.

Thus, while the exact distribution of costs and benefits is not specified in advance, situations in which the burden is shouldered by a few, but the benefits are reaped by others is to be avoided.

Benefits from air pollution control may be spatially heterogenous. For example, certain sensitive ecosystems that are affected by air pollution (e.g. aquatic systems, soils, etc.) may occur in some countries, but not in others. Hence, the benefits occur only in countries where these ecosystems are located.

For the revision of the Gothenburg Protocol in 2011 four alternative approaches for target setting have been developed that illustrate the implications of different policy choices:

(i) Targets could establish uniform environmental quality criteria that should be achieved everywhere in Europe, so that all European citizens and ecosystems could enjoy equal air quality conditions. However, this would require areas with currently the highest pollution to invest most into clean-up, while there would be no incentives for improvements that are possible in less polluted areas.

(ii) Targets could call in each country for equal relative improvement in environmental quality compared to the situation in a base year. Such a target setting approach would result in a more equal distribution of efforts. However, countries at the fringes of Europe that already enjoy relatively clean conditions, but are strongly dominated by emissions from non- European sources (e.g., Cyprus) would face disproportionately high costs as they have only little potential to efficiently improve their air quality through additional measures within the country. Aligning the quantitative targets for all countries with the feasible range for such countries will not trigger further improvements in other parts of Europe, where additional measures are available that would lead to substantial environmental improvements.

(iii) Targets could aim in each country for equal relative progress within the feasible space of environmental improvements, i.e., between the baseline and the maximum reduction cases. By definition such reductions are technically feasible in all countries and would give a more equal distribution of costs, but they are sensitive to weakly defined reference cases, i.e., the baseline and maximum reduction cases.

(iv) As a variant of option (iii), a fourth approach would optimize total environmental improvements for Europe as a whole irrespective of their location. Such an approach would offer a more cost-effective result than target setting approaches that entail equity criteria, and would lead to lower costs for almost all countries. This concept has been accepted as a rationale for the Clean Air For Europe (CAFE) program of the European Commission for human health Tuinstra (2007). However, in the pan-European context of the Gothenburg Protocol such an approach would shift additional efforts (and benefits) to countries with less stringent emission control measures in their baseline (e.g., non-EU countries). The different target setting options are analyzed in more detail in Amann et al. (2005, 2010).

One concept that addresses questions of burden and benefit sharing is the 'gap closure', an approach that has been applied extensively in the context of target setting approaches in Europe. The starting point is the fact that the feasible range of scenarios lies between the CLE (COB)[10] scenario and the MTFR scenario.

This range represents the gap between what is currently planned and what is feasible. It can be calculated for each impact indicator in each receptor region k. The absolute value of the gap will be different for different receptor regions. For example, in a region with a high AAE in the COB scenario the absolute difference to the AAE in the MTFR scenario is like to be higher than for a region where the AAE was small in the first place, or even zero (in the latter case the gap is zero too).

The main idea of the gap closure concept is to require that the gap between COB and MTFR is to be reduced by the same percentage for all receptors k. In this way heavily polluted areas benefits more in absolute terms the comparatively clean areas, but in relative terms in all areas the same progress towards MTFR effect levels is made. In this way, the benefits of a policy are shared proportionally by all affected areas.

In principle, different gap closure percentages can be chosen for different impact indicators, and this is what typically happens in practice too. The gap closure percentages represent ambition levels, ranging from 0 % (no ambition) to 100 % (maximum ambition), and policy makers may chose to select different ambition levels for different impact indicators to reflect relative value or urgency, as required or desired.

Setting targets using the gap closure procedure does imply a priori a fair sharing of cost, whatever 'fair' means in this context. After all, it is a procedure for distributing environmental benefits relatively evenly. However, experience shows as a rule of thumb that the more integrated the assessment is, i.e. the more impact indicators and pollutants are involved the more one can expect that the heterogeneities of individual effects cancel and a 'fair' distribution of costs emerges from the optimization.

6 Some Results

In this section we illustrate the optimization procedure through example results. Basis of these results is the baseline scenario used for the negotiations of the revision of the Gothenburg Protocol in 2011, details of which can be found in (Amann et al. 2011*b*). Unless stated otherwise all results are for the year 2020.

[10]For consistency emissions control costs of cost-optimal policy scenarios should be compared to the COB scenario. Hence it is appropriate to base the gap closure on the COB and not the CLE scenario, but as discussed above, the difference in terms of emissons and impacts will typically be small anyway.

6.1 Optimizing for single environmental objectives

As described in Sections 3.5 and 5.3 the gap closure procedure can be applied to each of the environmental impact indicators. As each of these indicators depends on the emissions of different sets of pollutants, and as the each of the impact indicators has a different geographic distribution, it is to be expected that the gap closure procedure results in different costs for each of the impact indicators. This is illustrated in Figure 10, from which can be seen that the health-related YOLL and SOMO35 indicators exhibit higher costs than the ecosystem-related indicator *at the same ambition level*.

Each of the graphs was obtained by iteratively minimizing the objective function Eq. (41), subject to the technology constraints and a non-trivial constraint for one of the impact indicators $\hat{\Omega}$ in every receptor region k of the form

$$\mathrm{EnvImp}_{\hat{\Omega},k} \leq \mathrm{Target}_{\hat{\Omega},k} \tag{49}$$

where the targets are set using the gap closure concept

$$\mathrm{Target}_{\hat{\Omega},k} = \mathrm{EnvImp}_{\hat{\Omega},k}(\mathrm{COB}) - \phi_{\hat{\Omega}} \cdot \Big(\mathrm{EnvImp}_{\hat{\Omega},k}(\mathrm{COB}) - \mathrm{EnvImp}_{\hat{\Omega},k}(\mathrm{MTFR})\Big) \tag{50}$$

with $0\ \% \leq \phi \leq 100\ \%$. Note that ϕ does not depend on the receptor k. This ensures that equal progress is made in all relevant receptor regions simultaneously. However, ϕ is specific to the impact indicator function $\hat{\Omega}$, i.e. a different gap closure percentage can be chosen for each impact indicator.

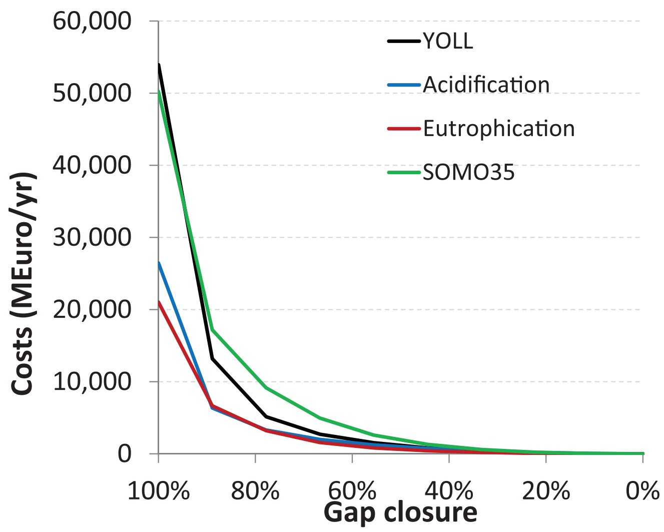

Figure 10: Emission control cost for cost-effective single impact reduction using the gap closure approach (see Section 5.3)

Figure 10 can be used to read off the costs for achieving a given ambition level in reducing a single impact. Conversely, the figure can also be used to read off which ambition level can be reached with a given budget. This can easily from Figure 11, which is just another version of Figure 10.

