International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Optimal Sulfur Dioxide Abatement Policies in Europe: Some Examples

Batterman, S., Amann, M., Hettelingh, J.-P., Hordijk, L. and Kornai, G.

IIASA Working Paper

WP-86-042

August 1986

WORKING PAPER

OPTIMAL SO_2 ABATEMENT POLICIES IN EUROPE:
SOME EXAMPLES

Stuart Batterman
Markus Amann
Jean-Paul Hettelingh
Leen Hordijk
Gabor Kornai

August 1986
WP-86-042

IIASA
International Institute
for Applied Systems Analysis

OPTIMAL SO_2 ABATEMENT POLICIES IN EUROPE: SOME EXAMPLES

Stuart Batterman
Markus Amann
Jean-Paul Hettelingh
Leen Hordijk
Gabor Kornai

August 1986
WP-86-42

INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

PREFACE

IIASA's Acid Rain project has developed an interactive computer model for the evaluation of acidification abatement policies. Two important additions to the RAINS model have been produced recently: a cost-of-control submodel and an optimization mode. Combination of these two new features and existing submodels allows a completely new approach to the European acidification problem. In addition to scenario evaluation, cost-effective emission reduction policies and environmentally targetted policies can now be constructed. The research reported in this paper illustrates the use of the new submodels. In a separate paper the cost-of-control submodel will be described in detail.

This paper has been prepared at the request of the secretariat of the Convention on Long-range Transboundary Air Pollution, and has been presented at a meeting of designated experts on costs and benefits, 19-21 August 1986, Geneva.

Leen Hordijk
Leader, Acid Rain Project

ACKNOWLEDGEMENTS

The authors are grateful to B. Lübkert (OECD), B. Schärer (Umweltbundesamt, FRG), D. Streets (Argonne National Laboratory, USA) and B. Tangena (National Institute for Public Health and Environmental Hygiene, Netherlands), who were involved in discussions about the cost of control submodel. We are also indebted to the many individuals who worked and have been working in the Acid Rain Project. Vicky Hsiung skillfully typed the several drafts of this paper. The World Meteorological Organization and the UN Economic Commission for Europe have given permission to use results from the EMEP programme. The Norwegian Meteorological Institute provided the atmospheric transfer matrices used in this paper. Support from the Nordic Council of Ministers, the Umweltbundesamt, FRG, the Dutch Priority Programme on Acidification and the US Department of Energy, is gratefully acknowledged.

The authors assume sole responsibility for the contents of this paper.

TABLE OF CONTENTS

OPTIMAL SO_2 ABATEMENT POLICIES IN EUROPE: SOME EXAMPLES

Stuart Batterman, Markus Amann, Jean-Paul Hettelingh,
Leen Hordijk and Gabor Kornai

1. INTRODUCTION

Governments of Europe and North America are under increasing pressure to take remedial action against acidification of the environment. Also increasing is the amount and diversity of scientific and engineering research devoted to this subject. The link between political decisions and scientific evidence concerning acidification has not been very strong, although a number of countries have started research programmes on acidification.

In an attempt to link science and policy making on the European level, the International Institute for Applied Systems Analysis started an Acid Rain Project in 1983. The principal goal of this project is the development of a policy-support system of models that could be used at international and national levels in the effort to develop coordinated strategies for reduction of emissions. To date the work has concentrated on emissions and effects of SO_2.

This paper focuses on two recent additions to the RAINS model (Regional Acidification Information and Simulation). In Chapter 2 the model is described briefly, whereas in Chapter 3 an overview of current SO_2 reduction plans in Europe is presented together with examples of graphical output options of RAINS. Chapter 4 presents the new costs and optimization submodels. Examples of various optimal reduction strategies for Europe are shown in Chapter 5.

