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IIASA Status Report
January 1993

Amann, M. and Klaassen, G. (1993) Cost-Effective Strategies for Reducing Nitrogen Deposition in Europe. IIASA Status Report.

Status Report

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SR-93-002
January 1993

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COST-EFFECTIVE STRATEGIES FOR REDUCING NITROGEN DEPOSITION IN EUROPE

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Part 3 of a Report to:
Ministry of Housing,
Physical Planning and the Environment
P.O. Box 450
2260 MB Leidschendam
The Netherlands
on
Project No. 64.19.23.01

SR-93-002
January 1993

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Acknowledgements

This work has been carried out under contract for the Netherlands Ministry of Housing, Physical Planning and the Environment (VROM), Directorate Air, The Netherlands. The financial support of the Ministry is gratefully acknowledged. The views expressed in this report are not necessarily those of VROM.

Foreword

Early international agreements on emission reduction strategies have focused on single pollutants, requiring equal relative reductions from all signatories of the protocols. In the meantime it has been recognized that such single pollutant strategies do not necessarily result in cost-effective allocation of resources. Consequently, multi-pollutant strategies are being explored to serve as a basis for further agreements on international emission reductions.

Reductions in ammonia emissions have not yet been very eminent on the international agenda as one possible approach to derive more cost-effective emission reduction strategies. This paper focuses on the simultaneous control of both nitrogen oxides and ammonia emission and examines to what extent this combined control could contribute to the cost effective attainment of deposition targets for nitrogen in Europe.

Peter E. de Jánosi
Director

Abstract

This paper explores the potential cost savings which would result from a combined control of emissions of nitrogen oxides and ammonia for the cost-effective achievement of nitrogen deposition targets in Europe.

Using the Regional Acidification INformation and Simulation (RAINS) model a framework has been constructed for a simultaneous optimization of NO_x and NH_3 emission reductions using nitrogen depositions from both pollutants as side constraints.

The paper first demonstrates that the same nitrogen deposition resulting from the currently committed reductions of NO_x emissions (without measures for NH_3 emissions) can be achieved at only 55 percent of the costs if measures for ammonia reduction would also be applied. The analysis shows that no large scale substitutions of NO_x reductions by ammonia measures occur. The cost savings mainly result from replacing the most expensive (and ineffective) NO_x abatement at a few places in Europe with inexpensive ammonia control measures. Consequently, the total level of NO_x emissions is hardly higher than in the reference case, but substantial NH_3 reductions are implemented lowering total cost.

The second case explores the potential contribution ammonia control can make for attaining the same nitrogen deposition levels resulting from the maximum application of NO_x abatement technologies solely. In this case reductions of ammonia emissions can lower total abatement costs by 23 percent, basically by modified manure handling, stable adaptations for poultry and the control of industrial ammonia emissions.

Key words: acid rain, nitrogen deposition, Europe, abatement strategy, cost-effectiveness, ammonia, nitrogen oxides, costs.

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1. Introduction

Although public concern about the detrimental impacts of acidification in Europe initially centered on sulfur, it is now widely accepted that nitrogen deposition is also an important factor contributing to acidification and to many other environmental problems. Nitrogen oxides (NO_x) and ammonia (NH_3) form the greatest amount of nitrogen compounds emitted by anthropogenic activities. The major source of nitrogen oxides emissions is energy combustion in traffic, power plants and industry. Ammonia is mainly emitted from livestock farming and from the application of artificial fertilizer.

Nitrogen oxides and ammonia can have negative *direct impacts* on vegetation and human health if concentrations are sufficiently high. Nitrogen oxides, together with emissions of volatile organic compounds, are important precursors for tropospheric ozone formation, which also has adverse impacts on vegetation and human health.

In addition to these direct effects there exist a variety of negative *indirect impacts* of nitrogen emissions on ecosystems:

- Nitrogen oxides contribute to nitrogen saturation of soils and lakes in remote areas. The resulting nitrogen leaching leads to nitrate pollution of groundwater and eutrophication of surface waters.
- Nitrogen oxides may be converted into nitric acid and thereby contribute to acidification of soils and lakes. This in turn can lead to leaching of nutrients and mobilization of heavy metals and aluminium, polluting ground- and surface water. Both nitrogen saturation and acidification cause changes in the composition of species of flora and fauna.

Similar indirect impacts on soil saturation and acidification are caused by ammonia. Ammonia is an alkaline component, able to neutralize acid.

- The nitrification of ammonium (NH_4^+) into which ammonia is converted, leads to the formation of acid and, as a consequence, other acids formed in the atmosphere are no longer neutralized by ammonia (Asman, 1987).

- High inputs of ammonia and ammonium lead to the supplanting of nutrient ions and this often results in potassium or magnesium deficiencies (Roelofs and Houdijk, 1991) and in the increased stress susceptibility of forests.

- Ammonia and ammonium act as plant nutrients. In normally nutrient deficient regions the increased nitrogen intake from ammonia emissions may lead to the disappearance of nitrogen poor species (such as heathland).

The direct impacts are more relevant in the vicinity of the sources, whereas the indirect impacts appear on an international level since both ammonium and nitrogen oxides are transferred over long distance.

Critical loads are quantitative estimates of an exposure to one or more pollutants below which significant harmful effects do not occur, according to present knowledge (Nilsson and Grennfelt, 1988). Strong evidence exists that in Europe the present levels of nitrogen deposition in Europe exceed these critical loads (Hettelingh et al., 1991). For example, throughout Europe the contribution of nitrogen to total potential acidification is estimated at some 50 percent, but is significantly higher in specific parts of Europe (e.g. in the Netherlands, 70 percent; Erisman, 1991).

After the importance of nitrogen deposition has been recognized by policy makers, the first international agreements were made, aimed at reducing emissions in Europe, particularly by addressing the role of nitrogen oxides. In 1988 a number of countries, cooperating under the aegis of the United Nations Economic Commission for Europe, signed the Sofia Protocol on the control of NO_x emissions. This protocol commits the signatories to stabilize their emissions up to 1994. Most Western and Northern European countries declared the intention to reduce their NO_x emissions by 30 percent.

Ammonia, however, was not part of the international agenda, although some countries (Sweden, Netherlands) have specified national objectives for reducing ammonia emissions. The exclusion of ammonia control from international attention leads to the situation that for a problem for which two pollutants contribute, measures are only considered for one source. Obviously, the unbalanced efforts do not result in a cost-effective allocation of resources.

1.1 The scope of this paper

The objective of this paper is to evaluate the cost-effectiveness of simultaneous control of nitrogen oxides and ammonia emissions. The paper focuses on strategies which are directed at reaching specific deposition levels of total nitrogen at certain receptors by allocating emission reductions at minimal cost.

The paper makes use of the Regional Acidification INformation and Simulation (RAINS) model. This integrated assessment model consists of a group of linked submodels which simulate the flow of acidifying pollutants from their sources to environmental receptors (Alcamo et al., 1990). The model covers all major countries in Europe and considers deposition at 547 receptor points in a regular 150 * 150 km pattern. The model can be operated in the scenario analysis and the optimization mode. Given a specified scenario of energy use in Europe the scenario analysis allows the evaluation of environmental consequences of emission reduction strategies in terms of nitrogen and sulfur deposition in Europe, acidification of forest soils and freshwater bodies and direct impact on forest vegetation. The optimization mode offers the possibility to identify the regional distribution of emission reductions which achieves environmental targets (sulfur and/or nitrogen deposition) in specific areas at a minimum cost.

For the purpose of this study the RAINS model has been extended with a data base on NH_3 emissions in Europe and with a submodel to evaluate the potential and costs of abating ammonia emissions (Klaassen, 1991a and 1991b). In addition, the optimization module was adapted to enable the optimization of nitrogen reduction measures. Potential and cost of controlling sulfur dioxide emissions (Amann and Kornai, 1987) and nitrogen oxide emissions have already been incorporated in the model (Amann, 1989).

The remainder of this paper is organized as follows: Section 2 provides a brief overview of the RAINS data base on costs and atmospheric transport of oxidized and reduced nitrogen compounds. Section 3 formulates the optimization problem for the simultaneous control of NO_x and NH_3 emissions. Section 4 analyzes four optimization runs for the simultaneous control of both nitrogen components. Conclusions and policy recommendations are the subject of Section 5.

2. The nitrogen related data bases of the RAINS model

2.1 The costs of controlling NO_x emissions

The RAINS model contains a submodule to assess the potential and costs for various NO_x abatement options. The evaluation is based on internationally reported performance and cost data of control devices (Amann, 1989).

For stationary sources (power plants, industry) the following control options are considered in the model:

- combustion modifications, such as low NO_x burners and optimized boiler design;
- selective catalytic reduction (SCR) of the tail gases;
- combined application of the above two options.

These options are implemented for both new and existing plants (at different costs, depending e.g. on the fuel type).

For mobile sources a distinction is made between gasoline and diesel powered vehicles. For *gasoline cars* two levels of control are considered:

- moderate reductions, reflecting the EEC-Luxembourg compromise for smaller cars (engine modifications such as lean burn engines or the use of uncontrolled catalytic converters);
- higher reductions to comply with the US 1985 standard through the application of a three-way catalyst.

For *diesel passenger cars* the model considers engine modifications (such as exhaust gas re-circulation) offering the option to reduce emissions by 30 percent.