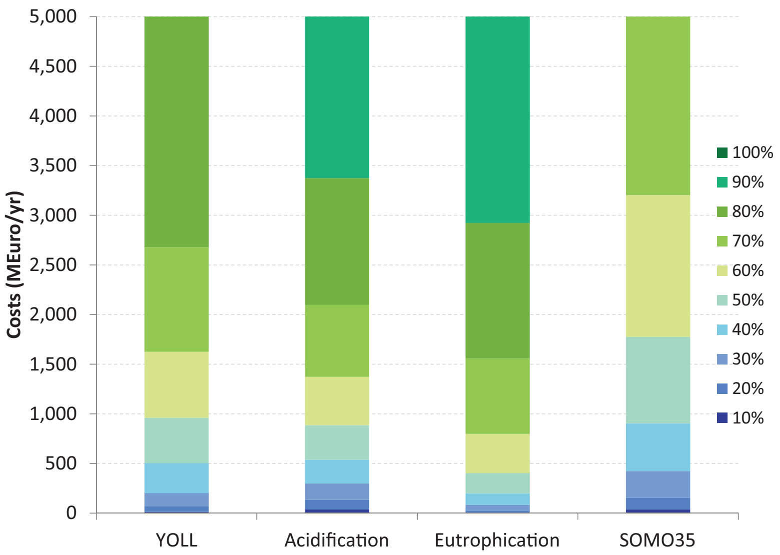

Figure 11: An alternative version of Figure 10 for identifying comparable ambition levels in terms of emission control costs

Here the relationship between a budget and ambition level within this budget is more obvious. For example, with a budget of, say, 2 billion Euros, the maximum gap closure amibition level for the YOLL and acidification indicator is around 70 percent, while for eutrophication it is approx. 10 percent higher and for the SOMO25 indicator approximately 10 percent lower. In practice this information may be used to prioritize multiple effects and to define targets accordingly (see Section 6.2). As is clear from Figure 1 above and will be illustrated in more detail below, addressing one impact indicators will also, via the reduction of multiple pollutants, also address other impact indicators. This offers significant potentials for synergistic effects.

In this report we are particularly interested in how air pollution objectives may affect the short-term forcing and to explore potential trade-offs. Figure 12 shows the implications of the gap closure procedure on the four impact indicators YOLL, acidification, eutrophication and SOMO35 on the radiative forcing over the EMEP region, calculated as described in Section 3.6.1, i.e. ignoring the ozone effect.

First, notice the range of RF values for these scenarios. All values lie between minus 560 and minus 700 milli-Watts per square meter. The YOLL gap closure implies an initial reduction of the forcing (as a result of initial $PM_{2.5}$and implied BC emission reduction), but then a steep increase (as a result of sulphur emission reductions), and finally a small decrease (as a result of further BC reductions). Similarly, a reduction in the acidification indicator is achieved cost-effectively by a reduction of SO_2 and NO_x, leading to a net increase in radiative forcing. Thus, these curves are the result of measures for different pollutants being taken at different ambition levels. Neither do the reduction of the eutrophication nor, in this setup, the SOMO35 indicator have significant impacts on the radiative forcing. We note, however, once again that the ozone effect is not adequately

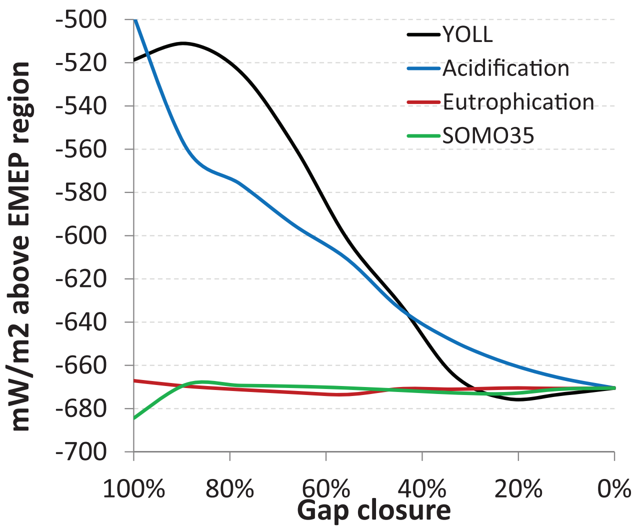

Figure 12: Radiative forcing from short-lived climate forcers over the EMEP modeling domain as a function of single impact gap closure targets

captured by the relations described in Section 3.6.1, and thus qualitatively different conclusions will be drawn when it is included in the calculations.

The above co-effect on regional radiative forcing depends on the domain that is considered. Figure 13 shows the radiative forcing changing in response to targets on YOLL, acidification, and eutrophication over four different domains (EMEP region, Northern Hemisphere (NH), Arctic region above 70 degrees, and Arctic region above 60 degrees). As expected the relative impact over the EMEP region is largest, while the effect over the Northern hemisphere is small. The effect of the SOMO35 gap closure procedure on the radiative forcing is negligible and therefore not shown.

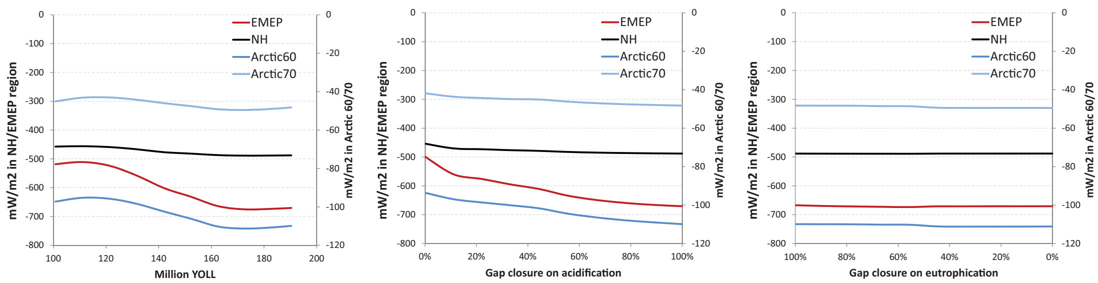

Figure 13: The effect of the single effect gap closure procedure on the radiative forcing over four regions.

Further details of the interaction between reductions of individual pollutants and RF and YOLL impact indicators is illustrated further in Section 6.3. The effect of cost-effective emission reduction on carbon deposition in the arctic is illustrated for selected scenarios in Section 6.2.

6.2 Multiple enviromental objectives: cost-effective measures

In policy applications the GAINS optimization is used to find cost-effective solutions that meet multiple environmental objectives simultaneously. This is done by minimizing the cost function Eq. (41) subject to target constraints on two or more environmental indicators are met (cf. Section 6.1). As expected, setting multiple targets simultaneously results in costs that are lower than the sum of the costs for reaching the individual targets separately.