2. THE RAINS MODEL

IIASA's model of acid deposition is an interactive set of submodels with graphical output. The model has been developed in collaboration with the UN Economic Commission for Europe and in the context of the Convention on Long Range Transboundary Air Pollution. The framework of the RAINS model consists of three compartments: *Pollution Generation, Atmospheric Processes* and *Environmental Impacts.* Each of these compartments can be filled by different and substitutable submodels. The submodels currently available are *Sulfur Emissions, EMEP Long Range Transport, Forest Soil Acidity* and *Lake Acidity.* The RAINS model has been presented in more detail in Alcamo et al. (1985) and Hordijk (1985).

Figure 1 depicts the current status of the RAINS model including the extensions discussed in this paper. Starting from the top of the figure the RAINS data bank contains a number of different energy pathways for Europe. These energy pathways have been derived from publications by the Economic Commission for Europe (1983) and the International Energy Agency (1985) for each of the 27 larger European countries. The energy use per country is broken down into 8 categories of fuel: hard coal, brown coal, derived coal, light oil, heavy oil, crude oil, gas and others (hydro, nuclear, biomass). The emission producing sectors are conversion (refineries), power plants, industry, domestic, transport and other. The emissions of SO_2 per fuel and sector have been calculated for combustion processes using sulfur content and heat values of the fuels. These numbers were collected from many different sources, both international (UN, OECD) and national.

The model user has many ways to influence model runs, beginning with the choice of an energy pathway. Since we consider the energy future to be one of the largest uncertainties, we have left the choice of a particular energy pathway to the user. The next submodel of RAINS, which calculates SO_2 emissions, can also be influenced by the user. A menu presents options for abatement strategies: fuel switching, physical or chemical fuel cleaning, desulfurization units, and combustion modifications. The user can select a combination of strategies for any country or combination of countries and the year of implementation. The costs of the control policy constructed by the user will then be presented.

The SO_2 emissions provide inputs to the atmospheric transport submodel. Currently RAINS uses transfer matrices derived from the atmospheric transport model developed at the Meteorologic Synthesizing Center-West of the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) in Oslo. This model has been described *inter alia* in Eliassen and Saltbones (1983) and WMO (1984). The transfer matrices are used to calculate sulfur depositions and SO_2 concentrations in grid squares of 150 x 150 km over all of Europe. A user of RAINS may obtain deposition output in the form of isolines, colored maps or three dimensional pictures.

