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The Compensation Mechanism in the RAINS Model: The Norwegian Targets for Acidification

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THE COMPENSATION MECHANISM IN THE RAINS MODEL: THE NORWEGIAN TARGETS FOR ACIDIFICATION[1]

by

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Abstract: The RAINS model is used to calculate cost minimising abatement policies subject to European-wide spatial restrictions on pollution. The principle for choosing environmental targets for the 1994 Oslo Protocol was closing a gap between benchmark- and critical loads for each grid with a uniform percentage. During the negotiations for the 1999 Gothenburg Protocol accumulated eco-systems exceedances was adapted as basis for gap closure, and overshooting of the constraints allowed as an option, provided compensation could be found within the same country. A theoretical discussion of this compensation mechanism is provided. A simulation study, using the full RAINS model, of the impact of different levels of targets for troublesome Norwegian grids is presented, and results in the form of changes in accumulated acidity excesses and costs for the participating countries are reported.

Keywords: Acid rain, RAINS, critical loads, gap closure, accumulated exceedances, compensation mechanism

JEL classification: C44, C61, Q25

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1. Introduction

Concerns about acidification of the environment caused by air pollutants crossing international borders grew in Europe in the late 60s, and was an important topic at the first United Nations conference on the human environment that took place in Stockholm in 1972. Empirical work on a European atmospheric transportation model started as an OECD project in the same year. The programme was later taken over by the UN Economic Commission for Europe (UN/ECE) in 1979 under the Convention on Long - Range Transboundary Air Pollution (LRTAP) to reduce air pollution in Europe. International cooperation from the early 70s to solve trans-boundary air pollution problems in Europe led to the development of the Regional Acidification INformation and Simulation model, or RAINS for short, at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria (see Alcamo et al., 1990 for the first general presentation).

The RAINS model basically integrates an atmospheric transportation model, the EMEP model, (see Eliassen and Saltbones (1983) for the start and Tarrason et al. (1998) for an update) linking the emissions from countries as sources of pollution to the deposition of pollutants at receptors, with purification cost functions for the emission sources at a country level. The EMEP model distinguishes the spatial pattern of deposition over Europe using as receptors a grid mash with a 150x150 km resolution. The model can be used for scenario analyses and to derive cost-effective European wide reductions of emissions. In this latter "optimisation mode", environmental objectives are linked to acid deposition by formulating standards in terms of depositions for each grid-cell. The present RAINS model deals with emissions of sulphur, nitrogen, ammonia and volatile organic substances as well as modelling the formation of ground level ozone (see Amann et al., 1998b), and can be used to address, in addition to acidification problems created by sulphur and nitrogen, also problems with eutrophication and ground level ozone. The latest development is to cover fine particles so related health problems might be studied (cf. www.iiasa.ac.at).

An innovative feature of the RAINS optimisation version used for the Oslo Protocol was the introduction of *Critical Loads* as environmental standards. Critical loads reflect, for a given ecosystem, the maximum amount of acid deposition at which no significant environmental damage is expected in the long run according to present knowledge, i.e. ecosystems should function normally as to reproduction and biomass stability (see Nilsson, 1986). The background analyses for the 1994 Oslo Second Sulphur Protocol soon revealed that it was not feasible to use critical loads as strict environmental standards. More relaxed targets for deposition loads of receptors had to be formulated. The principles for formulating such target loads became crucial as to fairness in a multinational setting of consensus decisions (see Tuinstra et al (1999) for a record of the discussion). Finally, the principle of closing the gap between the critical loads and some benchmark deposition levels with a *uniform* percentage was chosen; the *gap closure* principle, which aims for an equal *relative* reduction of excess deposition for all grid-cells[2].

But also when using the gap closure approach, it was quickly recognized that optimised cost-effective solutions might depend on the constraints of very few, in the extreme case on only one, grid-cell. In view of the uncertainty attached to the critical load levels involved in the environmental constraints, in order to aim for more robust optimisation results when negotiating the 1999 "Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone", the basic optimisation problem was reformulated by introducing a *compensation mechanism* (introduced in the Fourth Interim Report to the European Commission, DG-XI, February 1998, and developed further in the fifth and sixth interim reports, see Amann et al., 1998a,b). Over-shooting of grid targets was allowed provided compensation could be found within the same country. Such a compensation mechanism softened the spatial inflexibility of the environmental objectives for receptors that was essentially driving the basic model solution[3].

However, even with this compensation mechanism two grid-cells in Southern Norway made a solution with otherwise preferred targets infeasible when IIASA was preparing background

2 The Norwegian meteorologist Anton Eliassen introduced the idea.

3 A feasible solution with a very dominating constraint (for Germany) triggered the development of the compensation mechanism (personal communication from Markus Amann).

documentation for the 22nd session of the Task Force on Integrated Assessment Modelling in 1998. Initially these troublesome targets were neglected. The Norwegian Ministry of Environment requested some alternative simulations so that more reasonable targets for Norway could be established. The purpose of this paper is to provide a theoretical discussion as well as to report on the simulation runs on how the compensation mechanism worked in the case of the Norwegian grids. In the theoretical Section 2 we will use a pedagogical version of the RAINS model, as presented in Førsund (1999b), focussing just on a single pollutant (e.g. SO_2). However, we believe that the basic principles will be exposed within such a simplified framework. Generalisations can be done more or less straightforwardly. The different gap closure principles used is reviewed, and average accumulated exceedances introduced in the basic model. The compensation mechanism is introduced in Section 3. A theoretical discussion of this mechanism is provided, including showing how conditions for optimality change using the mechanism. The simulation runs using the full RAINS model, of the impact of different levels of targets for Norwegian grids is presented in Section 4, and results in the form of changes in accumulated acidity excesses and costs for the participating countries are reported. Section 5 concludes.

2. The Basic RAINS Model

The optimisation approach of the RAINS model used for background analyses during the negotiation process of the Oslo Protocol reflects the overall environmental policy objectives by specifying constraints on the maximum deposition. A cost-effective cooperative solution is then obtained by finding a spatial pattern of emissions that minimise total emission control costs over countries as sources, measured in a common currency (Euro) for the countries involved, that meet the specified constraints on deposition. The model version that is used for the simulation studies encompasses emissions of sulphur, nitrogen, ammonia, and volatile organic compounds, and addresses the environmental problems of acidity, eutrophication and ground-level ozone in each grid-cell. In order to bring out the essence of the change from “hard” environmental constraints to “soft” ones by introducing the compensation mechanism we will simplify the large-scale computer model by using one pollutant only[4], and specify a smooth purification cost function. The model structure is shown by the formal optimisation problem corresponding to the type of model used for the background scenarios for the Oslo Protocol:

$$\text{Min}_{e_i} \sum_{i=1}^{N} c_i(e_i^o - e_i, e_i^o)$$

subject to

$$e_i^{\min}(e_i^o) \le e_i \le e_i^o, i = 1,..,N \quad (1)$$

$$\sum_{i=1}^{N} a_{ij} e_i + b_j \le d_j^*, j = 1,..,R$$

where $c_i(.)$ is the control, or *purification*[5], cost function for country i ($i=1,..,N$), e_i^o is the reference emission from country i, e_i the emission, a_{ij} the atmospheric unit transportation coefficient from country (source) i to receptor j ($j=1,..,R$) (i.e., the EMEP grid-cells with a 150x150 km resolution in the RAINS model), b_j the background deposition and the variables d_j* reflect the environmental objectives specified as deposition targets. The model is static, but the reference emissions are for a future year and based on projections for use of different types of energy, agricultural activity, transportation, and some industrial process-industry activities. The best practice purification technology of today is assumed also to hold for the future year. Thus the RAINS model is used for exploring cost efficient allocations of emission reductions for a future year (e.g. 2010).