Which ambition levels and targets are to be met is a policy decision, but what has been said so far on the costs and feasibilities of targets on single environmental indicators can guide such a policy decision. For example, we have already shown in Section 6.1 how to identify those ambition levels for each of the effects that can be reached within the same budget. Selecting ambition levels that imply similar costs for different single environmental effects can be politically acceptable as it suggests a comparable weighing of environmental objectives using an economic metric. While a precise definition of such a metric may not be possible nor desirable, such an approach may be a good heuristic.

In the following we use this heuristic to identify five scenarios that differ in the overall ambition level and how much weight is put on individual environmental objectives, taking into account cost-effectiveness considerations in two directions. These five scenarios have been used in the context of the negotations of the revision of the Gothenburg protocol to illustrate various ambition levels (Amann et al. 2011*b*)

First we define two scenarios in which each of the four environmental impact indicators YOLL, acidification, eutrophication and SOMO35 reaches the same gap closure ambition level. The 'LOW' scenario achieves a uniform 25 percent gap closure and the 'HIGH' scenario a 75 percent gap closure. A third scenario, the 'MID' scenario takes into account Figure 12, namely that while a 50 percent gap closure appears as a natural midpoint for a YOLL and acidification optimization, a more (less) ambitious gap closure target can be reached within the same budget for eutrophication (SOMO35). Therefore, the cost-balanced 'MID' gap closure ambition levels are 50/50/60/40 percent, respectively, for YOLL, acidification, eutrophication and SOMO35.

We then define two further scenarios. The 'Low*' scenario is obtained by using the same targets as for the 'LOW' targets (25 percent gap closure for each of the indicators), except for eutrophication, for which the more ambitious 50 percent gap closure is used. This scenario is motivated by the fact that, if one aims for higher ambition than the 'LOW' level, one would first increase the ambition level of the impact indicator that can be changed at lowest cost, in this case eutrophication (cf. left panel in Figure 14). Similarly, if 'HIGH' (i.e. 75 percent gap closure on all four indicators) is considered too ambitious, it is economically meaningful to relax the ambition level of that indicator for which a reduction would reduce overall costs the most (cf. right panel of Figure 14), i.e. SOMO35 (which in the 'High*' scenario is lowered to 50 percent).

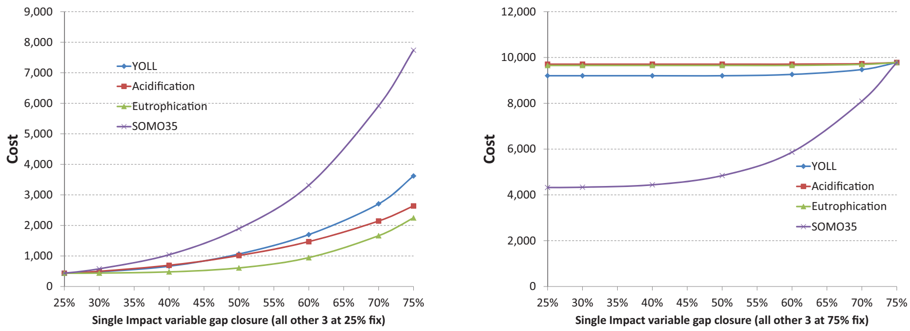

Figure 14: Sensitivity of overall costs to increasing (left) and relaxing (right) the ambition level for a single indicator function, leaving the other three indicator functions at the 'LOW' (left) and 'HIGH' (right) ambition level.

Table 1 summarizes the ambition levels for the five scenarios described. Raising or lowering the ambition level by 25 % is an arbitrary choice which we only used for illustrative purposes.

	YOLL	Acidification	Eutrophication	SOMO35
HIGH	75	75	75	75
High*	75	75	75	**50**
MID	50	50	**60**	**40**
Low*	25	25	**50**	25
LOW	25	25	25	25

Table 1: Summary of the gap closure ambition levels of the scenarios discussed in this section.

Each of these ambition levels leads to country-specific emissions of each of the pollutants, arising from a cost-optimal mix of control technologies, as calculated with the GAINS model. As an example, Figure 15 shows, for all five scenarios, the implied NOx emissions in relation to their year 2000 and baseline level. This way of representing the solution helps to gauge the emission reductions in the baseline versus the extra effort implied by the ambition levels.

Naturally each of the resulting scenarios can be further analyzed in terms of distribution of emission reductions and costs across countries and sectors. As an example, Figure 16 shows for the MID scenario primary SO_2, NO_x, primary $PM_{2.5}$, NH_3 and VOC the percentage reductions for each of the European countries, coloured by (an aggregation of) measures. This representation helps to identify the relative role of individual sectors in the overall effort, but also to detect potential imbalances.

These portfolios are the most cost-effective sets of measures to reach the prescribed environmental targets in each of the European countries. These measures imply certain costs and, in order to make them comparable across countries, in Figure 17 these costs are

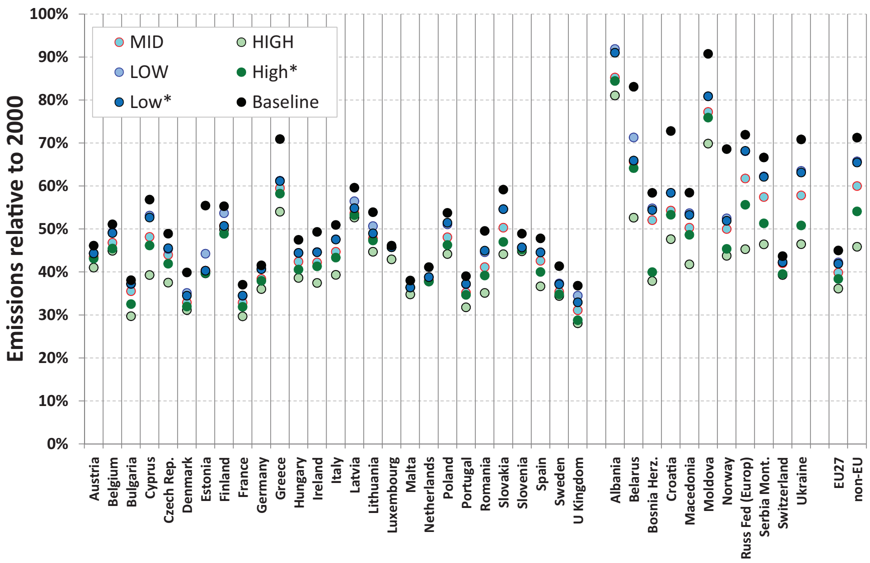

Figure 15: NOx emission levels relative to year 2000 values for the five scenarios and the baseline

shown scaled to the national gross domestic product (GDP) in the year 2020. While this is useful information it must also not be over-interpreted. Emission reductions and costs for non-EU countries tend to be higher than in EU countries. However, in the assessment one also needs to take into account that many cost-effective measures are already taken in the EU. As a consequence the cost-effectiveness approach tends to identify more cost-effective measures in non-EU countries, and shifts a relatively higher burden to these countries. However, measures prescribed in the current legislation (CLE scenario) in the EU tend to be costly too and have contributed to lower emissions than in a business as usual scenario. Hence Figure 17 cannot be used alone to establish whether or not the distribution of costs among all countries is 'fair'.