For *heavy duty trucks* two classes of measures are specified:

- the US 1988 standards, to be met through incremental changes in existing technology;
- the US 1991 standards, requiring in-cylinder emission control, electronically controlled fuel injection and maximum cooling of compressed air.

Cost estimates for specific technologies are extrapolated by the model to reflect country specific conditions such as operating hours, boiler size, and fuel price (Amann, 1989).

2.2 Costs estimates for NH_3 control

In contrast to the cost estimates available for controlling nitrogen oxide emissions, the cost estimates for ammonia emissions are more uncertain due to a lack of practical experience. In brief, the following major options to control ammonia emissions from livestock farming can be distinguished:

- changes in the nitrogen content of the fodder;
- adaptations during stable period and during storage of manure;
    - stable adaptations (such as manure flushing);
    - covered manure storage;
    - cleaning of stable air (bio-filtration or bio-scrubbing);
- low emission applications of manure (such as direct ploughing down or injection of manure).

These options can be applied for various categories of animals, such as dairy cows, other cattle, pigs, laying hens, and other poultry. Additional reduction measures can be applied in various branches of the chemical industry, e.g., application of stripping and absorption techniques. Including the combinations of the various abatement techniques, 47 different options are considered by the RAINS model (Klaassen, 1991b).

Cost estimates are country-specific, depending on animal type and technology. Important parameters are the stable size, the fertilizer price, the amount of manure applied per hectare and the investments per place for each animal.

2.3 National cost curves for emission control

The optimization algorithm implemented in the RAINS model makes use of 'national cost curves' for emission control representing the cost-minimal combination of emission reduction measures within a country.

National circumstances result in varying costs for applying the same technology in different countries in Europe. Another source of difference is to be found in the structural differences between the energy and agricultural systems, especially in the structures for energy use, livestock population, the intensity of use and the type of fertilizer, which determine the potential for application of individual control options. To explore the influence of these factors on emission control costs 'national cost curves' have been constructed. These curves display the lowest costs for achieving various emission levels by applying the cost optimal combination of abatement options. This is done by ranking the options according to their marginal costs and their individual potential for removal. The resulting piece-wise linear cost curves are input to the optimization problem.

An example of national cost curves for controlling nitrogen emissions is given in Figure 1. The curves are based on the governmental projections of energy use for the year 2000 (for NO_x) and on the generally expected level of agricultural activities for NH_3 emissions (Klaassen, 1991a and Amann, 1989). These two curves describe for each country the marginal, as well as the total annual costs of emission reductions, as a function of the remaining emissions. To allow a direct comparison of NO_x and NH_3 emissions the marginal costs have been expressed in a common unit (related to one ton nitrogen abated). Figure 1 shows that, up to a certain level, reducing ammonia emissions is less expensive than controlling NO_x emissions.

2.4 The atmospheric dispersion of oxidized and reduced nitrogen compounds

Source receptor coefficients, relating (country) emissions to deposition at a receptor point, can be derived from various atmospheric long-range transport models. For this exercise coefficients have been extracted from results of the model developed by the European Monitoring and Evaluation Program (EMEP) at the Norwegian Meteorological Institute (Iversen et al., 1990). This model includes 10 different chemical components in the air, three of which are man-made: SO_x, NO_x and NH_3. Input data for the model consist of emissions for the three pollutants and meteorological data such as precipitation, wind speed and temperature. The model calculates transboundary fluxes of sulfur and of oxidized and reduced (ammonia and its product ammonium) nitrogen compounds and deposition of these species on a 150*150 km grid over all of Europe. In this paper all calculations are based on transfer coefficients reflecting the average meteorological conditions of the years 1988 and 1989.

According to the results from the EMEP model the pattern of sulfur deposition reflects to a much higher degree the pattern of emissions, if compared to the emission- and deposition patterns of oxidized nitrogen. The major reason for this is the longer residence time of NO_x emissions in the atmosphere due to the low dry deposition rate of oxidized nitrogen. The effective dry deposition of ammonia results in a short atmospheric lifetime of ammonia, making the deposition pattern closely follow the regional distribution of emissions. A certain fraction of ammonia, however, is transformed into ammonium compounds (NH_4^+) which have a rather long residence time in the atmosphere. Consequently, ammonium travels over significant distances before deposited on the ground. Tables 1 and 2 provide the country-to-country source-receptor balances as calculated by the EMEP model for 1988.

3. The formulation of the optimization problem

Effect-based strategies, minimizing the cost of attaining regional exposure levels resulting from one or several pollutants, may be formulated as linear programming (LP) problems. Such formulations for a single pollutant, e.g. for reducing SO_2 emissions, have been expressed elsewhere (e.g. Ellis, 1987; Batterman and Amann, 1991). In this paper the optimization concept is extended to multi-pollutant problems to limit total nitrogen deposition. The following paragraph gives a brief summary of the modified problem formulation.

The total cost C to be minimized is

$$C = \sum_z \sum_i \sum_j c_{i,j,z} \, R_{i,j,z} \rightarrow \min \qquad (1)$$

where decision variable $R_{i,j,z}$ is the emission reduction of pollutant z in a country i at the jth level. In our example a total of 27 countries is utilized. Marginal cost $c_{i,j,z}$ gives the slope of the emission removal cost curve (see Section 2.2.3) for pollutant z in the country i at the jth control level. The reductions in the p segments of each cost curve are limited:

$$0 \le R_{i,j,z} \le R_{i,j,z,\max} \qquad for\ i = 1 \ldots 27, j = 1 \ldots p, z = 1 \ldots Z \qquad (2)$$

An identity relates reductions $R_{i,j,z}$ with unabated emissions $S_{o,i,z}$ and optimized emissions $S_{o,i,z}$

$$S_{i,z} = S_{o,i,z} - \sum_j R_{i,j,z} \qquad for\ i = 1 \ldots 27,\ z = 1 \ldots Z \qquad (3)$$

The total deposition D_k at a receptor site k is calculated at m locations assuming additive effects from each source i

$$D_k = \sum_z \sum_i T_{i,k,z} S_{i,z} + D_{k,bak} \qquad for\ \ k = 1 \ldots m \qquad (4)$$

where transport coefficients $T_{i,k,z}$ gives the source-receptor relationship of pollutant z from country i to receptor k as developed by an atmospheric transport model. $D_{k,bak}$ is 'background' deposition which is uncontrollable or unrelated to specific sources. Limits on deposition are set

$$D_k \le D_{k,tar} \qquad for\ each\ k = 1 \ldots m \qquad (5)$$

The solution to Equations (1-5) provides an allocation of emission reductions which is optimal in a single criterion (cost). Other objectives or constraints can be easily handled. For example, emission abatements (e.g. tons of pollutants) may be minimized by setting costs $c_{i,j}$ to unity. In our formulation transfer coefficients must reflect not only the atmospheric dispersion behaviour of individual pollutants but also the chemical conversion processes of various emission components into the deposited species (e.g. the transformation of nitrogen oxides emissions, usually expressed as volumes of NO_2, into various compounds of deposited nitrogen measured in their nitrogen content).

In addition, so-called 'policy constraints' can be added which restrict the minimum (or maximum) emission reductions in a region:

$$\sum_j R_{i,j,z} \geq S_{o,i,z} - S_{p,i,z} \qquad for\ i = 1...27,\ z = 1...Z \tag{6}$$

The equation system as outlined above has been implemented for solution on a microcomputer, using the HYBRID software (Makowski and Sosnowski, 1988) for solving the LP problem.

4. Results

This section explores features of optimized simultaneous control strategies for NO_x and NH_3 emissions based on four examples derived from the model setup outlined above. To explore the major principles of cost-optimized simultaneous emission reduction strategies the first two exemplary cases focus on strategies to attain deposition targets for a small region only. After this, potential cost savings of simultaneous emission reduction strategies are explored for more realistic cases by expanding deposition targets over all of Europe for modest deposition targets. Finally, the potential gains from a simultaneous NO_x/NH_3 strategy are analyzed for stringent deposition targets.

4.1 Optimized emission reductions to restrict the annual nitrogen deposition in Austria to 2 grams/m^2

The first example explores the basic mechanisms of balanced NO_x/NH_3 reduction strategies. For this purpose, constraints on total nitrogen deposition have been defined for a restricted target area only, i.e. for the eight receptor grids in Austria a maximum nitrogen deposition level of 2 grams/m^2 per year has been specified. The optimization has been used to identify the internationally cost-minimal allocation of reduction measures. For illustration two strategies are analyzed:

- Scenario 1 with only the control of NO_x emissions (keeping NH_3 emissions unaffected at the no-control level),

- Scenario 2 with a simultaneous control of both NO_x and NH_3 emissions.

Results of the optimization are displayed in Table 3. Costs of Scenario 1 (controlling NO_x emissions only) amount to more than 16 billion DM/year. Compared to this strategy, simultaneous control could attain costs savings of almost 80 percent; total costs for controlling both pollutants would only be 3.5 billion DM/yr.