The reference emission, e_i^o, is shown explicitly in the cost function to enable an analysis of the impacts of changing these references. The formulation is also suitable for representing the actual piecewise linear cost function in the RAINS model (see e.g. Førsund, 1999b). The reference emissions are also present in the constraints on emissions, thus being crucial for the occurrence of

4 The reader may note that the joint interaction of sulphur and nitrogen in the creation of acidity is not represented, neither the non-linear ozone formation process.
5 Purification costs are used instead of the expression control costs or abatement cost to remind the reader that abatement in the form of reducing the production of goods generating emissions, or structural changes as changes in fuel mix, e.g. substitution of natural gas for coal, are not considered in the RAINS model.

infeasible solutions. We will return to this below discussing the solution to problem (1).

Gap closure principles

The environmental objectives, d_j*, are connected to the critical loads (CL), and they were originally termed *target loads* in the negotiation process (see Tuinstra et al., 1999). The calculations of target loads are based on the 1990 depositions as benchmark depositions, d_j^o, and the critical load for the ecosystems in each grid . The Coordination Center for Effects[6], which is a part of the LRTAP body, calculates the critical loads.

However, different principles have been used to calculate the targets (see Posch et al. (1999) and (2001) for definitions and a discussion of the principles). For the Oslo Protocol the principle was closing the gap between the benchmark deposition and the critical load for a grid. Other principles introduced later have been *ecosystem area* gap closure and *average accumulated exceedance* gap closure. The different principles are illustrated in Figure 1. The grid -cell is assumed to have eight eco-systems, and they are ordered according to increasing value of CL. The horizontal bars for each system from the vertical axis to the CL-values represents the eco-system areas. The CL cumulative distribution function is represented by the bold step-curve in Figure 1. Grid -cells may actually contain from a few to several thousands of eco-systems. (The most problematic Norwegian grid has 112 eco-systems.) The main types are forests of different tree species, lakes, grassland, bogs, moors, and tundra[7].

To apply a deposition gap closure principle the CL for the grid-cell has to be defined. It has been usual to define the CL for a grid -cell by having five percent of eco-system area unprotected. Let us assume that eco-system No.1 has an area share of five percent. The CL for eco-system No. 2 in the figure then determines the CL for the whole grid -cell. The gap to be closed with a given fraction (or percentage), x, is $(d^o - CL_2)$. The target deposition will then be

6 See Posch et al. (1995), Posch et al. (1997), Posch et al. (1999).
7 Details of distribution of types of eco-systems on countries and area covered are found in Amann et al. (1998b) and Hettelingh et al. (2001).

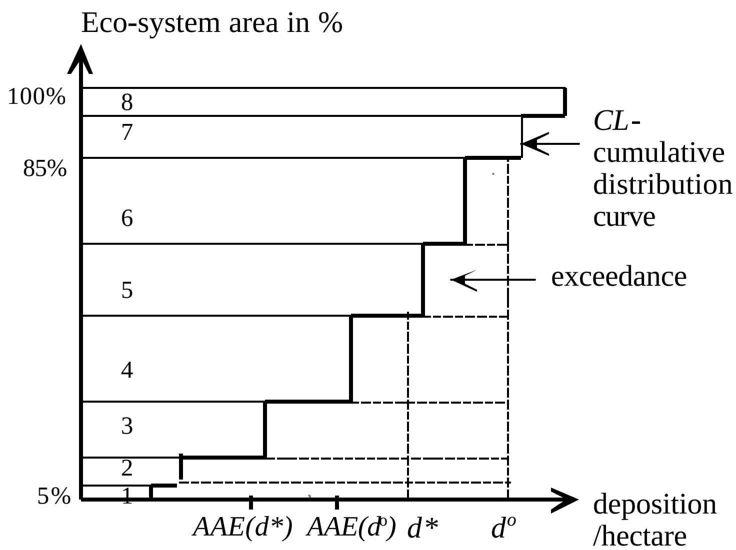

Figure 1. Gap closure principles

$d^* = (1\text{-x})\ (d^o - CL_2)$. In Figure 1 a gap closure of about $x = 1/3$ has been used, resulting in deposition d^*, protecting systems 5 and 6 in addition to 7 and 8 already protected at deposition level d^o.

A weakness with this principle is that the CL value representing the whole grid depends on only one observation on the CL distribution curve, and the resulting target load d^* is also one point on the curve. For different shapes of the CL distribution curve, but going through both the same CL grid value and the benchmark deposition value, d^o, we may then have quite different eco-system area protection.

The area gap closure principle focuses on reducing the unprotected area with a certain percentage. The percentage unprotected area in a grid is the share of the ecosystem area where the critical loads are less than the deposition. Let A_{ij} be the area of eco-system i in grid-cell j, and let S_j be the set of eco-systems in grid-cell j. We will partition this set into the unprotected eco-systems, $S_j^-(d) = \{i : CL_{ij} < d\}$, and the protected systems, $S_j^+(d) = \{i : CL_{ij} \geq d\}$ and obviously we have $S_j^- \cup S_j^+ = S_j$. In Figure 1 the ecosystems 1 to 6 belong to the unprotected set at the benchmark deposition level d^o, and eco-systems 7, 8 belong to the protected set. Eco-system area gap closure is usually interpreted as finding the deposition, d*, that corresponds to a given percentage, x, reduction of unprotected area at a benchmark deposition, d^o. Using our notation it means finding the maximal level of deposition d* satisfying:

$$\sum_{i \in S_j^-(d_j^*)} A_{ij} \le (1-x) \sum_{i \in S_j^+(d_j^o)} A_{ij}$$

In Figure 1 eco-systems 5 and 6 have about 45% of the total area of systems 1-6. Applying a gap closure fraction of e.g. 0.4 results in protecting systems 5 and 6, i.e. more than 40%, and corresponds to a deposition exactly equal to the CL of system 5. It is regarded as a weakness of the principle (see Posch et al., 2001) that since the CL distribution curve is a step curve, equality will in general not hold in the equation above when calculating target depositions, d*. This means that target depositions may vary over grid-cells also located in different countries, which may create problems of fairness. Also left out is the distribution of the *degree* of excess of depositions over eco- systems, it is just a question of protected or unprotected eco- systems.

The average accumulated exceedance principle focuses on the exceedances in each eco-system of a grid-cell. In Figure 1, the deposition of d^o represents an excess over critical loads in systems 1 to 6, as illustrated by the broken line extension of the area bar for eco-system 5. For a formal definition of the *average accumulated exceedance* for a grid-cell, consider an ecosystem, i, in grid-cell j. The *excess* for eco-system i, $EX_{ij} \ge 0$, is the difference between actual deposition, d_j and the CL_{ij}, and the average accumulated exceedance, AAE_j, is calculated by weighing each eco-system excess with eco-system area share:

$$\begin{aligned} &AAE_j(d_j) = \sum_{i \in S_j} \frac{A_{ij}}{A_j} EX_{ij} = \sum_{i \in S_j} Max\left\{\frac{A_{ij}}{A_j}(d_j - CL_{ij}), 0)\right\}, \\ &AAE_j(d_j) > 0, AAE_j' > 0 \;\; for \; d_j > Min \; CL_{ij}, \qquad (2) \\ &AAE_j(d_j) = 0, AAE_j' = 0 \; for \; 0 \le d_j \le Min \; CL_{ij}, \; i \in S_j, \; j = 1,..,R \end{aligned}$$

A_j is the total eco-system area of grid-cell j. The minimum CL is the CL for the first eco-system, i.e. No. 1 in Figure 1, since CL is the cumulative distribution function. In Figure 1 systems 1 to 6 contribute to exceedance illustrated by the continuation of the area bars with broken lines from the CL- values up to the d^o level, while systems 7 and 8 obtain the value of zero in the second expression in (2). There is a one to one correspondence between average accumulated exceedances and deposition d^o through the *AAE*-function for deposition values above the minimum CL of a grid-cell's eco-systems[8]. This value is indicated on the horizontal axis in the figure as $AAE(d^o)$. It is measured in the same units as depositions, and obviously we must have $AAE(d^o) < d^o$ (as long as $d^o > CL_1$, see (2)). The target for accumulated excess for a grid-cell, j, with x as the gap closure fraction, e.g. expressed as per cent, may be calculated as:

$$AAE_j^* = (1-x)AAE_j(d_j^o),\ j = 1,..,R\ , \qquad (3)$$

which implicitly gives a target also for depositions. As pointed out above there is a unique correspondence between depositions and *AAE*-numbers. Using (2) targets for average accumulated exceedance in (3) can be translated to targets for depositions. Assuming d^* in Figure 1 is such a calculated target, the target for average accumulated exceedance, $AAE(d^*)$, is indicated in the figure. We must have $AAE(d^*) < AAE(d^o)$ for $d^* < d^o$.