As a result of the emission reductions for each of the scenarios in Table 1 we can calculate - ex post - the implications for the radiative forcing and carbon deposition, e.g. in the Alps. Figure 18 shows these values. Also shown is the lowest possible value of these two indicators, which may be different from the MTFR scenario value as defined in Section 5.2 and from each other, considering that these two lowest values may not be achievable simultaneously. This is because measures that reduce the carbon deposition do not necessarily reduce the radiative forcing.

6.3 Multiple objectives: Human health, radiative forcing and costs

In the previous section we have seen (1) how multiple environmental targets could be set using the gap closure procedure; and (2) how cost-effective sets of emission reduction measures also have implication on regional radiative forcing and carbon deposition. In this section we discuss how these climate related effect indicators can be included in

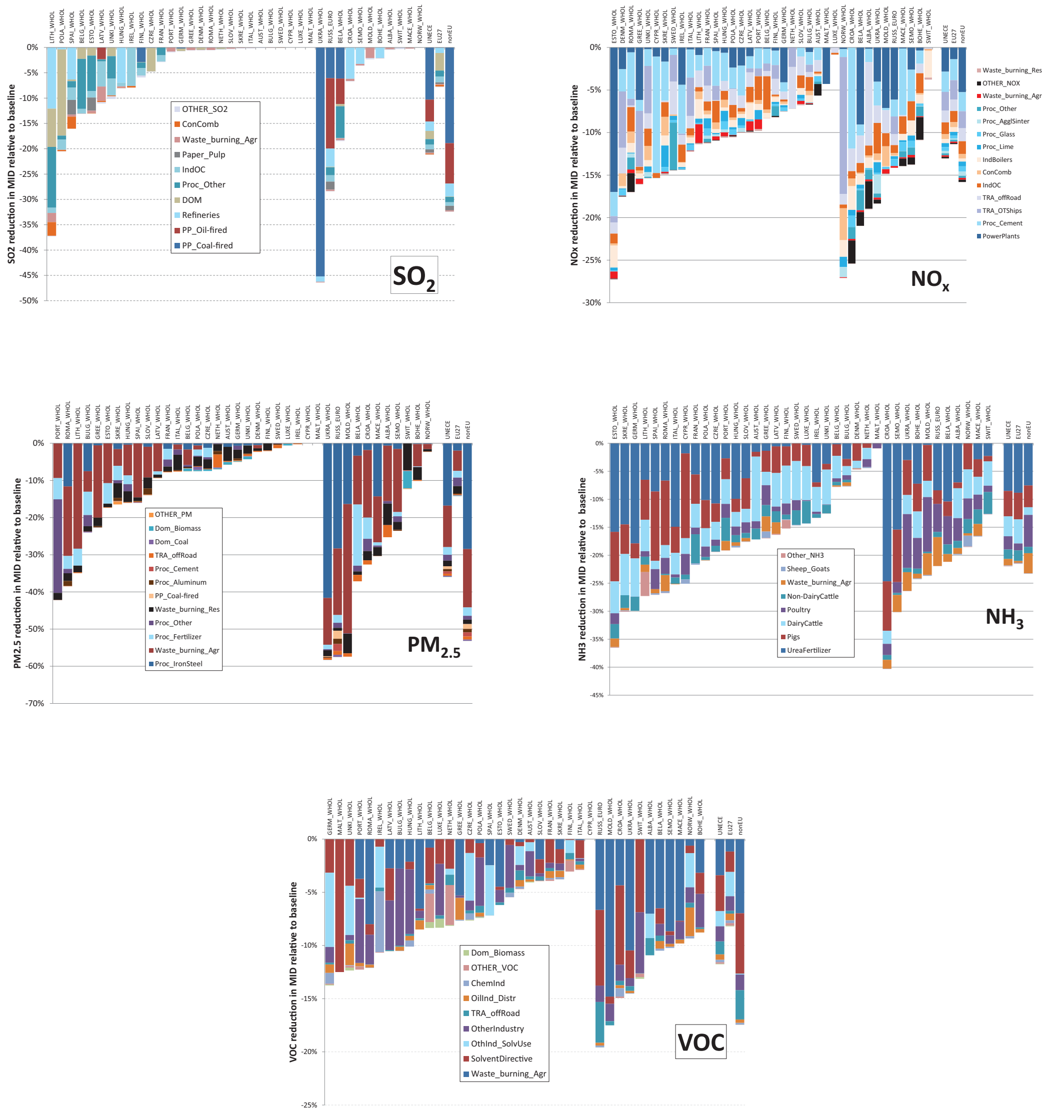

Figure 16: Groups of measures and their contribution to emission reductions relative to baseline for the 'MID' scenario

the optimization to identify cost-effective control strategies that respect both climate and non-climate related effect targets. As a first step we have already explored in the previous section the feasible range of climate related indicators, cf. Figure 18. But have also already indicated that there may be a trade-off between climate and non-climate impact targets.

Figure 19 illustrates this trade-off further. It shows the emission reduction costs for reaching the five policy scenarios described in Section 6.2, while simultaneously staying below a target value on regional radiative forcing over the EMEP domain. The radiative forcing increases as we move from the LOW to the HIGH scenario (right endpoints of the dark blue and light blue lines, respectively). The High* scenario further increases the radiative forcing, because relaxing the constraint on ozone results in relatively higher

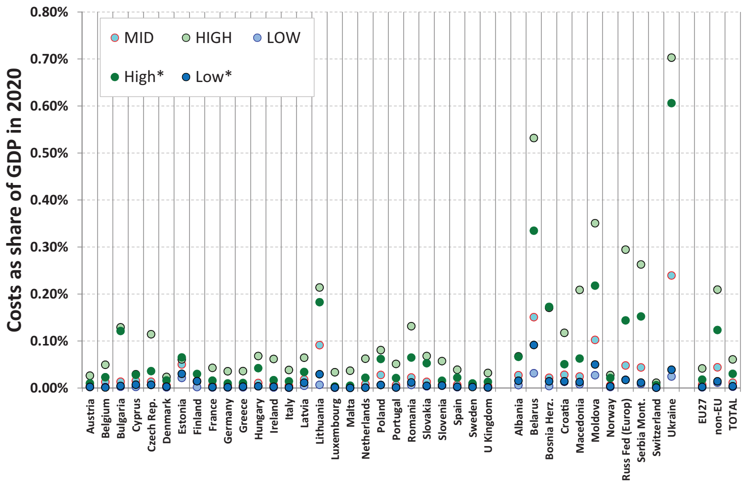

Figure 17: Emission control costs above baseline for the five scenarios described in the text scaled by the GDP in the year 2020

NO_x emissions, which in turn are compensated, inter alia, by lower SO_2 emissions to achieve the same YOLL and acidification targets, resulting in higher radiative forcing.

For each of the policy scenario one may ask whether (a) the radiative forcing can be reduced, while achieving the same targets on the non-climate related impacts; and (b) at what cost. The five lines in Figure 19 show how the costs increase as the radiative forcing is reduced and the non-climate targets are kept constant. It can be seen that while a small low-cost potential exists in each case, the costs for reducing the radiative forcing grow very quickly. Also, one can see that certain levels of radiative forcing cannot be reached anymore (even at high costs) for ambitious target levels of the non-climate related effects.