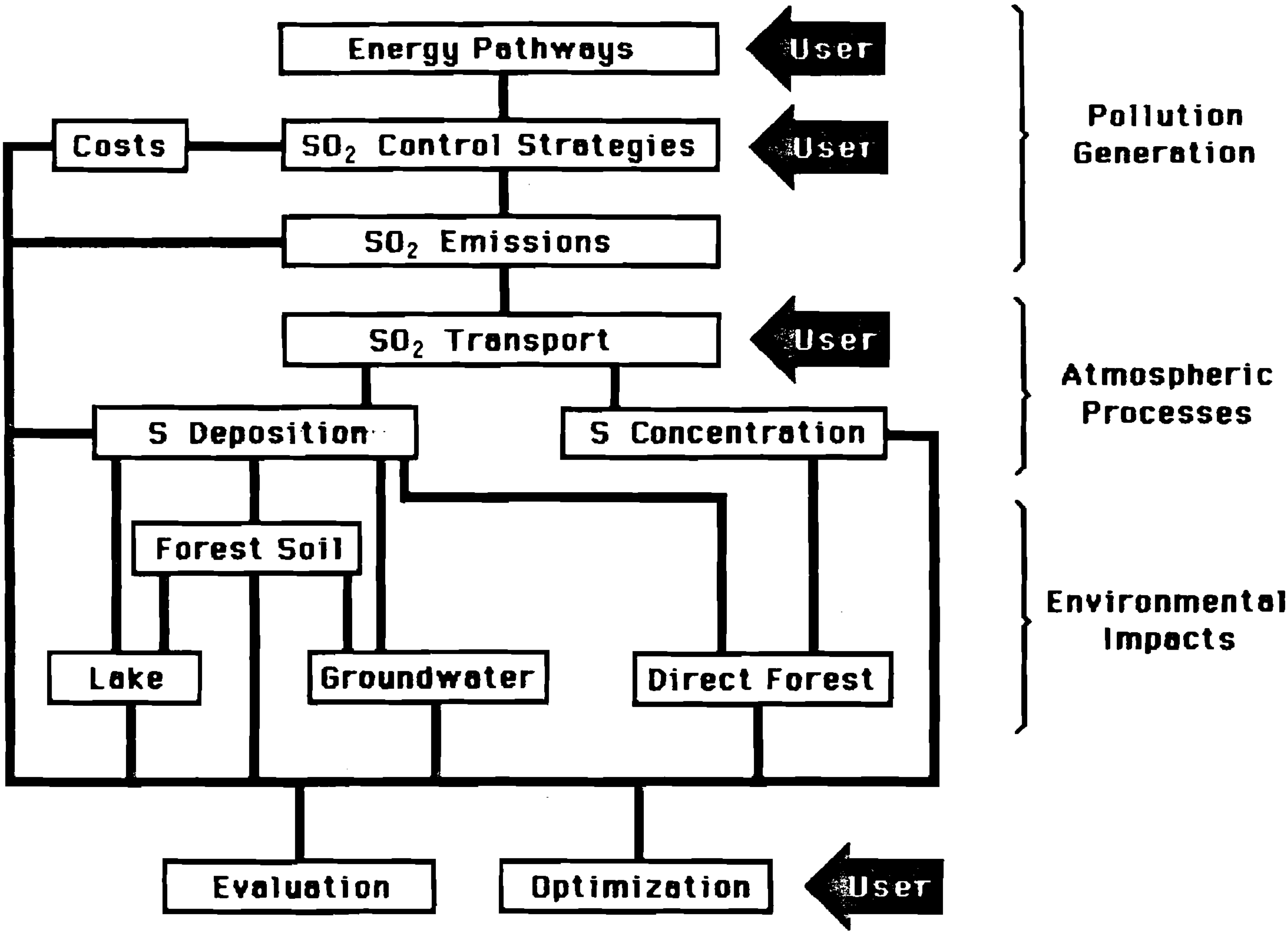


Figure 1. Structure of the RAINS model and its submodels.

The outputs of the atmospheric transport submodel are used in the forest soil and lake acidity submodels. Soil acidification has been described as a decrease in the acid neutralizing capacity of the soil (van Breemen et al., 1984), which may coincide with a decrease in soil pH. The reaction of the soil to the incoming acid stress depends on the soil's buffering properties. These properties are described using two variables, one for the gross potential (buffer capacity) and the other for the rate of the reaction (buffer rate). Buffering is assumed to be governed by several reactions: carbonate, silicate weathering, cation exchange and aluminum buffering. The data bank for the forest soil submodel contains the spatial distribution of 88 soil types in grids of 1^o longitude by 0.5^o latitude. Model output is provided in maps and graphs for soil pH, Al^{3+} concentration, Ca^{2+}/Al^{3+} ratios and base saturation levels. The forest soil submodel has been described in detail in Kauppi et al. (1985), Kämäri et al. (1985a) and Posch et al. (1985).

The lake acidification submodel consists of several components for meteorology, hydrology, soil chemistry and water quality of lakes. The meteorologic submodel regulates input flows of water and deposition to the soil and directly to the lake. The hydrologic and soil chemistry submodels together determine the flow of ions leaching from the terrestrial catchment to the lake. New equilibrium concentrations in the lake water are then computed in the lake submodel. Currently this submodel has been implemented for Finland and Sweden. Model output is in the form of maps showing spring or summer pH of lake areas. Documentation of the submodel is provided in Kämäri et al. (1985b,c, 1986).