A measure based on average accumulated exceedances of depositions is more robust as to the location of the *CL*-function and also takes into consideration the whole distribution of excess. Notice that applying a gap closure to average accumulated exceedances we do not have to use a percentile as the lower limit to the critical load; there is no use for the concept of a CL for the whole grid. Depositions have to be reduced to a level less or equal to the CL of the most sensitive eco-system for no environmental pollution to occur. In the background work for the Gothenburg Protocol, the major targeting principle changed from deposition gap closure to eco-system area gap closure and finally to using average accumulated exceedances as the gap to be closed. But notice that it might not be unproblematic to sum together exceedances in different ecosystems. It

8 It should be mentioned that when addressing acidification in RAINS due to both sulphur and nitrogen unique CL *values* do not longer exist, but the problem is solved by measuring excess as the shortest distance from the deposition point for the substances to the now relevant concept of a critical load *function*, see Posch et al. (1999) and (2001).

implies that damages from exceedances are assumed to be directly comparable, as would be the case if damages were the same linear function of exceedance for all eco-systems in a grid-cell.

The cost-effective solution

Introducing the average accumulated exceedances gap closure principle the environmental constraint in (1) reads:

$$AAE_j(d_j) = AAE_j(\sum_{i=1}^{N} a_{ij}e_i + b_j) \leq AAE_j^* \tag{4}$$

Using (2) we may convert this constraint into a constraint formulated in depositions as in (1), but for a comparison with later development we will use the form (4). The Lagrangian for the cost minimisation problem (1) with (4) as constraint may be written:

$$\begin{aligned} L = & -\sum_{i=1}^{N} c_i(e_i^o - e_i, e_i^o) \\ & - \sum_{j=1}^{R} l_j \left[AAE_j(\sum_{i=1}^{N} a_{ij}e_i + b_j) - AAE_j^* \right] \\ & - \sum_{i=1}^{N} m_i(e_i - e_i^o) \\ & - \sum_{i=1}^{N} g_i(-e_i + e_i^{\min}(e_i^o)) \end{aligned} \tag{5}$$

The necessary first order conditions are:

$$c_i' - \sum_{j=1}^{R} l_j AAE_j' a_{ij} - m_i + g_i = 0 \;, i = 1,..,N \tag{6}$$

The first term is the marginal purification cost of country i, and the second term is the marginal evaluation of depositions resulting from emissions of country i. The term is composed multiplicatively of three components; starting from the last this is the deposition per unit of emission from country i ending up in grid-cell j, the next component is the marginal impact of this deposition on the average accumulated exceedances in grid-cell j, and the last component is the shadow price on the environmental constraint for grid-cell j. The shadow prices, l_j, on the environmental standards in the form of average accumulated excess are in general non-negative and only strictly positive if the corresponding constraint is binding. The shadow prices, μ_i and g_i, on the upper and lower constraints on emissions from a country cannot both be positive at the same time. If we are at the upper boundary μ_i will be positive and g_i zero, and vice versa at the lower boundary. For an interior solution both are zero. We then have the standard textbook condition: it is necessary for an optimal emission level that marginal purification cost equals the total marginal "shadow value" of unit depositions. Note that marginal purification costs differ between countries due to the country-specific atmospheric dispersion coefficients.

The shadow prices, l_j, on average accumulated exceedances constraints are in general interpreted as the change in the objective function of a marginal change in the constraint (evaluated at the optimal solution). Relaxing a binding constraint will in general improve the optimal value of the objective function; in our case it will decrease total purification costs. Tightening the environmental standard, i.e., lowering the average accumulated exceedances target, AAE_j*, will impose an increased cost in the aggregate on the participating countries.

An infeasible solution to problem (1) means that we cannot find an admissible emission vector that satisfies all the constraints. Specifically, even using all purification possibilities to the maximum, implying by definition that emissions are set at minimum levels, $e_i^{\min}$, for all countries, will lead to one or more deposition constraints being violated. Using critical loads as target loads within the model version used for the Oslo Protocol background studies lead to such an infeasibility, and made the development of target loads necessary. However, it should be born in mind that the benchmarks, e_i^o , are kept fixed. By reducing these exogenous variables more room is created for satisfying constraints, keeping the same targets. Reduced levels may be obtained by restructuring the sectoral composition of the economy or simply holding back on economic growth[9].

Returning to a feasible solution, if we have dominating upstream-downstream configurations as to transboundary flows of pollutants, it is to be expected that many constraints will not be binding, i.e. average accumulated exceedances or depositions will be below targets in these grids. Among the participants at the UN/ECE task force meetings discussing model results it has been expressed

9 This is actually an alternative to using resources on purification. This aspect of the RAINS model is addressed in Førsund (1998).

concern with the “zero- one” nature of environmental considerations. Only binding constraints influence the optimal cost-effective solution, while enjoyment of cleaner environments than specified by targets loads does not count. We will return to this point in Section 5.

3. Softening hard environmental constraints

The use of the basic model (1) with deposition gap closure soon met with problems of infeasible solutions, solutions being driven by just a few environmental constraints, and instability of solutions (in the sense that small perturbations in exogenous data would lead to significant changes in the spatial distribution of depositions and costs while the value of the objective function remained almost the same). Mainly due to cost considerations the negotiating countries was seeking an interim solution on the way to the ultimate goal of achieving critical loads everywhere. It turned out that even for politically realistic ambition levels when formulating target loads within the gap closing mechanism, the model may yield infeasible solutions, as explained above.

The solution to the infeasibility problem when using the RAINS model for negotiating process leading to the 1994 Oslo Protocol was to remove grid-cells that caused the infeasibility for an otherwise acceptable deposition gap closure level (60%). Such a procedure removes any influence of the problem grids on the solution and may be questioned both from a scientific - and policy point of view of the concerned countries.

The Compensation Mechanism

Instead of focussing on environmental targets for individual grids as constraints, the compensation mechanism keeps the grid-specific targets for average accumulated exceedances, but as a constraint takes the total average excess deposition within a country (or more generally a group). A positive a violation in one grid-cell, as illustrated in Figure 1 with $AAE(d^*) < AAE(d^o)$, can be compensated by a *negative* “violation” in another grid. Notice that according to the definition of average accumulated exceedances in (2) a deposition below the minimum critical load for the eco-systems of a grid-cell cannot be used for compensation. *AAE* is zero until the minimal CL is exceeded. Actual average accumulated exceedances below the target exceedances, $AAE_j(d_j) < AAE_j^*$ in gird-cell j, can be used to compensate overshooting the target, $AAE_f(d_f) > AAE_f^*$, in another grid-cell, f, of a country.

The arguments put forward for introducing a compensation mechanism as an option varies. Amann et al. (1998b) convey the arguments well (p. 99):

> In order to limit the potential influence of small and perhaps untypical environmental receptor areas on optimised Europe-wide emission controls and to increase the overall cost-effectiveness of strategies, a mechanism was developed to tolerate lower improvements at a few places without discarding the overall environmental ambition level.

There are technical concerns like problems of infeasibility and robustness (lack of stability) of a solution, and more user-based strategic concerns about a few grid targets driving the solution and "holding up" scenarios viewed as more "balanced" or appealing. It is easy to understand less enthusiasm for hard targets by delegates from countries not influencing the solution via their own targets, but facing the bill for a few targets being fulfilled[10]. People may feel more comfortable with a solution strategy where a number of spatially more balanced restrictions influence the solution. A rationale for the specific design of the mechanism may be that countries are more concerned with total (harmful) excess deposition within their whole territory than about excess deposition of solution on the way to the ultimate goal of achieving critical loads everywhere.