Table 4 reveals the major causes for these cost savings: to achieve a maximum total nitrogen deposition of 2 g $N/m^2/yr$ in Austria in the year 2000, in the NO_x-only case (Scenario 1) NO_x emissions must be reduced to 27.7 million tons of NO_2. The development of agricultural activities will lead to a slight increase of NH_3 emissions to 8.6 million tons (no abatement applied). With both emissions controlled in a cost-optimal way (Scenario 2), the most expensive measures to reduce NO_x emissions taken in Scenario 1 would not be applied and, consequently, remaining NO_x emissions could be 13 percent higher (31.3 million tons). Costs for controlling the NO_x emissions, however, would decline by 89 percent from 16.8 billion DM/yr to 1.9 billion DM/yr. To compensate for the increased deposition from higher NO_x emissions in Austria, measures to reduce NH_3 emissions have to be applied. The relative short-ranged dispersion characteristics of ammonia allow focussing emission control on a small area around the target area, i.e., around Austria. Ammonia control implemented there has a large impact on deposition in Austria and is therefore rather effective. Consequently, a six percent reduction of ammonia emissions will be sufficient to compensate the Austrian impact of the 13 percent increase of NO_x emissions. The cost savings on NO_x control clearly outweigh the additional efforts for abating NH_3 emissions (compare Table 3).

A more detailed analysis of country abatement schedules explains how the cost savings are achieved. About 60 percent of the cost savings for NO_x results from relaxed emission reductions in West Germany. In this country marginal cost of NO_x control go down from 11800 DM/ton NO_x to 3000 since relatively expensive measures such as catalytic reduction on industrial plants, US-standards for heavy duty trucks, and process emissions controls are no longer required. To compensate these increased nitrogen emissions, measures for ammonia are applied in West Germany, where high emission densities occur in the south.

Some 60% of the additional costs of ammonia control of all of Europe emerge in West Germany. Measures taken involve low ammonia application of manure for all animal categories, the control of industrial process emissions and stable adaptations for laying hens. Hence, to restrict nitrogen deposition in Austria the control of NH_3 emissions in West Germany would be a much more cost-effective strategy than advanced NO_x abatement.

Apart from the bulk of cost savings achieved in Germany, minor modifications of the solution of Scenario 1 take place in a large number of countries (e.g. in East Germany, CSFR, Austria, France, The Netherlands, Belgium, Poland, Luxembourg). In East Germany, the CSFR and in Austria only the least expensive options to reduce NO_x emissions (combustion modifications at stationary sources) remain in the abatement schedule, whereas effects of prominent measures at higher costs (selective catalytic reduction in power stations, control of process emissions) are compensated by the reduced ammonia emissions. Low ammonia application for all, or parts of, animal categories and control of industrial ammonia emissions are required in Austria, France, Italy, Switzerland, the Netherlands and in Belgium (due to the influence of the prevailing wind direction!).

In summary, simultaneous control of NO_x and NH_3, geared at a target deposition of 2 grams nitrogen/m^2/year in Austria, is expected to result in cost savings of nearly 80 percent, when compared to controlling NO_x emissions only. The cost savings are achieved by shifting from expensive measures in a wide area of Europe with high marginal costs related to reduced nitrogen deposition in Austria to low-cost control of NH_3 emissions mainly in Austria and its neighbouring countries. The major part of the cost savings occurs in the western part of Germany.

As will be shown in the next sections, an extrapolation of these findings (i.e. the magnitudes of potential cost savings) to other conditions with changed geographical scope of the target area, with relaxed or tightened target deposition levels, or by taking into account already implemented national legislation on emission reductions, is not straightforward and should be carried out most carefully.

4.2 Optimized emission reductions to restrict the annual nitrogen deposition in Austria to 2 grams/m^2, taking into account current reduction plans

The example presented in the previous section did not take account of national legislation currently in force to regulate emission control in many European countries. It has been assumed in the optimization that such regulations are reversible, possibly leading to 'optimized' emission levels above the current policies. This section will demonstrate that such legal commitments might impose strong side constraints on optimized emission reductions by restricting the available degree of freedom for the optimization.

The emission reductions published by the individual governments as their policy targets for the year 2000 are presented in Figure 2. Obviously, many countries will face restrictions in relaxing their NO_x emission control above these envisaged levels and can therefore not exchange them freely for NH_3 additional emission control, even if this would be a less expensive means to achieve the Austrian deposition targets set in the previous section. In this section these emission projections $S_{p,i,j}$ are introduced as an additional set of constraints into the optimization (so called 'policy constraints').

The results of the introduction of these policy constraints (Scenario 3) are displayed in Tables 5 and 6. Table 5 clearly shows that taking current legislation as constraints the cost savings drop sharply from 80 to only 13 percent. In absolute terms the cost savings, with current reduction plans as constraints, are 3.7 instead of 13 billion DM/year.

A comparison of Table 5 and Table 3 shows that many European countries have specified policies with higher NO_x reductions than would be necessary to achieve the assumed deposition targets in Austria (admittedly, these targets were not the major driving force in most countries). The additional commitments increase total European costs to 29 billion DM/yr (compared to 17 billion DM/year of Scenario 1). According to the definition of this scenario, only NO_x emissions above the committed reductions are eligible for compensation by ammonia measures. Therefore, the optimal use of NH_3 reduction potential would increase European NO_x emissions only by 1.5 million tons (compared to 3.5 million tons in Scenario 1). Cost savings, with 3.7 instead of 15 billion DM/yr, are accordingly smaller.

Table 6 shows that only very little ammonia emissions control takes place now: NH_3 emissions are mainly reduced in Austria, in total by 0.033 million tons at a cost of 0.06 billion DM/year.

In conclusion, the results suggest that limited freedom for the rearrangements of emission reductions, such as national legislation already in force, seriously restricts the possibilities for achieving substantial cost savings by optimized abatement schedules.

4.3 Cost-optimal achievement of the nitrogen deposition pattern in Europe resulting from the current NO_x reduction plans.

The large difference in the atmospheric residence times between reduced and oxidized nitrogen compounds is a major reason for the large potential cost savings demonstrated in the previous section. Measures to reduce NO_x emissions in Germany which affect large parts of Europe, but have only relatively little impact on deposition in Austria, could be substituted by (local) NH_3 control targeted solely at the Austrian nitrogen deposition. The results presented above are therefore too optimistic if a larger target area (e.g. all of Europe) is taken into account.

In order to allow conclusions relevant to current policies, this section examines the potential cost savings of combined control of NO_x and NH_3 for attaining the same deposition levels in the whole of Europe, as would result from implementation of the current reduction plans for NO_x. Starting point for this scenario is the pattern of total nitrogen deposition displayed in Figure 3, assuming reductions in NO_x emissions according to current policy and no explicit control measures for NH_3 emissions. Thereby, according to the expected changes in animal population and fertilizer use, ammonia emissions are predicted to slightly increase.

The following strategies are examined:

Scenario 4: Reference case. Currently committed reductions of NO_x emissions, no control of NH_3 emissions. The pattern of total nitrogen deposition is displayed in Figure 3.

Scenario 5: The optimal control for NO_x emissions only (no control for NH_3) to attain nitrogen deposition equal to Scenario 4.

Scenario 6: Optimally combined control of NO_x and NH_3 emissions to achieve nitrogen deposition equal to Scenario 4.

Table 7 displays the annual costs of the different scenarios for attaining the same deposition pattern. As the Table shows, the currently committed NO_x reductions are not cost-effective means to achieve the resulting pattern of nitrogen deposition in Europe. If, for example, an optimization would be restricted to NO_x control only (Scenario 5), the same deposition pattern could be achieved at 10 percent lower costs, i.e., at only 22 instead of 25 billion DM/yr. If also ammonia measures would be open for optimization (Scenario 6), the annual costs would drop by 44 percent to 14 billion DM. Out of this, 10 billion DM would be spent on NO_x control and nearly 4 billion on reducing ammonia emissions.

Table 8 indicates that the total sum of the emissions of both pollutants (expressed by their nitrogen content) are in both Scenarios 5 and 6 only slightly lower than in the reference case Scenario 4. This fact indicates that the majority of costs savings do not result from an increase in emissions in general, but that they are, to a great extent, a consequence of an effective regional allocation of measures for the individual pollutants.

That such an effective re-allocation occurs can be derived from an analysis of the country-specific optimization results (Table 9). In comparing the current reduction plans (Scenario 4) with the optimal NO_x control only (Scenario 5), we observe that countries in which costs of current reduction plans are high, relax their NO_x abatement efforts (this is the case for Austria, Bulgaria, Denmark, Finland, France, FRG, Italy, Netherlands, Norway, Sweden and the United Kingdom). Other countries, which have not yet committed expensive measures, employ the least expensive group of NO_x control measures (e.g. Albania, Belgium, CSFR, East Germany[1], Greece, Hungary, Ireland, Luxembourg, Poland, Portugal, Romania, Spain, Turkey, the former USSR and Yugoslavia). However, cost savings by not implementing the most expensive options in countries of Group 1 are larger than the increased costs occurring in the latter group of countries, resulting in an overall cost saving of some 10 percent.

In Scenario 6 (simultaneous control) most countries face lower costs for NO_x control, only a few will experience modest increases (e.g. Spain), and only the former USSR will have to apply more control (because of its high energy use it has a high potential for cheap NO_x control measures such as combustion modifications). To compensate the increased nitrogen deposition from the higher NO_x emissions nearly all countries will control ammonia emissions, however at different levels. Efforts in France, Germany and Italy will be considerably higher than in other countries (Table 9).