Current and future work on the RAINS model concerns the following topics. In collaboration with OECD, a model for estimating NO_x emissions is under development. The number of energy pathways will be extended to include options which maximize the use of natural gas and which reflect increased efforts in energy conservation throughout Europe. The structure of the energy and emissions submodel is being changed to allow for increased user interaction. The *Environmental Impacts* compartment will contain two more submodels: *Direct Impacts on Forests* (Mäkelä, 1986) and *Groundwater Acidification* (Holmberg, 1986). Quantification of the sensitivity and the uncertainty of the submodels forms a substantial part of the work program. A method for uncertainty analysis has been developed and applied to the EMEP model (cf. Alcamo and Bartnicki, 1985 and Alcamo et al. 1986) and is being applied to the sulfur emissions submodel. Results of analogous studies for the forest soil and lake submodels are reported in Posch et al. (1985) and Kämäri et al. (1986) respectively. To improve the transportability of RAINS the computer code for use on a micro computer will be available shortly. Other additions to RAINS include the cost of control of SO_2 emissions and an optimization mode. These additions are discussed in Chapter 4.

3. CURRENT REDUCTION PLANS

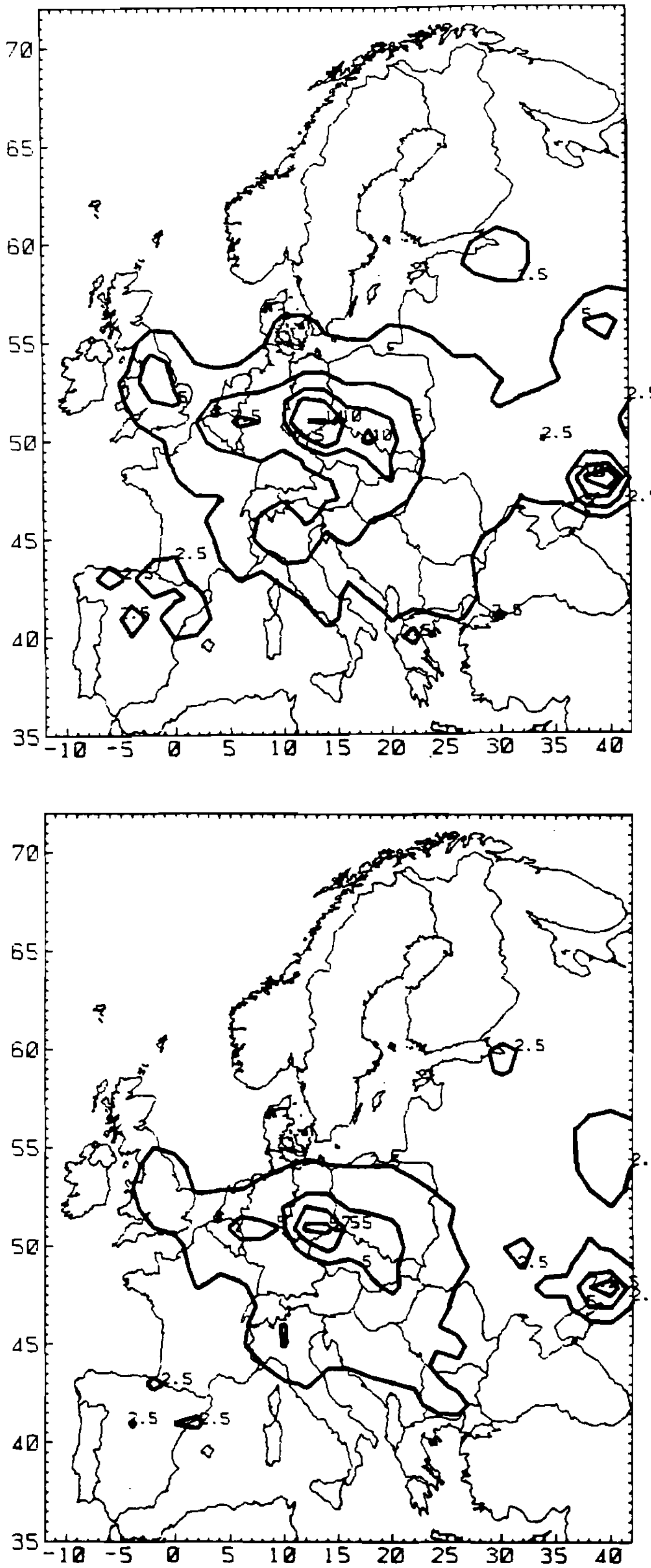
International negotiations focus on the year 1980 as a basis for SO_2 emission reductions. The Protocol to the Convention on Long-Range Transboundary Air Pollution states in Article 2: "The Parties shall reduce their national annual sulphur emissions or their transboundary fluxes by at least 30% as soon as possible and at the latest by 1993, using 1980 levels as the basis for calculation of reductions" (ECE, 1985, Annex I). It is therefore important to have a good estimate of the 1980 emission levels of SO_2. Table 1 lists 1980 emissions of SO_2 (measured as kilotonnes sulfur). In the first column of the table emissions currently used in the EMEP programme are given (see Dovland and Saltbones, 1986). The second column provides results from the RAINS submodel for energy and emissions. For most countries the differences are small. The RAINS emissions are used in subsequent chapters of this paper.