Alternative ways of meeting this problem have been proposed in the literature. Batterman (1992) introduced a sub-square approach by grouping ecosystems within a grid-cell into unattainable and attainable shares with respect to critical loads at maximal purification. Then *relative* critical load coverage was used for the attainable part, and a deposition reduction goal was introduced for the unattainable.

10 The feeling of paying "too much" may be misplaced in view of distributions of environmental costs and improvements see Wolfgang (2001).

Ellis (1988a,b) advocated a multi-objective approach including a weighted sum of deposition violations in the objective function, and introducing excess depositions as endogenous variables (see Gough et al. (1994) for an exposition). In the latter paper the problem formulation in (1) is turned around and weighted exceedances are minimised subject to a total cost constraint and the transportation matrix as in (1)[11]. The weights were called slopes of damage function, and the possibility of performing cost benefit analysis is mentioned. However, one should be careful with using such a model framework for this latter purpose, see Førsund (1999a) and (2000) for clarification.

As mentioned in Section 1 and in Gough et al. (1994) reformulations of how to calculate intermediate targets have helped towards relieving problems caused by few binding grids and instability. Basing the gap closure on accumulated excess reduces the dependency on single very sensitive ecosystems, and reflects better the whole distribution of critical loads, as discussed above.

In order to set up the formal model encompassing the compensation mechanism let us allocate receptors uniquely to each country (another grouping may easily be used) and for simplicity assume that no receptors are shared (this assumption can also easily be generalised). The set L_k is the set of receptors within country k, and the sum of receptors over all countries is equal to R. Let us further introduce I as the set of N countries, and M as the set of R receptors. The average accumulated exceedances gap closure principle is used. The cost efficient allocation of emissions is then found by solving the following problem:

11 This approach has been presented at a succession of meetings in the UNECE Task Force of Integrated Assessment Modelling by researchers from SEI (Stockholm Environmental Institute at York).

$$\text{Min}_{e_i} \sum_{i\in I} c_i(e_i^o - e_i, e_i^o)$$

subject to (7)

$$e_i^{\min}(e_i^o) \le e_i \le e_i^o \;, \forall i \in I$$

$$\sum_{j\in L_k}\left[AAE_j(\sum_{i\in I} a_{ij}e_i + b_j) - AAE_j^*\right] \le 0 \;, L_k \subset M, \forall k \in I$$

For notational ease the index, j, for grid-cell receptor on the average accumulated exceedances function, transportation coefficient and background deposition is kept as before without country identification. The R receptor deposition constraints in the basic model (1) are replaced by N country balance constraints (in the recent implementation of RAINS, R is of the order of above 700, and N is about 38). The grid constraints involving the environmental targets, AAE_j*, in the basic model (1) with (4) as constraints are called "hard" because all grid-cell targets have to be satisfied, while using the country balances in model (7) the environmental targets are called "soft" because they may be exceeded, provided compensation can be found in other grid-cells. Notice that that there is no longer a one to one correspondence between using depositions and accumulated exceedances in the environmental constraint as it was for the basic model, unless the AAE-functions in (2) are all the same linear function.

The Lagrangian for the cost-effective allocation model with the compensation mechanism and average accumulated exceedances gap closure principle is:

$$\begin{aligned} L = & -\sum_{i\in I} c_i(e_i^o - e_i, e_i^o) \\ & -\sum_{i\in I} m_i(e_i - e_i^o) \\ & -\sum_{i\in I} g_i(-e_i + e^{\min}(e_i^o)) \\ & -\sum_{k\in I} f_k [\sum_{j\in L_k} (AAE_j(\sum_{i=1}^{N} a_{ij}e_i + b_j) - AAE_j^*)] \end{aligned} \qquad (8)$$

The necessary first order conditions are:

$$c_i' - \sum_{k\in I} f_k \sum_{j\in L_k} AAE_j' a_{ij} - m_i + g_i = 0 \;, i = 1,..,N \qquad (9)$$

The shadow prices for the limits of emissions, μ_i and g_i, have the same interpretation as for the basic model. The discussion of these shadow prices is therefore not repeated. Assuming an interior solution (i.e., both μ_i and g_i are zero), we see that marginal purification costs should be equal to an expression involving sums over the country grids of unit transport coefficients multiplied with marginal derivatives of the average accumulated exceedances functions, and then multiplied with country shadow price, f_k, and summed over countries.

Note that the evaluation of deposition to a grid-cell of country k is the same for all of its grids. As long as the country balance is binding an emission reaching a grid-cell with average accumulated exceedances lower than the target has the same shadow cost as emission reaching a grid-cell with an excess over the target. Shadow prices of country balance constraints can be interpreted as the impact on total purification costs of all countries if the constraint is relaxed marginally, i.e., of a marginal increase in the room for violation. As we have set up the Lagrangian function, the impact on costs is negative when the violation constraint is relaxed. Using the envelope theorem we have that the marginal impact of increasing a target load for a grid within a binding country constraint is evaluated at the shadow price of the country balance. A relaxation of a target for a grid j in country k decreases total purification costs with the amount expressed by the country k balance shadow price. The concept of a *hot spot* characterising a grid-cell with a binding constraint in the basic model is replaced by a *hot country* in the case of only country balances being binding.

We must typically have at least one country balance being binding for environmental considerations to influence the solution to problem (7). Shadow prices on country balances are only strictly positive if the constraints are binding. For such countries the environmental targets only holds on average, and we must have that one or more of the average accumulated exceedances targets in the country are violated compared with the basic model, assuming the same targets. The country balance cannot typically be binding if no average accumulated exceedances targets are exceeded. But notice that one or more targets may be exceeded without the country balance constraint being binding.

With the compensation mechanism there are no longer shadow prices on the *hard* constraints on average accumulated exceedances targets for individual grid-cells, but shadow prices on the country balances instead. To illustrate the difference between the hard and soft constraints models let us assume that a country with some binding and some non-binding grid-cell constraints in the basic model (1) - with (4) as constraints - now has a binding country balance in model (7) with the same targets for grids. The shadow prices that in the basic model consist of zeros and different positive numbers will now, with the compensation mechanism, in a way be *aggregated* to a common positive value for all grid-cell average accumulated exceedances. Comparing the expressions for total marginal evaluation in (6) and (9), we have that the grid-specific shadow prices, l_j, in a sense are averaged into country shadow prices, f_k, for country k grids. It is tempting to conjecture that this average shadow price is lower than the average of the positive prices in the basic model, but this may not be the case in general. A shadow price on a country balance may also get an extreme value. If only one country had binding grid-cell constraints in the basic model, and only one and the same country a binding country balance, and if all target loads are the same, then this will be true.

The marginal costs are still country-specific as in the basic model. It is in general the country-specific atmospheric dispersion coefficients a_{ij} that give rise to country-specific marginal costs. Whether the differences between marginal costs are larger or smaller in the model with compensation mechanism follows the reasoning for the shadow prices above. Actual experience with the full-scale model is that decreased purification in one country leads to increased purification in other countries with emissions reaching the same countries with binding constraints.

The question may be asked if the solution to the problem with the compensation mechanism implies *higher* overall emissions than in the basic model. However, there is no unique answer to this question, and the question is not really interesting within our framework with an emphasis on the spatial distribution of deposition. We can state in general that an optimal solution with the same grid-cell targets to the basic model (1) is always an admissible solution to model (7), but not vice versa. Therefore the solutions with respect to total costs will either be identical (border case), or the model with the compensation mechanism will yield smaller total costs. Intuitively, since the objective functions of the two problems (1) and (7) are the same, and the country balances are summations of constraints in the basic model (with the average accumulated exceedances constraint (4)), for identical deposition targets in general the total optimised purification costs must be *less* with the compensation mechanism.