In Scenario 6 the major measures to control NO_x emissions are combustion modifications (low NO_x-burners) at stationary sources, selected in nearly all European countries. In addition, all new hard-coal fired power stations are equipped with selective catalytic reduction devices. Other measures vary per country since the importance of location renders some measures cost-effective in some countries. In central and western Europe, for instance, combustion modification and selective catalytic reduction at large emitters in the industrial and refinery sector, as well as in base-load operating oil-fired power stations, is necessary to relieve the high emission densities in this region. In other countries, e.g. in southern Europe, measures are restricted to combustion modifications at stationary sources. In addition, tight control of emissions from mobile sources (e.g. US-85 standard for heavy duty trucks or the introduction of the three-way catalysts) is required in the north and the west of Europe (e.g. in Belgium, Finland, France).

An overview of the type of measures taken for NH_3 in Scenario 6 reveals that nearly all countries have to apply poultry manure on arable land and grassland with the help of low ammonia application techniques (e.g. injection, direct ploughing under) and they have to

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[1] This analysis does not yet take into account recent application of West German legislation to the eastern part of the country.

control industrial ammonia emissions. For a smaller number of countries (around 10) low ammonia application is cost-efficient for all animal categories. Moreover, stable adaptations for laying hens and broilers are cost-effective. Low nitrogen fodder is too expensive and only selected in a few exceptional cases to compensate extremely expensive NO_x measures.

In summary, the costs of controlling both ammonia and nitrogen oxides emissions to attain the same nitrogen deposition as would result from the current reduction plans for NO_x are only 55 percent of the CRP. This does not result from increasing NO_x emissions and decreasing NH_3 emissions, since both pollutants are reduced further than under the current reduction plans. More than two thirds of the cost savings occur in areas where ammonia measures can locally replace extremely expensive NO_x reduction options. However, it must be stressed that the regional distribution of required reduction measures is mainly the result of the currently committed level of NO_x reductions and does not necessarily have a relation to environmental sensitivities. Basing target deposition levels on indicators for environmental susceptibility to nitrogen deposition might considerably change the regional distribution of abatement burdens derived in this section.

4.4 Cost-optimal achievement of the nitrogen deposition pattern in Europe resulting from the maximum technical NO_x abatement

There exists strong evidence that in large parts of Europe current nitrogen deposition substantially exceeds safe levels at which no harmful effects to ecosystems are assumed to occur. Rapid and significant reductions in emissions are considered necessary to avoid costly environmental damage. In the past, analyses of strategies to reduce nitrogen deposition were often restricted to options for reducing nitrogen oxides, and the resulting costs for extreme reductions were considered too high. However, reduction of ammonia emissions can also be used to enable similar deposition patterns at substantially lower costs.

To explore the potential contribution of joint NO_x/NH_3 strategies to be made for extreme reductions of nitrogen deposition a so-called 'Maximum Technically Feasible Reduction' scenario (MTFR, Scenario 7) will be analyzed. The nitrogen deposition resulting from such maximum application of emission control technologies for NO_x (assuming no control for NH_3) is displayed in Figure 4.

Table 10 shows that the costs of reaching this nitrogen deposition would be 95 billion DM/year if only NO_x would be controlled. A simultaneous control (Scenario 7) could achieve cost savings of 23 percent or 21 billion DM per year. In such a case, costs for NO_x control could be reduced by roughly one third (34 billion DM/year), whereas compensating measures implemented for ammonia would cost some 13 billion DM/year.

A comparison of Tables 7 and 10 reveals that the relative cost savings of simultaneous reductions are smaller for high emission reductions such as the MTFR scenario (Table 10) than for moderate reductions such as the Current Reduction Plans (Scenario 6, Table 7). The reason for this lies in the implied range of deposition targets. If many control possibilities are exhausted (as is the case in the MTFR scenario), less freedom for the optimization is left than in a rather unconstrained case in which major rearrangements of emission reductions (avoiding expensive measures) are possible for reducing costs. This is a typical result also observed in other studies (Tietenberg, 1985). Note, however, that although the percent cost savings are smaller the absolute amount saved is higher (22 versus 11 billion DM/year).

Table 11 shows that the cost savings are not so much due to an increase in emission levels: remaining total NO_x emissions are only 4 percent higher. The cost savings are mainly attained by eliminating expensive NO_x abatement measures, increasing NO_x emissions, and replacing them by relatively cheap options to control ammonia. Table 11 shows that NO_x emissions increase by 4400 kiloton to nearly 18000 kt NO_x whereas NH_3 emissions are reduced by over 2000 kt.

The distribution of costs throughout the various countries is shown in Table 12. All countries will experience cost savings for NO_x, and at the same time incur costs from NH_3 control. Highest NH_3 reduction takes place in France, Italy and the former USSR. Net cost savings occur in most countries with the exception of Italy, Norway, Spain and Turkey; in these countries higher costs occur than in the NO_x-only control case.

Whereas in the NO_x-only scenario all measures to reduce NO_x emissions (see Section 2.1) are applied, the utilization of NH_3 reduction options relaxes the most expensive NO_x abatement options. For stationary sources combustion modification is applied for all sectors and all fuel types throughout Europe. In addition, all hard-coal fired power stations and many new facilities for oil and gas will be equipped with selective catalytic reduction devices. NO_x emissions from mobile sources will be controlled according to the U.S. 1985 standards (for heavy duty trucks), and process emissions will be generally reduced by 30 percent. Further measures, however, are in some countries substituted by NH_3 control, e.g. retrofit of existing power stations, the stricter U.S. 1991 standard for heavy duty trucks, controlled three-way catalysts for gasoline cars, selective catalytic reduction in the industrial sector and more stringent measures to further reduce process emissions. Instead of this bundle of measures, low ammonia application of manure for all animal categories, stable adaptations for poultry stables as well as control of industrial emissions are necessary to achieve the same nitrogen deposition in Europe.

In conclusion, combined control of NO_x and NH_3 emissions will enable accomplishing the same nitrogen deposition pattern as would result through the application of the maximum feasible reductions of NO_x emissions only. The annual emission control cost, however, would be 23 percent lower.

5. Conclusions

Emissions of nitrogen oxides and of ammonia are the major contributors to nitrogen deposition. Whereas current strategies to reduce nitrogen deposition in Europe focus mainly on reducing NO_x emissions, the simultaneous consideration of ammonia emissions can lead to substantial cost savings. The extent of the cost savings, however, depends crucially on the absolute level and regional distribution of the target levels for nitrogen deposition.

The examples in this paper show that, depending on the deposition targets, simultaneous reductions of both pollutants can reduce European abatement costs between 13 and 80 percent. The costs savings are mainly attained by replacing expensive measures for controlling NO_x emissions, such as the prescription of the U.S. 1991 standard for heavy duty trucks, the three-way catalyst for gasoline cars, stringent control of industrial process emissions and advanced flue gas purification for industrial combustion and existing power stations, by inexpensive control of ammonia emissions. Among the cost-effective options to reduce ammonia emissions are the low-ammonia application of manure for all animal categories, stable adaptations for poultry stables as well as control of industrial emissions.

Whereas these considerations fully apply to acidification problems caused by nitrogen deposition, a reduction of emissions of nitrogen oxides might have additional environmental impacts (positive or negative), which are not accounted for in this analysis. The use of some NO_x control equipment (such as catalytic converters for cars) simultaneously reduces also emissions of volatile organic compounds, for which no credit is given in this analysis. Similarly, no credit was given to the fact that a reduction of the nitrogen content in fodder (aimed at reducing ammonia emissions) will also alleviate nitrogen pollution in soils, in surface- and in groundwater. Whether such credits should be given depends on local and regional circumstances, such as the exceeding of air quality standards for ozone or drinking water quality standards for nitrate. Incorporating these credits might influence the optimal blend of NO_x and NH_3 control measures but would not have major effects on the main results of this study.

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Figure 1. Cost functions for Austria for the year 2000