To illustrate the cost-effective emission reduction strategies as a function of the additional constraint on the regional radiative forcing Figure 20 shows the emission levels for each of the five policy scenarios and for the scenarios in which also a target on radiative forcing is reached.

Thus, as expected, SO_2 emissions increase from their - initially optimal with respect to the non-climate related targets - with more and more stringent targets on the radiative forcing. Starting from the Low* scenario, they even reach baseline levels again.

These increases in SO_2need to be compensated. As one can see from Figure 20, this is achieved by further reductions in NO_x, primary $PM_{2.5}$ and NH_3 (in fact in the Low* scenario, even emissions of NO_x increase due to the small nitrate cooling effect. In extreme cases, even VOC is significantly reduced to compensate for this effect).

Finally, the analysis of whether climate-related and non-climate related targets are compatible and how they influence the overall emission control costs can be extended and performed systematically. In Figure 21 we restrict ourselves to the relationship between the YOLL indicator, the radiative forcing over the EMEP domain and the emission control cost.

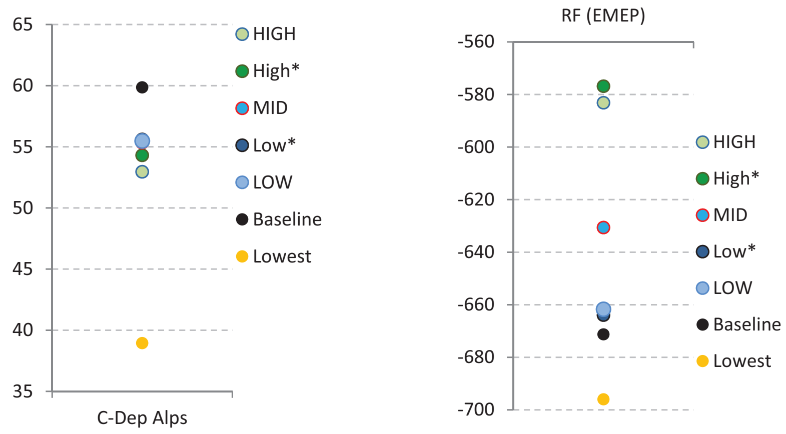

Figure 18: Implications of the five policy scenarios and baseline on carbon deposition on the Alps (left: mgC/m^2) and radiative forcing over the EMEP region (right: mW/m^2)

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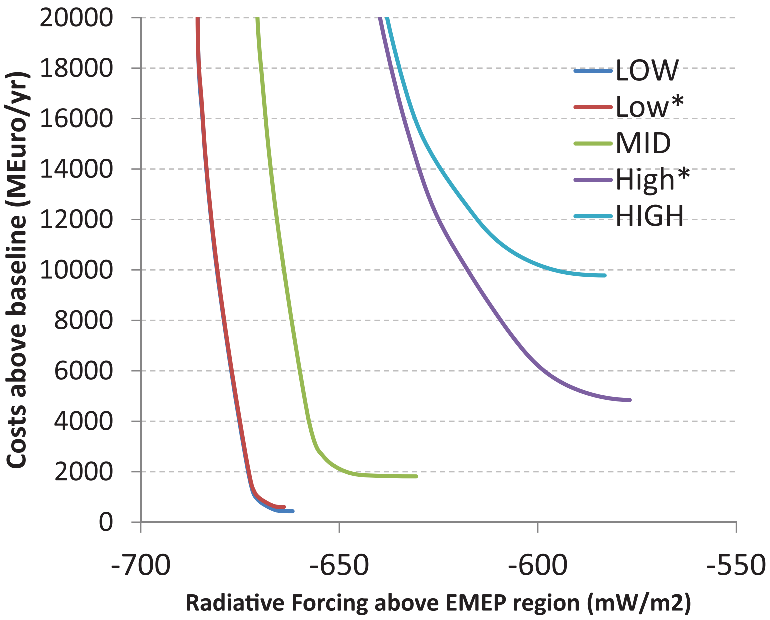

Figure 19: Emission reduction costs for reaching the five policy scenarios described in Section 6.2, while simultaneously staying below a target value on regional radiative forcing over the EMEP domain.

The figure shows the lowest costs above baseline costs (colour) as a function of a joint YOLL and forcing target for the year 2020. The baseline is represented by the most eastern point of the coloured areas. There are white areas in the graph for three reasons. First, the area to the right of the baseline is white because GAINS will not increase emissions