Although exceedances for individual eco-systems within a grid is already summed together within the accumulated exceedances gap closure approach, one may feel uncomfortable with summing together exceedances for *different* grids belonging to the same country within the compensation mechanism. The RAINS model opens for using grid-specific weights on exceedances (see Makowski et al. (1998) for details):

$$\sum_{j\in L_k} w_{kj}\,[AAE_j(\sum_{i=1}^{N} a_{ij}e_i + b_j) - AAE_j^*] \le B_k \;, k\in I \;, L_k \subset M \qquad (10)$$

where w_{kj} is the weight assigned grid j in country k. The average of the average accumulated exceedances used as a constraint may also be generalised to a number different from zero[12]. The balance of country k is B_k (a positive (negative) number increasing (decreasing) the scope for violations). Notice that the introduction of weights, w_{kj}, may be seen as a step towards a *damage function* for grids as is standard in environmental economics (see e.g. Baumol et al., 1988); lake-grids are weighted relative to forest grids, etc[13].

As a further safeguard against unduly exceedences in sensitive grids a constraint may be added to the problem (7) to ensure that the exceedances of a target, AAE_j^* for a grid-cell j in a country is limited (by a given positive number, h_j), thus preventing unintentional environmental “disasters”

12 In the discussion of emission trading between countries at UN/ECE Task-force level country balances opening up for the average target load being violated by a fraction were introduced, see Førsund and Nævdal (1998).

13 To our knowledge weights w_{kj} have all been set to 1, and zero have been used for country balances B_k in official scenarios.

due to using the mechanism[14]:

$$AAE_j(\sum_{i=1}^{N} a_{ij}e_i + b_j) - AAE_j^* \leq h_j > 0\ ,\ j = 1,..,R \qquad (11)$$

This limit may be set uniform for all grids, as in Amann et al. (1998c)[15]. Note that if the upper limits, h_j, are set to zero, we are back to model (1). A binding constraint for a grid implies that the shadow price is positive, and there will be an extra term in the first order condition (9) consisting of the sum of positive shadow prices on (11) weighted with the relevant transportation coefficients. The marginal cost will *cet. par.* increase. However, as noticed above, when one country increases purification one or more other countries usually decrease purification, so the impacts are not so straightforward to predict. We may have a solution with no binding constraint (11) for exceedances of targets. Then at least one country balance constraint must be binding. But more interestingly, now we may also have *no* country balance binding if a constraint (11) on the excess over target is binding.

14 Note the similarities with mechanisms for emission trading between countries elaborated at UNECE Task-force level (see Klaassen et al.,1994).Trade between countries implies that some deposition levels may be increased, but various balancing constraints may be added (Førsund and Nævdal (1998)). Ho wever, whereas the idea of emission trading was met with hostility the compensation mechanism has been introduced in RAINS without much discussion or attention.

15 The concern expressed by the constraint may also be implemented as an upper (uniform) limit on the exceedance of the CL for a percentile (e.g.2%) of the critical load distribution within a grid, see Seventh Interim Report.

4. The compensation mechanism simulations

Background for the simulations

In the fifth and sixth interim reports from the TAP project at IIASA, it was suggested that targets for acidification should be set differently for Norwegian grids than for grids in the rest of Europe. The reason for this is that the cost-minimising strategy for reduced acidification in Europe becomes very expensive if the target for relative improvement in two EMEP grids in Southern Norway (with grid coordinates 17/19 and 17/20 (the most studied Birkenes grid) in the EMEP model) is the same as the targets for relative improvement in the rest of Europe. For ambitious targets it is even impossible to obtain the required improvement in the two grids for the abatement strategies considered in the RAINS model. As a consequence, there were no targets for acidification in the two grids in the scenario called E8/2 of the fifth interim report, while the F8 scenario of the sixth interim report required much smaller relative improvement for these grids than for other grids (80% versus 95% exceedances gap closure).

One may argue that the targets for reduced acidification in two grids in Norway should have only limited influence on the all-European abatement strategy for reduced acidification. On the other hand it seems illogical to totally ignore those environmental targets, which are relatively hardest to obtain. After all, there are ecological reasons for low critical loads and strict targets for acidification in Southern Norway. Therefore, in the wake of these interim reports, it was a strong Norwegian interest for sensitivity analyses that could establish reasonable targets for Norway in the all-European optimisation.

The settings for the model runs

The general settings of exogenous variables and parameters in the simulations were quite similar to the ones used in the sixth interim report. Therefore, only limited information about the settings are presented in this paper. As to gap closure, the gap is the accumulated excess in 1990 (the benchmark year), $AAE(d^{1990})$, minus 5 eq/ha. The subtraction (somewhat ad hoc) was introduced to further relieve the problem of influential grids with low critical loads of the eco-systems. A 95% gap closure target is in general the level of accumulated excess that reduces the benchmark accumulated excess by 95%. The gap closure share is given by *x* (see (3)):

$$AAE^* = AAE(d^{1990}) - (AAE(\mathrm{d}^{1990}) - 5) \cdot \mathrm{x} \qquad (12)$$

Due to the subtraction of 5 in (12) the gap closure percentage is somewhat less than 95%.

The targets are also influenced by the depositions in a scenario called the *reference scenario* (d^{REF}). In this scenario the emissions are set to the minimum of what is already agreed upon in protocols, and in addition calculated using current legislation on emission standards and energy projections for the year 2010. If, for a particular grid, the gap closure target in (12) is larger than the calculated accumulated excess in the REF scenario, $AAE(d^{REF})$, then the latter is used as target. Also, if the minimum of the gap closure target and the calculated accumulated excess in the REF scenario is less than 5 eq/ha, then the target is 5 eq/ha:

$$AAE^* = \max\left\{\min\left\{AAE^*(1-x), AAE(d^{REF})\right\}, 5\right\} \qquad (13)$$

Using the compensation mechanism should reduce the influence of single grids like the two sensitive Norwegian grids in the optimisation. In addition two other measures were introduced to reduce the impact of single grids: Norwegian grids are given a smaller gap closure than other grids, and by subtraction of 5 eq/ha in (12) all targets increase with 5x%. This increase in targets might reduce the influence of those targets that are hardest to achieve.

Along the lines of the F8 scenario of the sixth interim report, a 95% gap closure is chosen for all grids outside Norway. In addition some grids in the North were treated as grids outside Norway since Norway touches these grids only marginally. Since all the Norwegian grids are modified, it will typically be some violation in the two Southern grids in the optimal solution. This feature might be blurred if targets where modified for these grids only. Therefore, all the Norwegian targets are modified. The targets in Norwegian grids at different gap closures from 70% to 93% are presented in Table 1. Targets that are equal to 5 eq/ha in all gap closure scenarios are not shown. Gap closures at 70% and less yields targets corresponding to the REF depositions, while gap closures at 93% and more are infeasible. Targets termed *base targets* are the 1990 accumulated exceedances. Running the optimisation with these targets for the Norwegian grids is defined as the *base scenario*. The influence of setting targets using the rule (13) in Norwegian grids is therefore discovered by the difference between the base scenario and the other scenarios. Notice that the two problem grids, 17/19 and 17/20, are the ones with the highest excesses and targets of all the Norwegian grids (see Table 1).

In principle the abatement costs is minimised subject to the country balance constraints. However, in the RAINS model the objective function consists not only of the abatement costs. There is also a linear penalty term in violation of targets in grids. In addition there is a *regularisation term* that causes some stability towards a reference level of emissions in

Table 1. Targets in acidity equivalents per hectare (eq/ha) accumulated excess (AAE) in Norwegian grids

Grids	**Gap closure levels (x) in % of average accumulated exceedances**											**REF 2010**	**Base 1990**
	93	92	91	90	89	87	86	85	80	75	70		
17/19	63.3	71.7	80.0	88.3	96.7	113.3	121.6	130.0	171.6	213.3	241.2	241.2	838
16/20	33.2	37.2	41.2	45.2	49.3	57.3	61.3	65.4	79.0	79.0	79.0	79.0	467
17/20	51.2	57.8	64.4	71.0	77.6	90.7	97.3	103.9	136.9	169.9	199.3	199.3	665
18/20	36.6	41.1	45.6	50.1	54.6	63.6	68.1	72.6	77.5	77.5	77.5	77.5	456
15/21	16.7	18.4	20.0	21.7	23.4	25.1	25.1	25.1	25.1	25.1	25.1	25.1	172
16/21	14.0	15.2	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	15.6	133
17/21	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	9.3	105
18/21	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	13.7	157
17/23	6.5	6.8	7.0	7.2	7.4	7.4	7.4	7.4	7.4	7.4	7.4	7.4	27
15/31	5.9	6.0	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1	18

case of no unique local optimum[16]. The values on penalty and stability where set equal to the values used in the sixth interim report. The databases on abatement costs, critical loads, atmospheric transport coefficients etc. were the state of the art at the TAP project when the simulations were performed between the sixth and seventh interim reports.