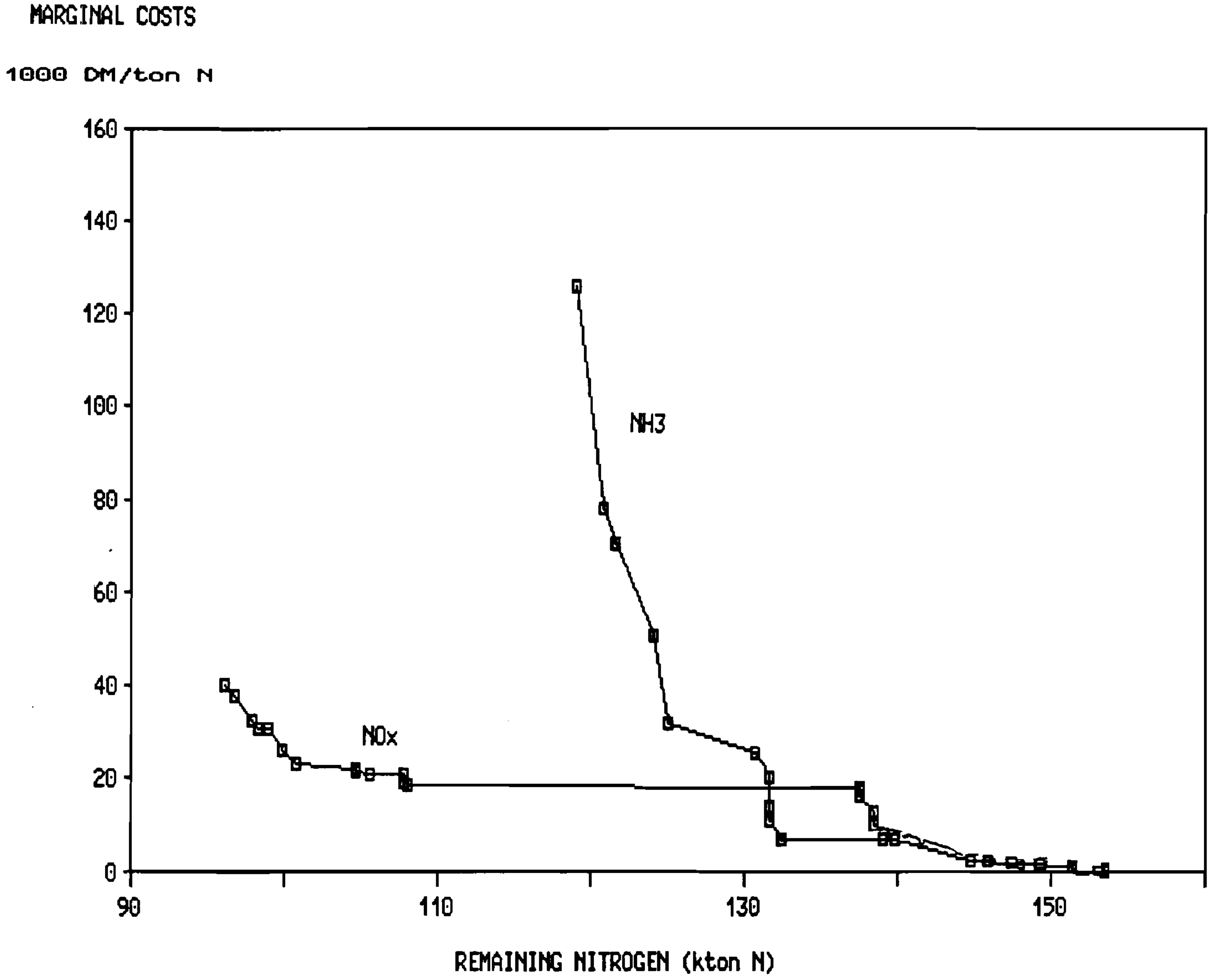

Figure 2. Current reduction plans NO_x

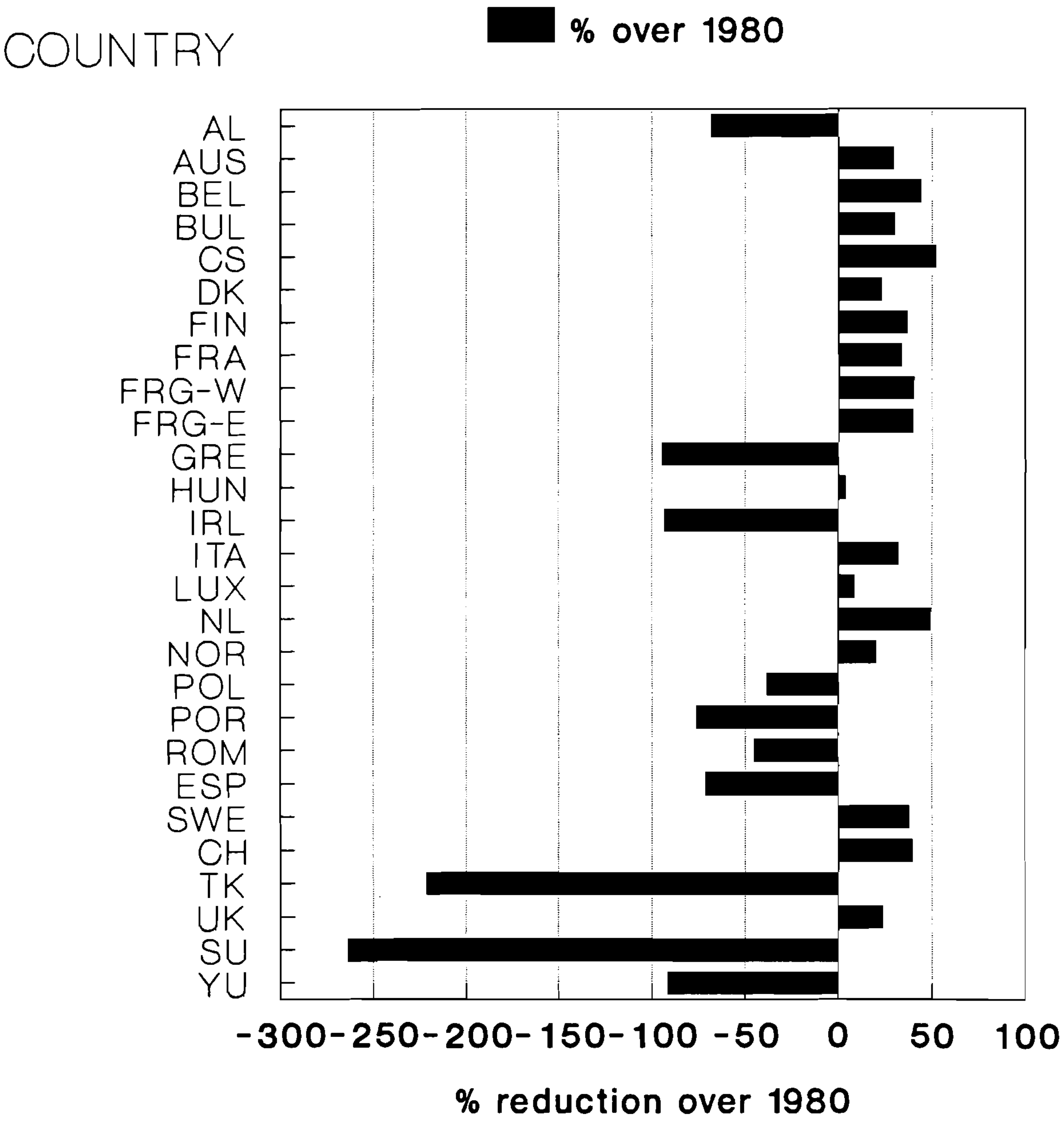

Figure 3. Nitrogen deposition with current reduction plans (year 2000)

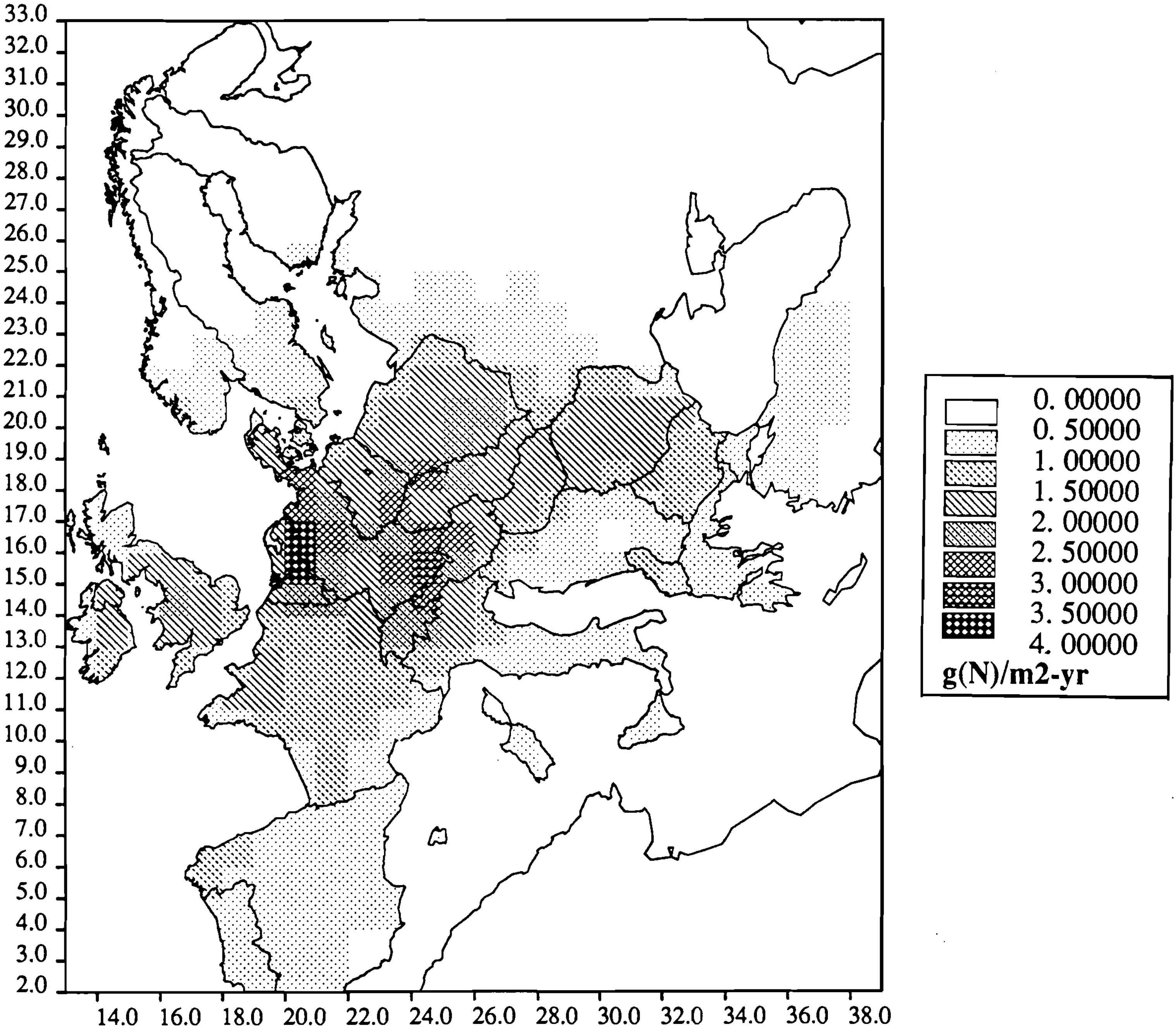

Figure 4. Nitrogen deposition of Maximum Feasible Reduction NO_x (year 2000)