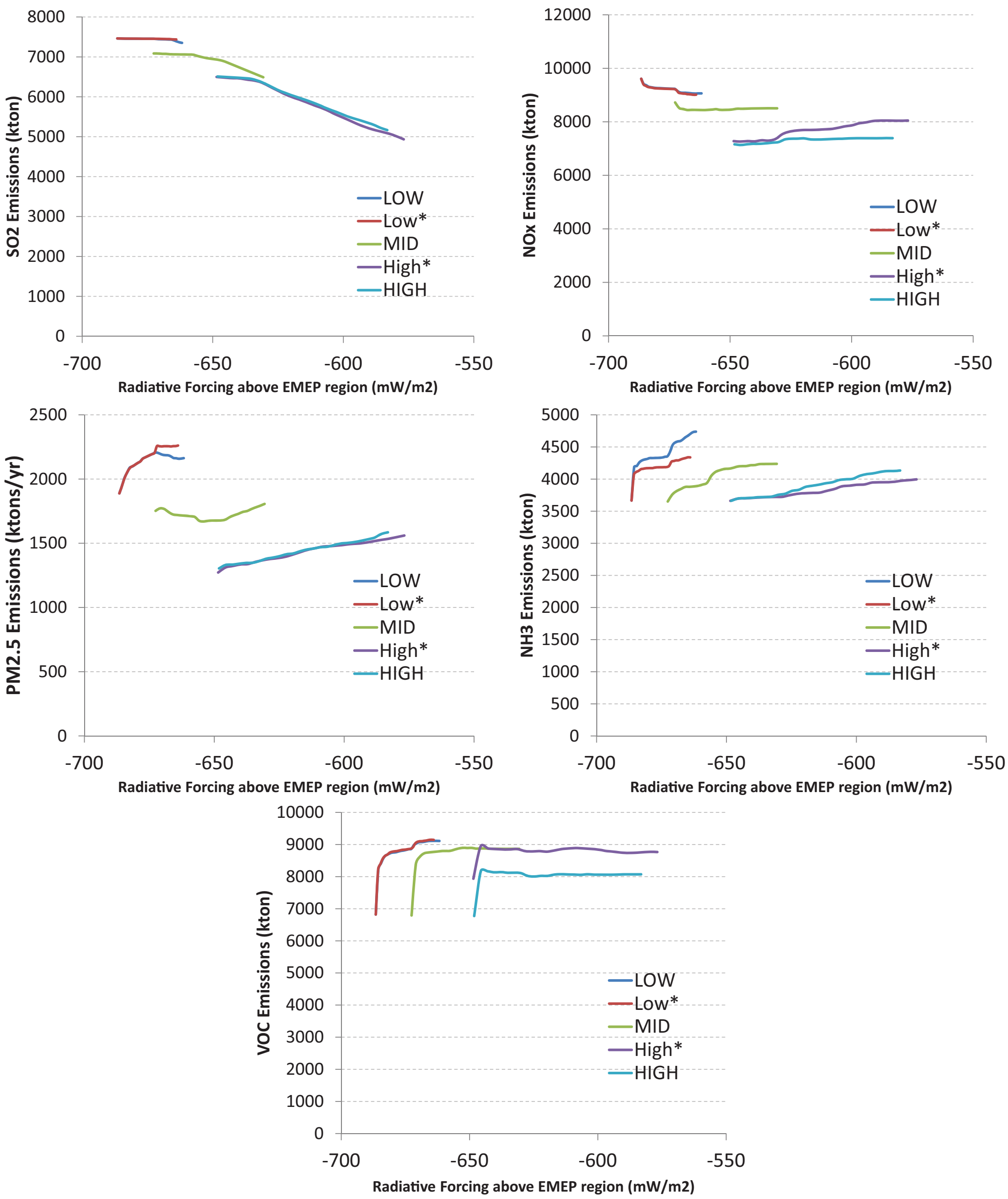

Figure 20: Emissions of SO_2, NO_x, $PM_{2.5}$, NH_3 and VOC as a function of targets on radiative forcing, starting from the five different ambition levels described in Table 1.

to higher than baseline levels, hence the YOLL indicator cannot be higher than in the baseline. Similarly, the area north of the highest coloured point (at around -560 mW/m^2 cannot be reached either, for this the (SO_2) emissions would have to be higher than in the baseline. Second, the area south of the coloured area is white because there are no feasible solutions in this area: it is simply not possible to reduce the radiative forcing below -696 mW/m^2, nor is it possible to reduce the YOLL indicator to the level of, say, 120 million YOLL, while keep the forcing level at around -680 mW/m^2. Third, the area in the north and northeast corner the area is white because there are no cost-effective solutions located in this area. Thus, Figure 21 should be read in the following way:

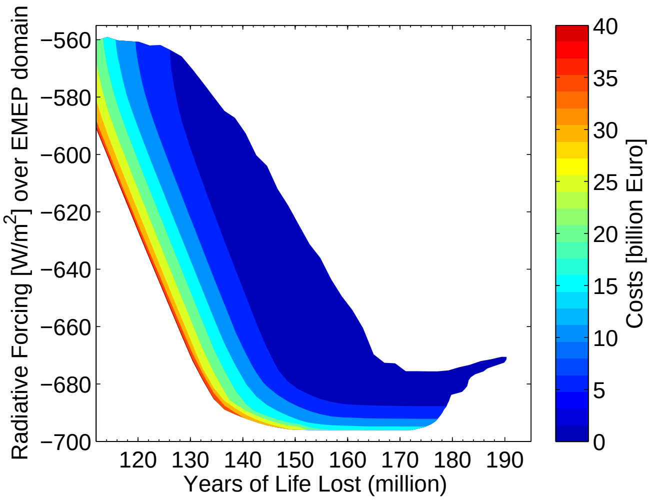

Figure 21: Additional cost for reaching a particular level of radiative forcing, given a YOLL level. The upper enveloping curve represents the cost-effective scenarios to reach a given YOLL level without constraint on the radiative forcing.

- starting from the baseline scenario on the right, iteratively setting a stricter and stricter constraint on the YOLL indicator, and minimizing costs in each the scenario, the resulting emission reductions lead to a change in radiative forcing such that all resulting scenarios are lying on the curve that envelops the coloured area on the upper end. This curve corresponds to the black curve in Figure 12 (The curve here looks more bumpy only because of a coarse graining the graphical representation.);
- for a given level of the YOLL indicator (we have divided the range between baseline and lowest YOLL level into m=40 steps) we minimize the forcing indicator and obtain the lower enveloping curve;
- finally, at a given value of the YOLL indicator, the range between the lower and the upper enveloping curve is divided into $n = 25$ steps, and for each step we minimize the cost to reach the n-value of the forcing indicator and the given value of the YOLL indicator. The colour code of each the 1,000 scenarios indicates the emission control cost above the baseline scenario.

Clearly, the environmentally 'desireable' directions in this graph are 'down' and 'left', i.e. lower health impacts and lower forcing. Thus, scenarios lying in the white area above the upper envelope are discarded, because they are not cost effective for a given target on the YOLL indicator: there are scenarios, at the same YOLL level, but with lower forcing **and** lower costs.

Figure 21 shows that within a moderate range of ambition levels on the YOLL (say, between 190 and 140 million YOLL), it is possible to find an alternative solution to the most cost-effective one which, at relatively low extra cost, achieves the same YOLL target, but keeps the radiative forcing below, say, -660 mW/m^2. For more ambitious YOLL targets the costs increase steeply, and below 130 million YOLLs such a forcing level cannot be achieved. In summary, at moderate health ambition level the regional forcing can be kept at baseline level, i.e. with the caveats mentioned abobe (in partricular the fact that here the ozone effect has been neglected) there is no significant trade-off between health and near-term, regional climate objectives.

7 Conclusion

In this report we have summarized the optimization module of the GAINS model, with a particular emphasis on finding cost-effective control strategies that address both environmental impact indicators related to air pollution, and the radiative forcing of (some of) these pollutants. The GAINS multi-pollutant multi-effect framework lends itself for analysing synergies and trade-offs between different objectives and for quantifying cost implications.

We have described various formal aspects of the optimization, including the dimension of the solution space, nature and use of decision variables and their relation to relevant functions, such as cost, emissions and environmental impact indicators. We have illustrated standard optimization configurations that are used to calculate commonly used scenarios such as the COB and MTFR scenarios.

The gap closure procedure, which makes use of the COB and MTFR scenarios, allows to set targets that are guaranteed to be feasible and which at the same time respect the need to distribute environmental benefits evenly, as far as possible, between countries.

We have further illustrated, for selected ambition levels, the trade-off between reductions in environmental impact indicators and radiative forcings. Furthermore, we have shown that, within certain ranges, these trade-offs in terms of physical effects can be compensated by changing to a more costly control strategy. The cost for compensation can systematically be calculated, and very specific recommendations can be made in terms of measures in different countries.

Unlike in multi-criteria optimization the current formulation of the GAINS optimization makes very explicit the distinction between environmental objectives and control costs. Thus, judgements about the relative value of various environmental benefits are not hidden in some model assumption but need to be made explicit and open in view of the results. In this way, GAINS can be used to aid policy makers to contemplate policy options with the required flexibility, without losing sight of cost-effectiveness considerations.

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A NH_3 measures and their combinations

In the case of NH_3 the relationship between measures is a little more complex than for most other pollutants. Control technologies for NH_3 from livestock can be applied at different stages. In order to keep the number of technology combinations manageable, in GAINS control technologies have been combined into packages. Since it is difficult to consistently define maximum application rates for these packages, we instead define applicabilities for the underlying basic technologies that can be applied at different stages, and constrain the total use of these basic technologies across all packages.