In accordance with the interim reports, the emissions of SO_2, NO_X, *VOC* and NH_3 are constrained to be no larger than the REF - emissions. Notice that these constraints ensure that the accumulated acidity excess, caused mainly by SO_2 and NO_x emissions, is below the $AAE(d^{REF})$ in all grids. The REF part of targets might therefore seem unnecessary. However, the REF part guaranties that contributions compensating for increased depositions elsewhere is only consisting of accumulated excess less than the amount corresponding to REF exceedances.

The results of the simulations

The optimal emissions and control costs for each country are outputs from the simulations, in addition to the accumulated excess in every grid. The outputs from the simulations do not show which country balances are binding, nor the shadow prices on the binding constraints. We present instead the total impacts of different gap closures in the Norwegian grids in Figures 2-4.

Each scenario is labelled according to the gap closure level in the Norwegian grids. The gap closure in the Norwegian grids in the scenarios t89 and t90, etc. is 89% and 90% respectively, while the gap closure in all other grids is 95% in all scenarios. In Figure 2 we can see that the increased gap closure yields increased costs and reduced accumulated excess in Europe. Of course, stricter targets in Norway will yield deposition reductions elsewhere in Europe too. The largest calculated gap closure is 92% since the 93% gap closure was infeasible. The 75% gap closure scenario is close to the base scenario. This might be surprising at first since there are

16 See Makowski et al. (1998) for details. However, the explanations are rather short. It may seem that also negative violations of targets are penalized, and the nature of the reference emission levels in the regularization term, forcing the solution in case on no unique local optimum, is not elaborated upon.

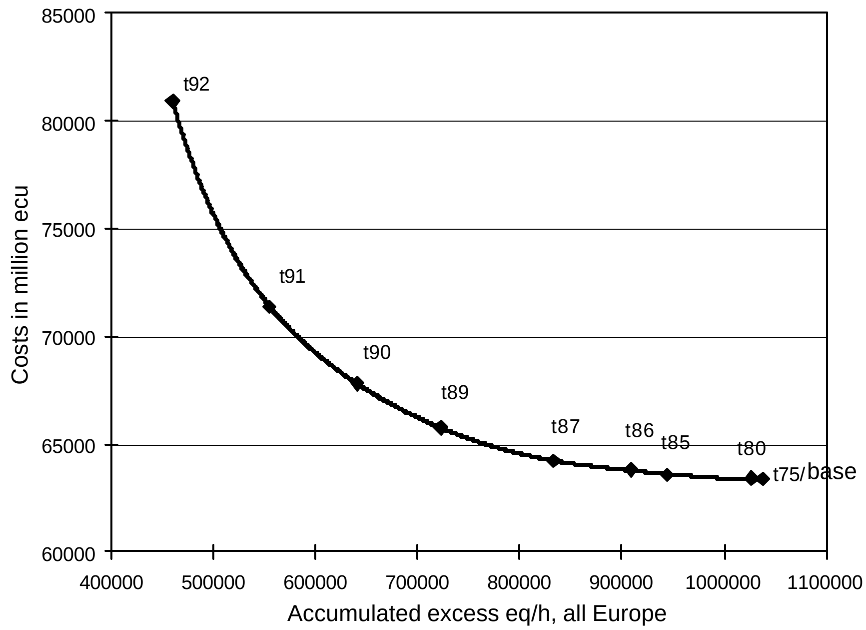

Figure 2: Costs and accumulated excess

substantial differences in targets. However, the emissions are constrained to be no larger than in the REF scenario. Therefore, the deposition will never be larger than the depositions in the REF scenario. Also, the targets at 75% gap closure are equal to the REF accumulated excesses for all grid-cells except 17/19 and 17/20. This explains why the t75 scenario is close to the base scenario. Since a 70% gap closure yields REF deposition targets, it is also evident that gap closures less and equal to 70% has the same effect as removing the Norwegian grids from the optimisation problem. Consequently the Norwegian grids have no impact on the optimisation in the base scenario, and changing the targets for the Norwegian grids causes all changes from this scenario. At gap closures up to 80%, the targets in Norwegian grids have insignificant impact on the optimisation results for costs and exceedances in the rest of Europe. At gap closures between 80% and 85%, the Norwegian grids have some impact on accumulated excess. However, the impact on costs is still insignificant.

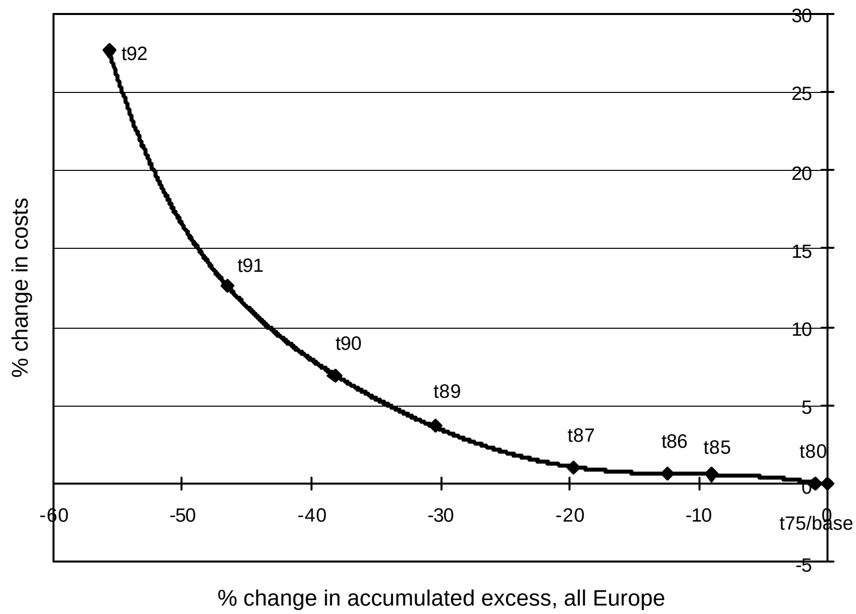

Figure3: Changes from base scenario

It may be more informative as to locating when significant changes occur to look at relative changes from the base case. In Figure 3 the percentage changes in European costs and accumulated excess are presented. Clearly, the targets for Norwegian grids have impacts on accumulated excess if targets are above 80%, the accumulated excess being reduced by 9% going for the 85% gap closure, and a further reduction of 11% to the 87% gap closure. But the relative cost changes are small up to the 87% gap closure, only 1.3% from the base scenario. So at the 87% gap closure level, total accumulated excess in Europe is reduced by almost 20% while the costs is increased with only 1.3% from the base case. However, starting from 87% gap closure, the targets in Norwegian grids have significant impact on costs too, and this impact increases rapidly as targets get stricter. From the 87% gap closure to the 89% costs increase with a further 2.4% while accumulated excess is reduced with additional 10%, but then the costs increase more rapidly. To go from the 91% gap closure to the maximal feasible 92% the costs increase with 15% and accumulated excess is further reduced with 9%.