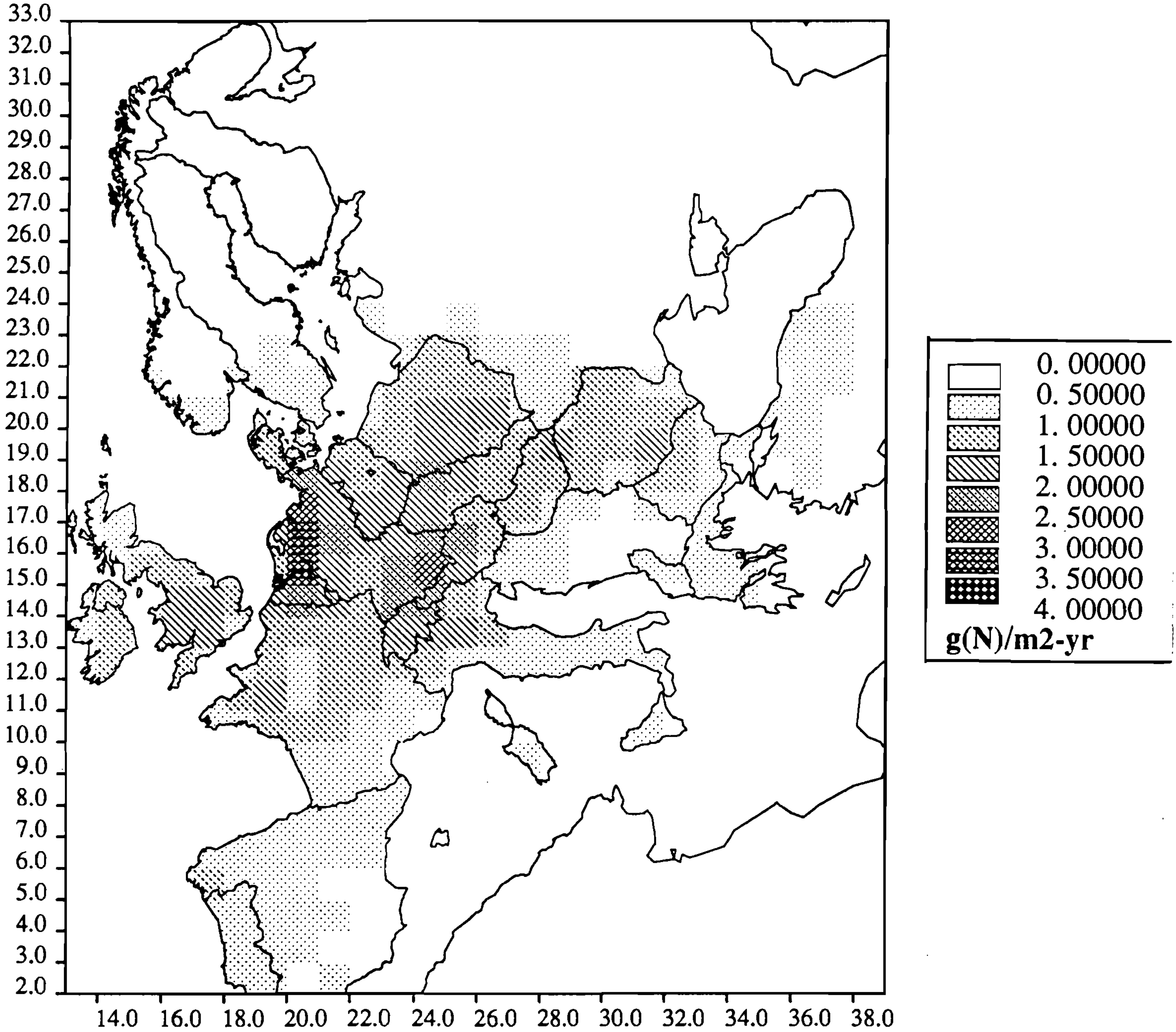

Table 1. Country-to-country matrix for NO_x in 1988 (unit: 100 tonnes as N)

Emitters

Receivers	AL	AT	BE	BG	CS	DK	FI	FR	DD	DE	GR	HU	IS	IE	IT	LU	NL	NO	PL	PT	
AL	1	1	1	1	5	0	0	4	3	7	10	2	0	0	22	0	1	0	4	0	AL
AT	0	34	15	0	62	4	1	83	50	238	1	9	0	1	88	1	23	1	30	0	AT
BE	0	0	26	0	2	1	0	58	4	50	0	0	0	1	1	1	25	0	2	0	BE
BG	0	4	1	24	17	1	1	5	10	20	36	14	0	0	23	0	3	0	18	0	BG
CS	0	24	19	1	207	8	1	63	143	281	1	37	0	1	38	1	33	2	115	0	CS
DK	0	0	8	0	6	17	0	17	18	71	0	1	0	1	1	0	20	3	14	0	DK
FI	0	1	7	0	16	21	119	16	30	83	0	2	0	1	1	0	18	13	54	0	FI
FR	0	4	74	0	21	5	1	777	35	295	2	3	0	7	81	5	81	2	12	10	FR
DD	0	4	28	0	76	14	1	72	170	356	0	2	0	1	9	2	56	3	44	0	DD
DE	0	11	103	0	67	18	1	329	122	993	0	5	0	5	40	8	175	7	43	1	DE
GR	1	2	1	9	10	1	0	8	6	16	129	6	0	0	28	0	2	0	10	0	GR
HU	0	18	5	1	59	2	1	21	30	67	3	59	0	0	55	0	9	0	50	0	HU
IS	0	0	0	0	0	1	1	1	0	3	0	0	2	0	0	0	1	1	1	0	IS
IE	0	0	1	0	0	0	0	8	0	5	0	0	0	9	0	0	2	0	0	1	IE
IT	0	16	13	1	40	4	0	162	33	138	10	15	0	1	480	1	18	1	29	2	IT
LU	0	0	1	0	0	0	0	5	0	5	0	0	0	0	0	0	1	0	0	0	LU
NL	0	0	23	0	4	1	0	42	6	73	0	0	0	1	0	0	51	1	5	0	NL
NO	0	1	18	0	17	34	11	38	42	146	0	1	0	4	1	0	47	60	42	0	NO
PL	0	19	37	1	237	39	9	97	330	481	1	31	0	2	34	2	81	7	579	0	PL
PT	0	0	1	0	0	0	0	5	0	3	0	0	0	0	0	0	1	0	0	28	PT
RO	0	14	6	15	81	4	3	22	49	87	21	65	0	0	62	0	13	1	104	0	RO
ES	0	0	11	0	2	1	0	103	3	31	0	1	0	2	9	0	17	0	2	48	ES
SE	0	3	20	0	43	68	51	43	92	210	0	5	0	3	3	1	48	43	111	0	SE
CH	0	2	8	0	6	1	0	88	9	76	0	1	0	1	47	1	11	0	3	0	CH
TR	0	3	2	12	16	1	1	11	11	24	89	10	0	0	24	0	4	0	27	0	TR
SU	0	34	41	15	299	89	176	129	323	561	29	104	0	3	80	2	90	31	984	0	SU
GB	0	0	13	0	3	3	1	55	11	54	0	0	0	19	1	0	22	2	7	1	GB
YU	1	29	11	10	89	3	2	64	52	130	32	59	0	0	252	1	19	1	73	0	YU
REM	0	4	8	1	10	2	0	73	9	40	12	2	0	1	53	0	11	1	5	4	REM
BAS	0	5	29	0	66	75	58	71	143	331	0	8	0	3	7	1	68	18	188	0	BAS
NOS	0	2	73	0	26	47	3	226	71	352	0	1	0	20	4	2	168	31	50	3	NOS
ATL	0	1	42	0	12	40	25	246	38	189	0	1	7	48	3	1	79	81	38	33	ATL
MED	2	24	29	15	77	11	2	313	60	222	220	34	0	2	546	2	43	2	70	10	MED
BLS	0	2	2	7	19	2	2	5	14	24	22	10	0	0	11	0	3	0	45	0	BLS
SUM	7	262	677	114	1594	516	470	3259	1916	5659	618	489	11	135	2003	36	1243	315	2758	144	SUM
	AL	AT	BE	BG	CS	DK	FI	FR	DD	DE	GR	HU	IS	IE	IT	LU	NL	NO	PL	PT	