A simple example will illustrate the point: Note that 'stable adaptation' (SA) appears in the following table in the first row as a basic or individual technology. It also appears in the last few rows of the table in the technology packages SA and SA_LNA. The package SA means that only SA is applied, whereas SA_LNA stands for a package in which both SA and LNA are applied.

	Stage-specific technologies										
Technology packages	BF	CS	CS_high	CS_low	LNA	LNA_high	LNA_low	LNF	PM_INC	SA	SUB_U
BF	x										
BF_CS	x	x									
BF_CS_LNA	x	x			x						
BF_LNA	x				x						
BF_LNA_high	x				x	x					
BF_LNA_low	x				x		x				
CS_LNA		x			x						
CS_high		x	x								
CS_low		x		x							
LNA_high					x	x					
LNA_low					x		x				
LNF								x			
LNF_BF	x							x			
LNF_BF_CS	x	x						x			
LNF_BF_CS_LNA	x	x			x			x			
LNF_BF_LNA	x				x			x			
LNF_BF_LNA_high	x				x	x		x			
LNF_BF_LNA_low	x				x		x	x			
LNF_CS		x						x			
LNF_CS_LNA		x			x			x			
LNF_LNA					x			x			
LNF_LNA_high					x	x		x			
LNF_LNA_low					x		x	x			
LNF_SA								x		x	
LNF_SA_LNA					x			x		x	
PM_INC									x		
SA										x	
SA_LNA					x					x	
SUB_U											x

Figure 22: Relationship between single measures at different stages (columns) and combinations of measures (rows)

If $q_{\mathrm{SA}}^{\max}$ is the maximum applicability of the basic technology SA, then it has to hold that

$$q_{\mathrm{SA}} + q_{\mathrm{SA\_LNA}} \leq q_{\mathrm{SA}}^{\max} \tag{51}$$

i.e. the sum of the application rates of technology packages has to be smaller or equal to the maximum application rate of the individual technology SA. Note that the left hand side of (51) is the sum over all technology packages that contain 'SA', i.e., those that have a '1' in the SA column. More generally, for NH_3 control technologies, we impose

$$\sum_{t \in T_{t_0}} q_{i,s,f,t} \leq q_{i,s,f,t_0}^{\max} \tag{52}$$

where t_0 is an individual or basic technology (i.e., appears in the first row in the above table), and T_{t_0} is the set of technology packages that contain the basic technology t_0. Elements of the set T_{t_0} are those that are indicated by a '1' in the appropriate column.

This methodology has been implemented in GAINS and the optimization. The costs and application rates of the above technologies in Europe has been assessed by Klimont & Winiwarter (2011).

B Chains of VOC control options

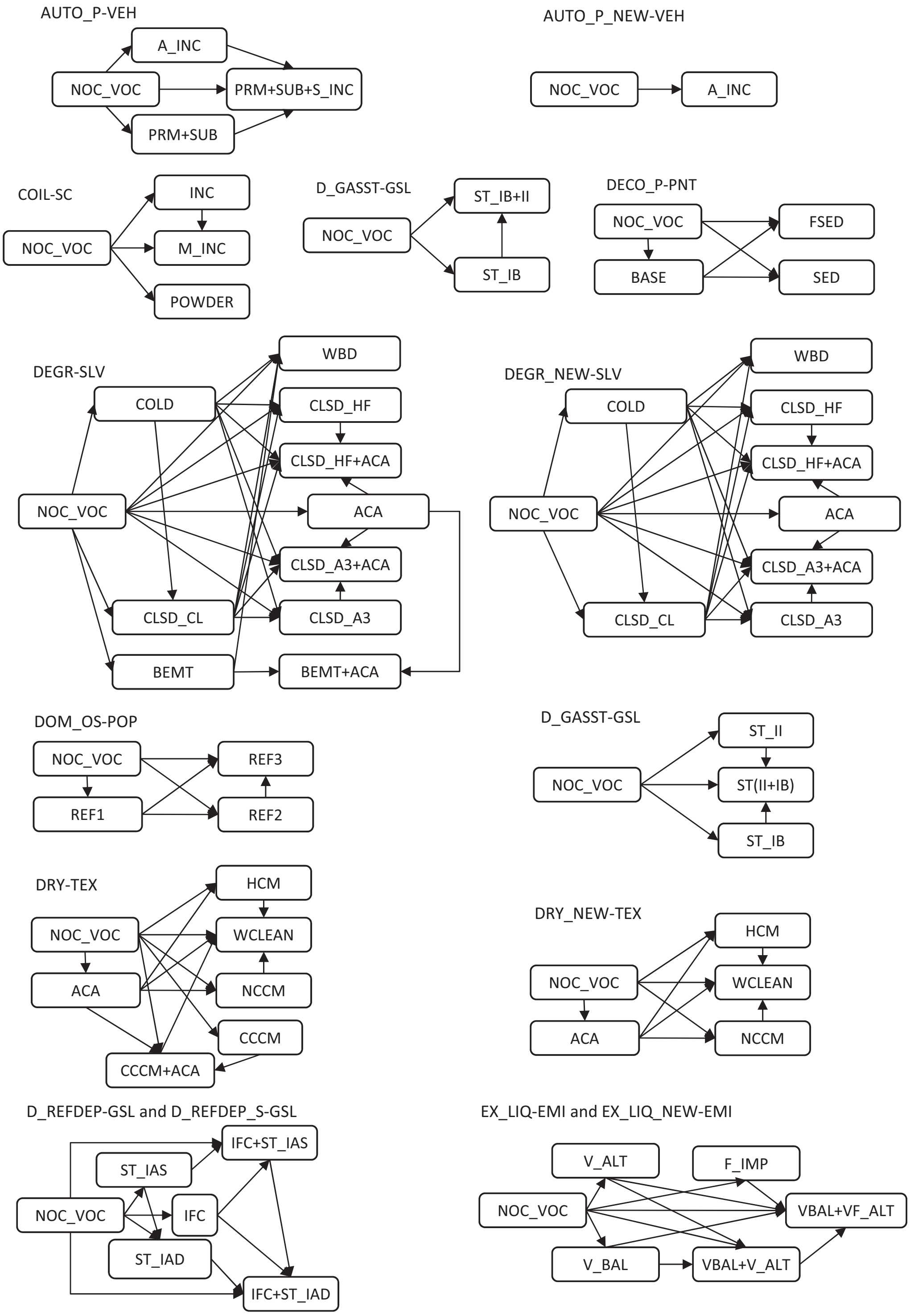

Figure 23: Chains of VOC reduction measures (Part 1)