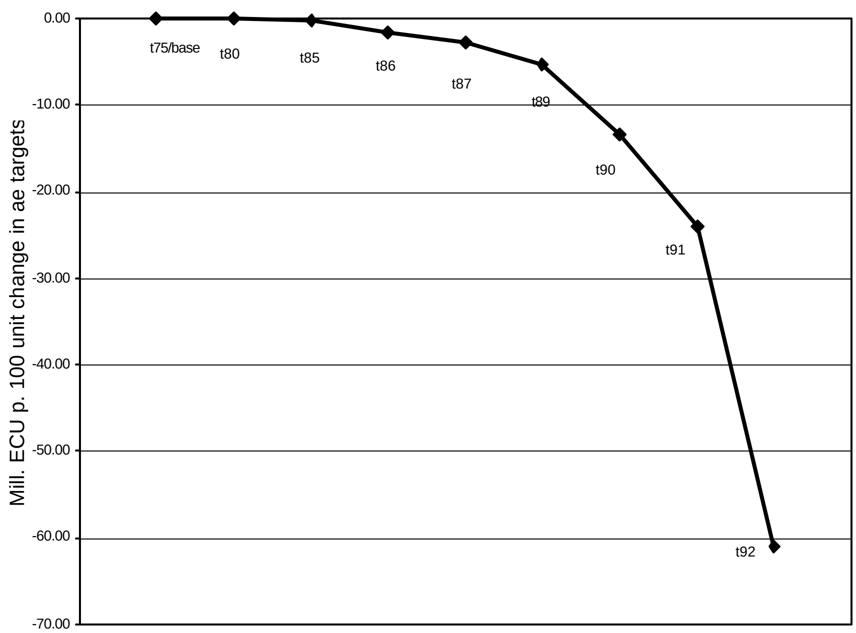

Figure 4. Estimated shadow price on the Norwegian country balance

The change in the objective function when constraints are changed marginally is called the shadow price of the respective constraint. In our context the relevant shadow price is the change in total costs if the Norwegian country balance is changed marginally. The Norwegian country balance must be binding when changing targets for Norwegian grids change the costs and depositions for other countries. As pointed out in Section 3 the shadow price on the country balance also measures the impact of changing accumulated acidity targets (identical effects for all targets), using the envelope theorem (disregarding the limit on exceedances violation and the optional penalty term in the objective function of RAINS). Unfortunately, as mentioned above, there is no shadow prices reported in the output of the available version of the RAINS model with compensation. However, the shadow price on the Norwegian country balance can be average approximated. For instance, the shadow price for the 90% gap closure is calculated as the change in costs from an 89% gap closure to a 90% gap closure, divided by the change in the Norwegian exceedances, etc. The estimated shadow prices are presented in Figure 4. The shadow price is close to zero at gap closures less than 85%. Between 85% and 89% the shadow price increases steadily, while it is accelerating from the 89% level, and is increasing with about 160% from gap closure 91% to 92%. At UN/ECE task force meetings "knuckle points" of total purification cost curves have been identified in other contexts and been selected as suitable ambition levels for emission reductions. Such a knuckle point seems to be located in the interval of 87 to 89% gap closure for the Norwegian grids. Changing the binding targets always yield changed costs and depositions. If the distribution of change in costs and accumulated excess where evaluated for all possible target combinations in Europe, the mass of information would be unmanageable. The exploring of distribution changes caused by targets in single counties might therefore be an unfruitful sidetrack. Still, since attention has been focussed on Norwegian grids it may be of interest to report on the distribution of costs increases and environmental benefits in terms of reduced exceedances when the Norwegian targets are varied.

In Figures 5 and 6 the relative changes in accumulated excess (AE) and costs compared to the base scenario, is presented for Norway and Europe in total[17]. From Figure 5 it is clear that Norway only experience approximately the same percentage improvement as the total of Europe when the targets in Norwegian grids are taken into consideration. At cap closures between 80% and 87% Norway in fact experience less percentage improvement than the total. These results might seem strange, but they are quite understandable. UK is for instance a major contributor to acidification in Norway. Therefore, the UK emissions are typically reduced when targets are made stricter in the Norwegian grids. However, only a small fraction of the UK emissions results in depositions in Norway. In fact, the grids in UK benefit much more from reduced UK emissions than grid-cells in Norway. The depositions resulting from UK SO_2 emissions for 1990 are affecting England most, then Scotland, Wales, Ireland, and to the west Norway, Southern Sweden, Denmark, Germany, Be-Ne-Lux and France and even further westward.

17 For theoretical work that explores the effects of changed targets see Wolfgang (2001).

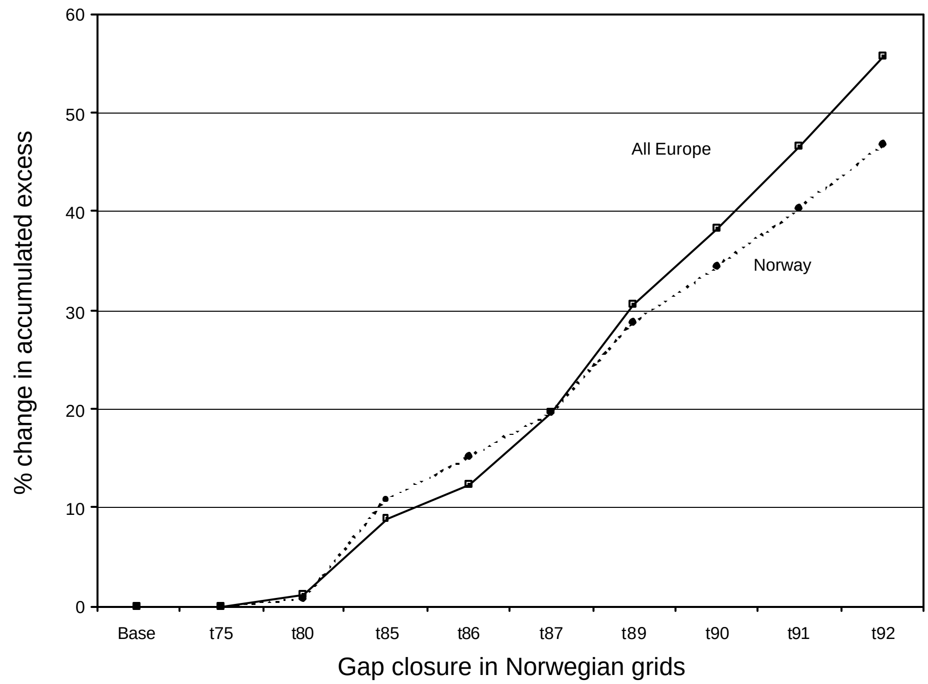

Figure 5: Change in accumulated excess from base case

The relative costs changes presented in Figure 6 show that Norwegian abatement costs is relatively more sensitive to the targets in Norwegian grids than the total European abatement costs. This reflects that a large share of the Norwegian emissions yield depositions in Norwegian grids. Norwegian SO_2 emissions (in 1990) mainly end up in Norwegian grids. The reduction in accumulated excess is about average in Norwegian grids, and the Norwegian costs increase relatively more than the total costs in Europe. A claim that the Norwegian targets make the rest of Europe pay for environmental improvement in Norway can therefore be questioned.