Emitters

Receivers	RO	ES	SE	CH	TR	SU	GB	YU	REM	BAS	NOS	ATL	MED	BLS	NAT	IND	SUM	
AL	2	1	0	0	0	2	2	8	0	0	0	0	0	0	0	18	96	AL
AT	3	5	3	19	0	3	42	15	0	1	5	2	0	0	0	57	796	AT
BE	0	3	1	0	0	1	55	0	0	0	6	3	0	0	0	17	258	BE
BG	37	1	1	0	2	43	4	26	0	0	1	0	0	0	0	54	345	BG
CS	8	3	6	6	0	12	51	18	0	2	7	2	0	0	0	72	1163	CS
DK	0	0	5	0	0	3	63	0	0	2	7	1	0	0	0	22	283	DK
FI	1	0	68	1	0	133	39	2	0	13	6	1	0	0	0	107	753	FI
FR	1	152	4	19	0	3	268	6	2	1	32	51	0	0	0	250	2203	FR
DD	1	3	6	4	0	6	84	2	0	3	12	3	0	0	0	58	1019	DD
DE	2	16	9	32	0	8	261	5	0	3	34	11	0	0	0	142	2450	DE
GR	11	2	1	0	3	17	4	15	1	0	0	0	0	0	0	72	360	GR
HU	15	1	2	3	0	10	14	40	0	1	2	1	0	0	0	42	510	HU
IS	0	0	1	0	0	3	12	0	0	0	1	1	0	0	0	27	58	IS
IE	0	2	0	0	0	0	48	0	0	0	2	7	0	0	0	22	108	IE
IT	4	32	3	26	0	5	59	42	3	1	5	4	0	0	0	173	1320	IT
LU	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	18	LU
NL	0	1	1	0	0	1	78	0	0	0	9	2	0	0	0	19	320	NL
NO	0	1	50	1	0	23	193	0	0	7	20	6	0	0	0	121	885	NO
PL	14	4	27	7	0	59	138	19	0	11	18	4	0	0	0	164	2452	PL
PT	0	24	0	0	0	0	5	0	0	0	1	16	0	0	0	38	123	PT
RO	136	2	4	3	3	128	18	65	0	1	3	1	0	0	0	118	1029	RO
ES	1	366	0	1	0	0	69	1	4	0	7	44	2	0	0	173	898	ES
SE	3	2	155	2	0	92	151	2	0	19	19	4	0	0	0	141	1331	SE
CH	0	8	1	28	0	0	30	2	0	0	3	2	0	0	0	31	360	CH
TR	24	2	2	1	72	109	5	16	1	0	1	0	0	0	0	264	731	TR
SU	125	6	154	10	25	3368	177	72	0	46	26	6	0	0	0	1463	8466	SU
GB	0	8	3	0	0	1	573	0	0	1	20	23	0	0	0	71	891	GB
YU	28	8	4	7	1	22	33	161	1	1	4	2	0	0	0	146	1247	YU
REM	1	56	1	4	0	2	41	8	37	0	4	5	1	0	0	333	726	REM
BAS	4	2	104	3	0	128	171	5	0	27	22	5	0	0	0	152	1692	BAS
NOS	0	13	23	2	0	10	978	0	0	7	73	34	0	0	0	221	2441	NOS
ATL	1	181	46	2	0	66	883	1	0	8	56	257	0	0	0	1379	3761	ATL
MED	28	170	9	17	12	44	127	92	24	2	12	13	1	0	0	579	2816	MED
BLS	30	0	3	1	20	226	6	10	0	1	1	0	0	0	0	133	598	BLS
SUM	477	1076	698	200	139	4526	4684	632	76	158	416	513	5	0	0	6678	42503	SUM
	RO	ES	SE	CH	TR	SU	GB	YU	REM	BAS	NOS	ATL	MED	BLS	NAT	IND	SUM	

Table 2. Country-to-country matrix for ammonia in 1988 (unit: 100 tonnes as N)

Emitters

		AL	AT	BE	BG	CS	DK	FI	FR	DD	DE	GR	HU	IS	IE	IT	LU	NL	NO	PL	PT	
	AL	77	0	0	2	1	0	0	2	1	1	6	2	0	0	8	0	0	0	1	0	AL
	AT	0	326	7	1	46	3	0	55	23	102	0	17	0	1	66	1	14	0	14	0	AT
	BE	0	0	321	0	1	1	0	79	2	13	0	0	0	2	0	2	40	0	1	0	BE
	BG	2	1	0	510	5	0	0	2	2	2	17	12	0	0	7	0	1	0	6	0	BG
	CS	0	28	7	1	721	5	0	31	73	71	0	49	0	1	15	1	17	0	71	0	CS
	DK	0	0	4	0	2	447	0	9	15	30	0	1	0	2	0	0	17	1	11	0	DK
	FI	0	1	2	0	5	11	197	6	13	15	0	2	0	1	1	0	9	3	29	0	FI
	FR	0	3	75	0	6	4	0	4033	17	59	0	3	0	17	36	6	54	0	6	6	FR
	DD	0	3	13	0	16	18	0	38	847	114	0	2	0	2	3	1	42	1	29	0	DD
	DE	0	13	82	0	28	27	0	270	91	1621	0	5	0	10	20	8	256	2	23	1	DE
	GR	6	1	0	22	3	0	0	4	1	2	333	5	0	0	8	0	1	0	3	0	GR
	HU	0	13	1	2	39	1	0	9	8	11	1	534	0	0	21	0	3	0	19	0	HU
	IS	0	0	0	0	0	0	0	2	0	1	0	0	10	1	0	0	1	0	0	0	IS
R	IE	0	0	0	0	0	0	0	7	0	1	0	0	0	540	0	0	1	0	0	0	IE
e	IT	1	12	6	1	12	2	0	126	9	33	2	14	0	1	1580	1	8	0	8	1	IT
c	LU	0	0	2	0	0	0	0	6	0	1	0	0	0	0	0	16	1	0	0	0	LU
e	NL	0	0	40	0	1	2	0	40	3	34	0	0	0	3	0	0	754	0	3	0	NL
i	NO	0	1	8	0	5	37	3	19	21	30	0	1	0	7	0	0	26	175	26	0	NO
v	PL	0	12	14	3	99	35	2	44	166	87	0	27	0	2	12	1	43	2	1964	0	PL
e	PT	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	179	PT
r	RO	1	6	2	66	30	2	1	10	13	13	8	88	0	0	22	0	4	0	43	0	RO
s	ES	0	0	5	0	0	1	0	104	1	4	0	1	0	4	4	0	8	0	0	55	ES
	SE	0	2	8	0	11	73	15	21	43	42	0	5	0	4	1	0	27	21	66	0	SE
	CH	0	2	5	0	2	1	0	107	5	32	0	1	0	1	47	1	7	0	2	0	CH
	TR	1	1	1	26	5	0	0	4	2	3	23	8	0	0	7	0	1	0	9	0	TR
	SU	1	17	14	38	104	50	44	59	111	96	9	99	0	4	30	1	45	7	589	0	SU
	GB	0	0	8	0	1	3	0	64	6	10	0	0	0	95	0	0	14	0	4	1	GB
	YU	12	22	3	25	34	1	0	35	12	18	16	79	0	1	108	0	6	0	24	0	YU
	REM	0	1	2	1	2	1	0	49	2	4	2	2	0	1	17	0	3	0	1	2	REM
	BAS	0	4	11	1	19	131	27	33	96	95	0	8	0	5	3	1	44	6	155	0	BAS
	NOS	0	1	61	0	8	116	1	303	41	111	0	1	0	49	1	1	181	20	35	1	NOS
	ATL	0	1	21	0	3	26	5	378	17	29	0	1	5	261	1	1	38	27	18	29	ATL
	MED	19	12	11	30	22	5	0	276	13	28	81	28	0	4	324	1	17	0	19	6	MED
	BLS	0	1	0	27	7	1	0	2	3	3	6	8	0	0	3	0	1	0	21	0	BLS
	SUM	122	486	737	757	1239	1005	296	6229	1656	2715	504	1003	15	1023	2345	42	1686	267	3200	283	SUM
		AL	AT	BE	BG	CS	DK	FI	FR	DD	DE	GR	HU	IS	IE	IT	LU	NL	NO	PL	PT	