The 21 parties to the Convention that signed the Protocol are also indicated in Table 1. In the third column we present percentage reductions for these countries, which reflect our current understanding of the reduction plans. The numbers are taken from several presentations by country representatives. A final column of Table 1 provides an estimate of 1993/5 emissions of SO_2 based on the 1980 emissions as estimated in RAINS and the reduction percentages given in the third column.

The graphical output modes of RAINS allow quick inspection and comparison of deposition isolines emerging from different emission patterns. Figure 2 depicts sulfur deposition isolines for the 1980 emissions and the 1993/5 emissions. A four-year averaged transfer matrix was used for the calculations. Another mode of graphical output of RAINS viz. a three-dimensional picture of depositions is shown in Figure 3.

Table 1. **Emissions of SO_2 in European countries in 1980 (Kilotonnes sulfur).**

Country	From EMEP data	Estimated within RAINS	Current reduction plans (percentages)	Emissions after reductions using RAINS estimates
Albania	25	39	0	39
Austria	162	159	50	80
Belgium	428	432	50	216
Bulgaria	500	507	30	355
Czechoslovakia	1550	1832	30	1282
Denmark	208	226	50	113
Finland	290	294	50	147
France	1635	1657	50	829
German Dem.Rep.	2000	2415	30	1691
Federal Rep. of Germany	1600	1602	60	641
Greece	352	345	0	345
Hungary	817	813	30	569
Ireland	108	119	0	119
Italy	1900	1898	30	1329
Luxembourg	14	20	30	14
Netherlands	240	243	60	97
Norway	70	72	50	36
Poland	1375	1741	0	1741
Portugal	79	130	0	130
Romania	100	757	0	757
Spain	1638	1879	0	1879
Sweden	248	243	65	85
Switzerland	60	67	30	47
Turkey	483	497	0	497
USSR	8100	8588	30	6012
United Kingdom	2335	2342	0	2342
Yugoslavia	588	837	0	837
Europe Total	26905	29754	25	22229



(a)

(b)

Figure 2. Sulfur deposition isolines for 1980 (a) and after implementation of current reduction plans (1995) (b). Isopleths for 2.5, 5, 7.5 and 10 g/m^2-yr are shown.