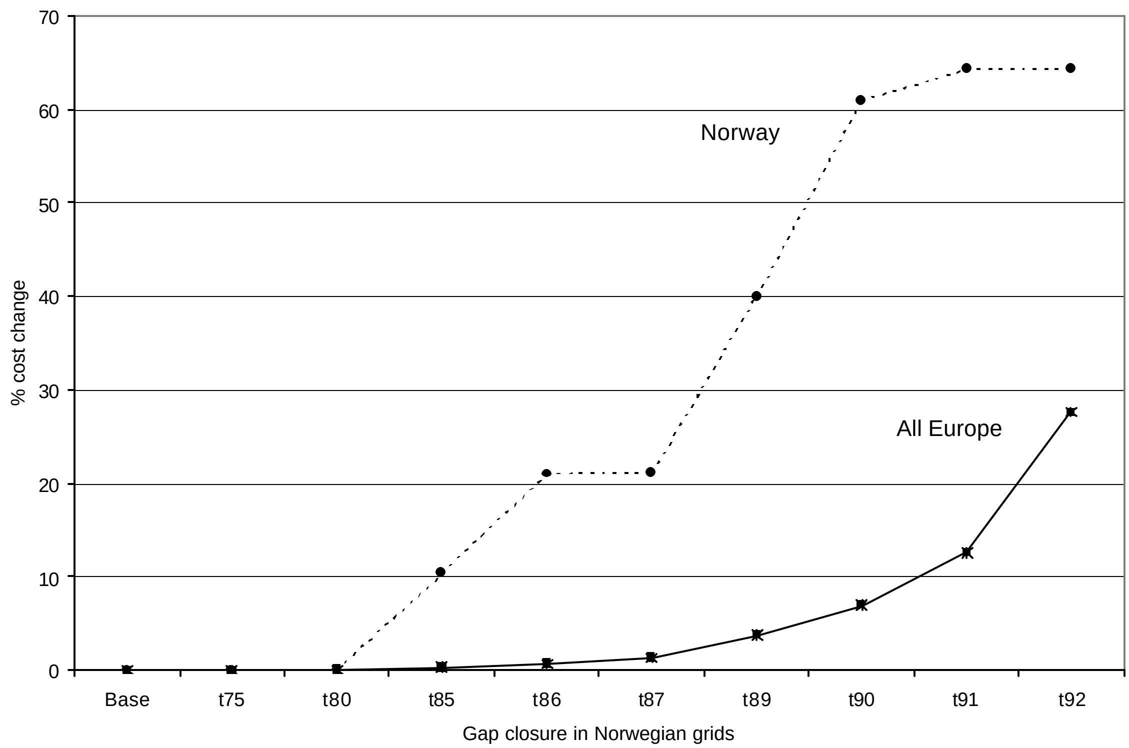

Figure 6. Change in costs from base scenar io

5. Conclusions

The original RAINS model has been continuously developed and extended to be able to serve the needs of cooperation in Europe to reduce trans-boundary air pollution problems. The model has been used for scenario analyses of spatial patterns of pollution not only from acidity, but also lately ground level ozone and eutrophication. The optimisation runs to explore cost-effective emission reductions have been most influential in choosing an interim strategy for emission reductions towards the ultimate goal of keeping loads in Nature within critical loads.

The structure of the optimisation model was that European-wide purification costs constitutes the objective function, while environmental goals have been entered as constraints. However, problems of infeasibility of solutions and solutions driven by a few, or in the extreme, only one constraint, lead to the development of several ways to relieve such influence. One such development in the focus in this paper was the compensation mechanism. The countries negotiating the 1994 Oslo Protocol accepted the interim strategy of closing the gap between some benchmark loads on the environment with the same relative factor for all receptors irrespective of country, as fair, but when negotiating the Gothenburg Protocol it was accepted to introduce the compensation mechanism. This compensation mechanism relaxes the spatial rigidity of the environmental constraints within each country. Overshooting a target load at one receptor can be compensated by depositing less than the deposition target constraint (but compensation is only allowed as long as depositions are above critical loads) in other receptors within the same country. As an analogy one can say that the compensation mechanism allows a country *emission trading* between its own receptors (see, e.g., Klaassen et al. (1994) and Førsund and Nævdal (1998) for emission trading building on RAINS).

Comparing the basic model without the compensation mechanism and the revised version with the compensation mechanism we conclude that in general total purification costs are lower with the compensation mechanism, given the same target loads. This is the *reward* for relaxing a strict spatial compliance with the environmental standards. But on the other hand it must be noted that targets that were hard or costly to be achieved now are permitted to be exceeded, and the compensation gained other places may not be in accordance with environmental preferences. Seen from the perspective of emitting countries all receptors of a receiving country with a binding country balance constraint have the same shadow evaluation, irrespective of the differences in target loads reflecting different environmental sensitivities to deposition, assuming that the “safety valve” (11) of restricting exceedances violations is not binding. The key question is how the “hard” constraints are interpreted concerning fairness of interim solutions. Is the spatial rigidity really wanted? If yes then the compensation mechanism should only be used if the nature of an “uncompensated” solution raises concerns about the robustness. The compensation mechanism is an available *option* in the RAINS optimisation model. Using the compensation mechanism as a general standard implies a change in the interpretation of the fairness principle of gap closure, from strictly applied to each receptor, to a more relaxed interpretation focussing on each country's deposition balance relative to its deposition targets.

The reason why the Norwegian grids were given special treatment in the use of the RAINS model by IIASA was that "hard" targets had "too" large influence on optimisation. However, one must accept that they have some influence. After all, the aim cannot be to ignore acidification problems in Norway. Historically this problem was one of the main reasons for the European concerns on trans-boundary air pollution[18]. Therefore, taking out Norwegian grids where targets were impossible or very expensive to obtain cannot be a satisfactorily approach. The purpose of the compensation mechanism was to treat problem grids in a better way, but this was not enough for high ambition levels.

The general approach of the simulations has been to use a range of gap closure values on accumulated acidity for Norwegian grids, keeping the gap closure at 95% for all other grids in Europe. Our results show that a gap closure of the level of 87% has substantial influence on accumulated excess in Europe, but only a small influence on costs. However, from this point on the targets have more significant impacts on costs, too. At a gap closure of 89% the change in total costs is still below a 4% increase from the base scenario, but the approximated shadow price on stricter targets in Norwegian grids accelerates from this level. There seems to be a "knuckle point" on the interval 87 – 89% gap closure. However, a gap closure of 85% was chosen for the key scenario (called medium ambition G5/2 in the sixth interim report, or central scenario J1in the seventh) of the negotiations with reference to the simulations reported in this paper, although there seems to be room for a somewhat higher ambition level. In Amann et al. (1998c) the term cost effectiveness of emission reductions seems to be used in the meaning of the reduction in exceedances obtained per Euro. The 85% ambition level for the Norwegian grids implies about

18 See Alcamo, Shaw, and Hordijk (1990), chapter 2.

the same reduction per Euro of total purification costs as a 95% ambition level elsewhere. However, such considerations are not expressed by the model formulation (7). The format is still total purification cost minimisation subject to environmental constraints. If other criteria or types of cost – benefit considerations are wanted, the model set-up should change accordingly. It is difficult to see how different spatial distributions of pollution can be compared without addressing the question of how to compare environmental *damages* at individual grid-calls. It is highly unlikely that the environmental damages are uniform across Europe and across different eco-systems, as implied by focussing on reducing exceedances at the same cost in all grid-cells.

Changing the binding targets always yield changed costs and depositions. If the distribution of change in costs and accumulated excess where evaluated for all possible target combinations in Europe, the mass of information would be unmanageable. The exploring of distributional changes caused by changes of targets in single countries might therefore be an unfruitful sidetrack, and may unduly disrupt the approach of basing calculations on commonly accepted principles of fairness. This approach has been used so far in the LRTAP, and it probably reduces the conflict level between countries. The compensation mechanism with different gap closure levels between countries should therefore be used with caution.

The recent development of the RAINS model with a penalty term in exceedances of targets and a stabilisation term added to the objective function, together with the possibility of introducing individualised constraints for grids and especially the weighting of exceedances at the grid level, and specifying country-specific balance constraints, is transforming the original concept of the RAINS model of a clear dichotomy between purification costs and “hard” constraints for environmental objectives at grid level into a type of environmental model found in the economics literature based on “damage functions” for environmental effects (see e.g. Baumol and Oates, 1988). Such a development is, of course, not a problem for economists, but it should be noted that operating with a set of coefficients, apparently not based on careful, controllable estimations or calibrations, changes a transparent model into an non-transparent one to the detriment of insights of persons outside the group of model experts.

We will finally give a general warning about using cost benefit arguments for using the compensation mechanism to overcome the influence of a few “problem-grids”. A mistake sometimes made is to compare the shadow price on a hard constraint with some estimate of the environmental damage in the grid in question, and then accepting overshooting of targets if the shadow price is (considerably) higher than the environmental damage. The point is that depositions are reduced in quite a number of other grids also due to the “problem-grid” constraint being biting. A piecemeal grid-by-grid approach to a cost benefit analysis is therefore not to be recommended.

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