Emitters

		RO	ES	SE	CH	TR	SU	GB	YU	REM	BAS	NOS	ATL	MED	BLS	NAT	IND	SUM	
	AL	2	0	0	0	1	2	0	11	0	0	0	0	0	0	0	16	134	AL
	AT	4	2	1	16	1	4	10	12	0	0	0	0	0	0	0	43	769	AT
	BE	0	1	0	0	0	1	20	0	0	0	0	0	0	0	0	15	501	BE
	BG	88	0	0	0	10	56	0	30	0	0	0	0	0	0	0	52	806	BG
	CS	13	1	1	3	1	20	10	10	0	0	0	0	0	0	0	54	1206	CS
	DK	0	0	5	0	0	5	17	0	0	0	0	0	0	0	0	18	585	DK
	FI	2	0	15	0	0	196	6	1	0	0	0	0	0	0	0	103	618	FI
	FR	1	67	1	15	0	4	91	3	2	0	0	0	0	0	0	231	4740	FR
	DD	1	1	2	2	0	7	18	1	0	0	0	0	0	0	0	41	1201	DD
	DE	3	5	2	38	0	11	74	3	0	0	0	0	0	0	0	112	2706	DE
	GR	13	1	0	0	12	17	1	14	1	0	0	0	0	0	0	62	509	GR
	HU	31	0	0	1	0	12	2	33	0	0	0	0	0	0	0	35	777	HU
	IS	0	0	0	0	0	2	5	0	0	0	0	0	0	0	0	19	42	IS
R	IE	0	0	0	0	0	0	31	0	0	0	0	0	0	0	0	16	599	IE
e	IT	4	12	1	22	0	4	11	26	4	0	0	0	0	0	0	148	2049	IT
c	LU	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	29	LU
e	NL	0	1	0	0	0	1	29	0	0	0	0	0	0	0	0	17	929	NL
i	NO	0	0	18	0	0	24	53	0	0	0	0	0	0	0	0	100	556	NO
v	PL	20	1	9	3	1	136	26	9	0	0	0	0	0	0	0	134	2855	PL
e	PT	0	27	0	0	0	0	1	0	0	0	0	0	0	0	0	17	230	PT
r	RO	1421	1	1	1	12	217	2	53	0	0	0	0	0	0	0	121	2137	RO
s	ES	1	1045	0	0	0	0	15	1	4	0	0	0	0	0	0	93	1346	ES
	SE	4	1	266	1	0	110	30	1	0	0	0	0	0	0	0	121	873	SE
	CH	0	4	0	237	0	1	7	1	0	0	0	0	0	0	0	27	491	CH
	TR	29	1	0	0	1821	116	1	9	1	0	0	0	0	0	0	218	2290	TR
	SU	256	2	36	4	182	14626	33	42	0	0	0	0	0	0	0	1525	18021	SU
	GB	0	2	1	0	0	1	1951	0	0	0	0	0	0	0	0	54	2216	GB
	YU	37	3	1	2	2	25	5	923	1	0	0	0	0	0	0	131	1527	YU
	REM	1	16	0	1	1	1	7	3	166	0	0	0	0	0	0	162	449	REM
	BAS	6	1	59	1	0	255	38	3	0	0	0	0	0	0	0	148	1148	BAS
	NOS	0	4	12	1	0	16	475	0	0	0	0	0	0	0	0	187	1625	NOS
	ATL	1	79	9	1	0	68	422	0	0	0	0	0	0	0	0	976	2419	ATL
	MED	32	76	1	7	52	42	24	68	34	0	0	0	0	0	0	478	1712	MED
	BLS	64	0	0	0	144	416	1	6	0	0	0	0	0	0	0	156	872	BLS
	SUM	2034	1353	443	359	2241	16394	3416	1262	217	0	0	0	0	0	0	5635	58959	SUM
		RO	ES	SE	CH	TR	SU	GB	YU	REM	BAS	NOS	ATL	MED	BLS	NAT	IND	SUM	

Table 3. Costs of N targets in Austria

Scenario	Total Costs (Million DM/year)	Total Costs (%)	Costs for NO_x (Million DM/year)	Costs for NH_3 (Million DM/year)
NO_x control only	16804	100	16804	0
Simultaneous control NO_x and NH_3	3552	21	1917	1635
Cost savings	13252	79	14887	-1635

Table 4. Emission levels of N targets in Austria

Scenario	Total Emissions (Kton N/year)	Total Emissions (%)	Emission NO_x (Kton NO_x/year)	Emission NH_3 (Kton NH_3/year)
NO_x control only	15548	100	27763	8620
Simultaneous control NO_x and NH_3	16239	104	31338	8137
Emission savings	-690	4	3575	-483

Table 5. Costs of N targets in Austria with current reduction plans

Scenario	Total Costs (Million DM/year)	Total Costs (%)	Costs for NO_x (Million DM/year)	Costs for NH_3 (Million DM/year)
NO_x control only	28718	100	28718	0
Simultaneous control NO_x and NH_3	25002	87	24954	57
Cost savings	3716	13	3764	-57

Table 6. Emission levels of N targets in Austria with current reduction plans

Scenario	Total Emissions (Kton N/year)	Total Emissions (%)	Emission NO_x (Kton NO_x/year)	Emission NH_3 (Kton NH_3/year)
NO_x control only	14995	100	25946	8620
Simultaneous control NO_x and NH_3	15429	104	27461	8587
Emission savings	434	3	1515	-33

Table 7. Costs of nitrogen deposition with current reduction plans

Scenario	Total Costs (Million DM/year)	Total Costs (%)	Costs for NO_x (Million DM/year)	Costs for NH_3 (Million DM/year)
Current Reduction Plans	24946	100	24946	0
Optimal NO_x control only	22443	90	22443	0
Simultaneous control NO_x and NH_3	13923	56	10095	3828
Cost savings	11023	44	14851	-3828

Table 8. Emission levels of current reduction plans

Scenario	Total Emissions (Kton N/year)	Total Emissions (%)	Emission NO_x (Kton NO_x/year)	Emission NH_3 (Kton NH_3/year)
Current Reduction Plans	15456	100	27461	8620
Optimal NO_x control only	14610	95	24680	8620
Simultaneous control NO_x and NH_3	14492	94	26607	7764
Emission savings	964	6	-854	-856

Table 9. Costs of Current Reduction Plans for NO_x per country

Scenario	Costs NO_x (mio DM)			Costs NH_3 (mio DM)		
Country	NO_x only	NO_x optimized	NO_x + NH_3	NO_x only	NO_x optimized	NO_x + NH_3
Albania	0	3	1	0	0	0
Austria	501	50	12	0	0	21
Belgium	1076	1509	153	0	0	120
Bulgaria	1131	250	37	0	0	9
CSFR	13	64	64	0	0	7
Denmark	453	283	120	0	0	178
Finland	657	137	102	0	0	14
France	4242	3815	1651	0	0	1338
FRG	4139	3689	842	0	0	438
GDR	0	27	27	0	0	13
Greece	0	24	23	0	0	0
Hungary	0	21	21	0	0	10
Ireland	0	7	53	0	0	7
Italy	5549	4947	1914	0	0	762
Luxembourg	69	119	10	0	0	6
Netherlands	1589	1347	147	0	0	222
Norway	442	375	245	0	0	191
Poland	0	143	143	0	0	13
Portugal	0	12	12	0	0	2
Romania	0	75	22	0	0	4
Spain	0	56	297	0	0	242
Sweden	619	300	122	0	0	95
Switzerland	509	562	2	0	0	53
Turkey	0	7	8	0	0	0
UK	3947	3807	3254	0	0	55
USSR	0	707	707	0	0	13
Yugoslavia	0	94	94	0	0	6
Sum	24936	22430	10083	0	0	3819

Table 10. Costs of maximum feasible reductions for NO_x

Scenario	Total Costs (Million DM/year)	Total Costs (%)	Costs for NO_x (Million DM/year)	Costs for NH_3 (Million DM/year)
Maximum Feasible Reduction NO_x	95033	100	95033	0
Simultaneous control NO_x and NH_3	73414	77	60545	12868
Cost savings	21619	23	34488	-12868

Table 11. Emission levels of maximum feasible NO_x reduction

Scenario	Total Emissions (Kton N/year)	Total Emissions (%)	Emission NO_x (Kton NO_x/year)	Emission NH_3 (Kton NH_3/year)
Maximum Feasible Reductions NO_x	11152	100	13316	8620
Simultaneous control NO_x and NH_3	10723	96	17724	6471
Emission savings	429	4	-4408	-2149

Table 12. Costs of maximum feasible reductions per country (DM/year)

Scenario	Costs for NO_x control			Costs NH_3 control		
Country	NO_x only	NO_x + NH_3	Difference	NO_x only	NO_x + NH_3	Difference
Albania	165	3	-162	0	53	+53
Austria	841	82	-759	0	130	+130
Belgium	1395	3339	-1062	0	120	+120
Bulgaria	1435	462	-973	0	101	+101
CSFR	1728	64	-1664	0	345	345
Denmark	1195	1082	-113	0	178	178
Finland	977	832	-145	0	88	88
France	7619	6043	-1576	0	1338	1338
FRG	8890	5680	-3210	0	954	954
GDR	1020	27	-993	0	296	296
Greece	1425	1312	-113	0	84	84
Hungary	637	154	-483	0	128	128
Ireland	373	261	-112	0	7	7
Italy	8033	7277	-756	0	1354	+1354
Luxembourg	92	119	+27	0	8	8
Netherlands	1824	147	-1677	0	222	222
Norway	848	717	-131	0	200	+200
Poland	4212	1078	-3134	0	731	731
Portugal	1109	412	-697	0	103	103
Romania	2781	75	-2706	0	397	397
Spain	6158	5273	-885	0	621	621
Sweden	1158	1081	-77	0	127	127
Switzerland	876	2	-874	0	53	53
Turkey	0	74	+74	0	185	185
UK	8786	7811	-975	0	583	583
USSR	28646	19770	-8876	0	4167	4167
Yugoslavia	2789	361	-2428	0	289	289
Sum	95012	60532	-34480	0	12862	12862