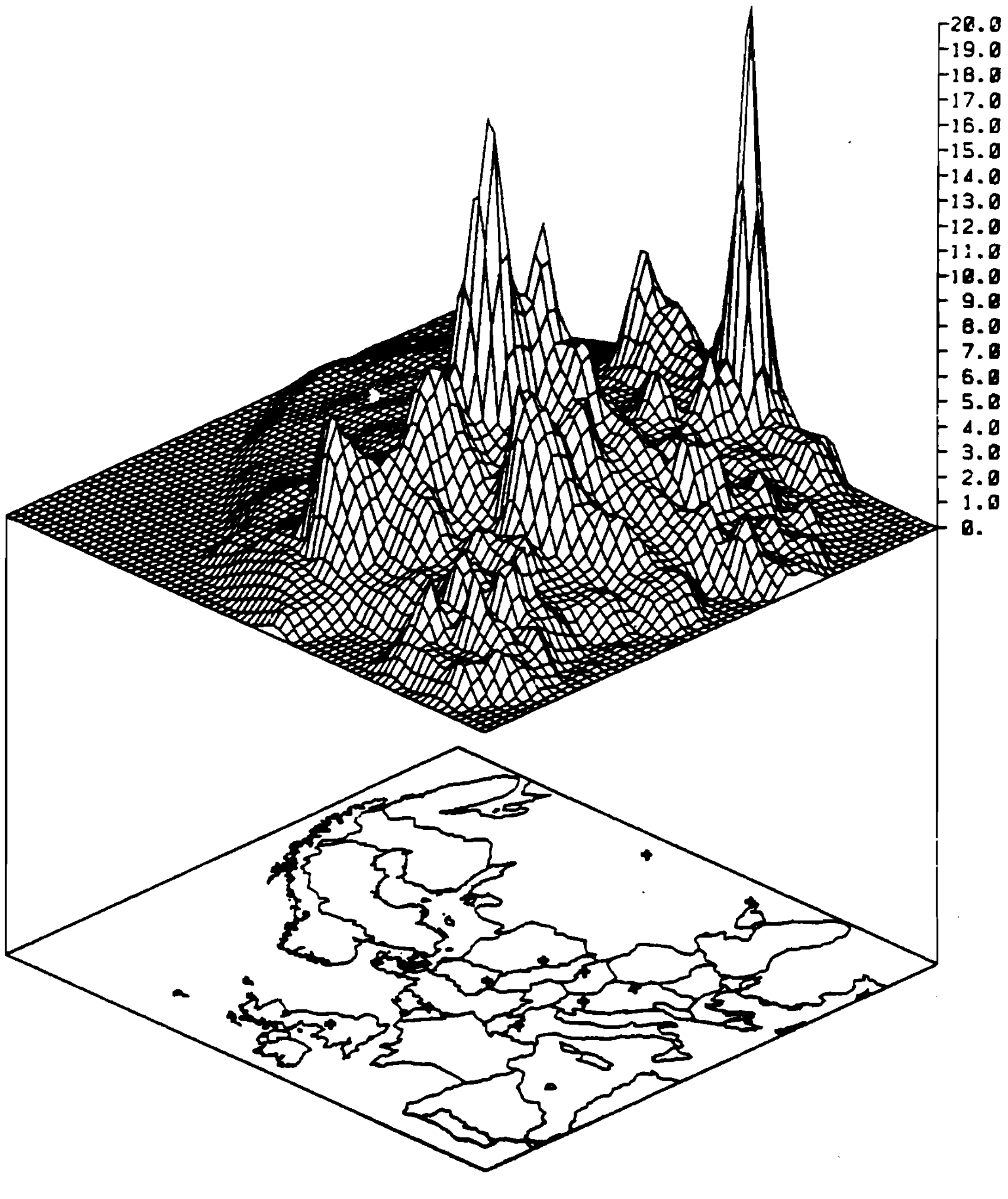


Figure 3. Calculated deposition (gram $S/m^2/yr$) in Europe, 1980. The ten highest deposition areas are indicated on the map.

4. EXTENSION OF RAINS

This chapter contains two parts describing the new submodels being incorporated into the RAINS model. In section 4.1 the cost-of-control submodel, which is under development, is presented. Section 4.2 discusses the formulation and use of the optimization submodel.