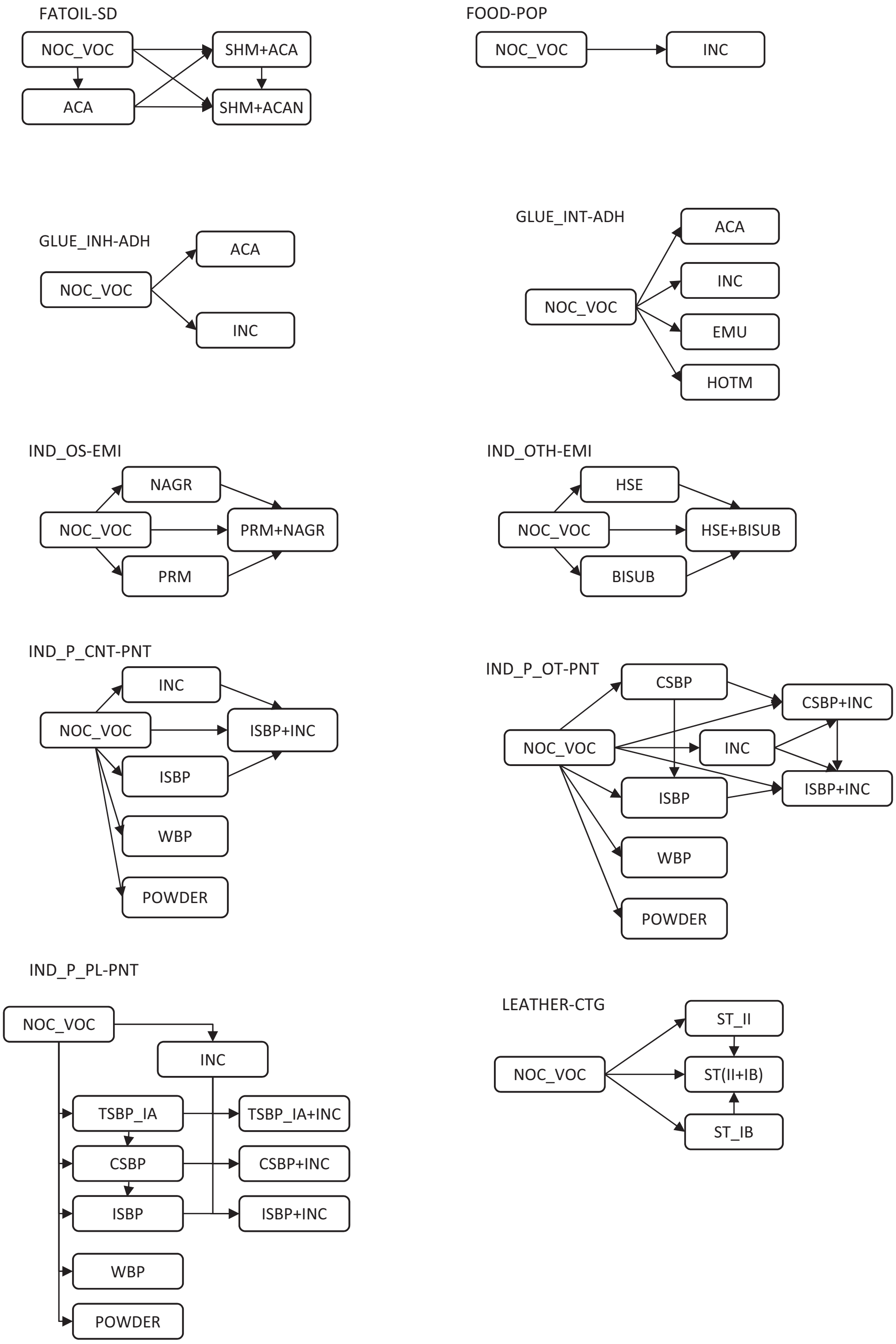

Figure 24: Chains of VOC reduction measures (Part 2)

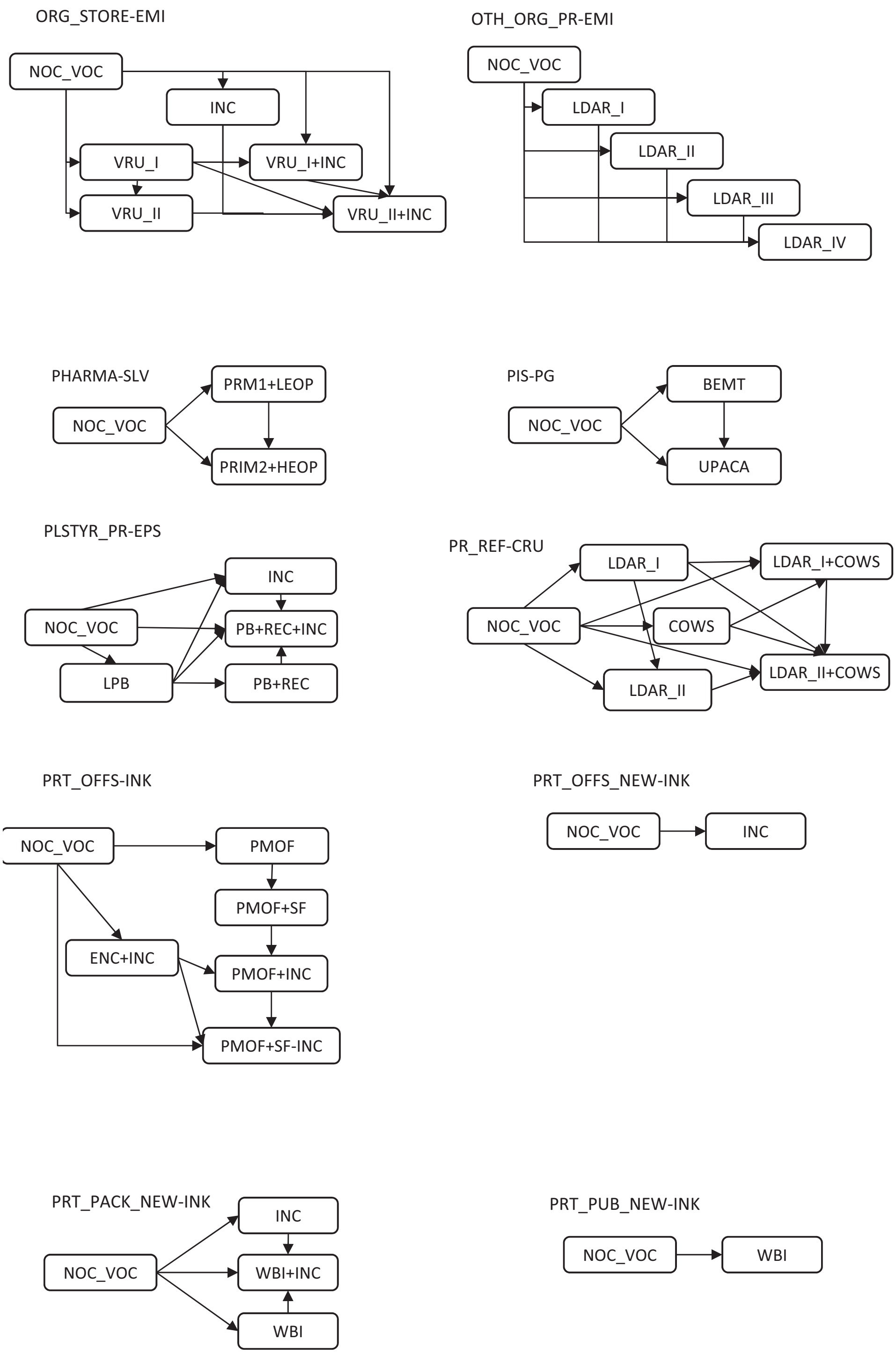

Figure 25: Chains of VOC reduction measures (Part 3)