4.1. Control costs

This section discusses the present preliminary status of the cost submodel of RAINS. First, an overview of the approach and its limitations are provided. Then the control options are discussed. Lastly the national cost functions are described.

4.1.1. Overview and limitations of the approach

Within the context of the overall goals of RAINS (see Chapter 2), the cost submodel estimates pollution control costs in an internationally comparable way. Rather than a statistical or economic analysis, an engineering approach was used to estimate control costs. In brief, the approach comprises the following steps:

- Specification of emission control options for each sector and fuel type.
- Specification of technology-specific cost functions by means of activity analysis.
- Derivation of country-specific national cost curves based on the technology-specific cost functions.

To avoid the misuse of this politically sensitive submodel, it is important to specify the limitations of the model. The present cost submodel is limited to the control of sulfur emissions. Of the many *social* costs and benefits of control policies we deal almost exclusively with the *direct* costs related to *certain* emission abatement options in combustion processes. We do not consider other pollutants, the costs of mitigation of environmental effects and second and higher order interactions between pollution control and economic growth, sectoral composition, supply and demand issues, international trade, etc.

Due to the lack of detailed data, control of sulfur emissions from non-combustion *processes*, is not yet included in our model. Further limitations are caused by the lack of internationally comparable emission control data for the 27 countries modeled.

During the development of RAINS it was decided that a number of energy pathways would be available to the user. Consequently, primary fuel switching and energy conservation are not yet considered as emission reducing options. However, the costs of these strategies can be obtained indirectly by comparing abatement costs of different energy pathways.

4.1.2. Emission control strategies

In general, four major strategies to reduce sulfur emissions from the energy-use sectors exist:

1. *Emission control technologies* applied before, during or after the combustion processes.
2. *Use of low sulfur coal and oil*
3. *Fuel switching* substitutes natural gas, hydro- or nuclear power for high sulfur coal and oil without substantially changing the final energy demand. Fuel switches may also be motivated by economic and political considerations.
4. *Energy conservation* uses less primary energy by either reducing the energy demand or increasing the efficiency of combustion processes. Associated costs and benefits may be related largely to economic and energy policies.

The first two control strategies are currently incorporated into RAINS. Work is underway to include fuel switching. Energy conservation strategies may be evaluated by modifying the energy pathway.

4.1.3. Technology-specific cost functions

The sulfur abatement technologies for combustion systems currently considered include the following options:

- *Pre-combustion*:
  - Desulfurization of oil reduces the sulfur content of light oil fractions to 0.15 per cent, heavy fuel oils to 1 per cent.
- *Low-emission combustion processes*:
  - In-furnace lime injection for coal combustion removing 30 to 60% of SO_2. In this technique, lime or limestone is blown into the combustion chamber and the end product is filtered out of the flue gas. The relatively large amount of residue requires disposal.
- *Flue gas desulfurization processes* (FGD) covering a range from 50 to 98% sulfur removal. The following processes are considered:
  - Wet lime/limestone scrubbing: binds the sulfur dioxide with a limestone slurry producing either solid gypsum or calcium sulfate and sulfite. Gypsum may be either sold or disposed. This process is used in about 90% of all FGD applications, typically accomplishing sulfur removal rates of 90% (Schärer and Haug, 1986).
  - Wellman-Lord process: here the sulfur dioxide is absorbed into a solution of sulfites and sulfates which may be further processed to obtain liquid SO_2, elemental sulfur or sulfuric acid. This relatively expensive technology is applied where the by-products can be directly used, or at locations with limited facilities for transportation and waste disposal. We assume a 98% sulfur removal efficiency.

Table 2 describes our assumptions regarding the applicability of these control technologies to the different sectors and fuels.

Annualized unit costs of sulfur removal are estimated based on total investment costs and fixed- and variable operating and maintenance (O&M) costs. Our analysis has concentrated on finding the most important indicators which reflect these items. Table 3 lists the variables used to compute abatement.

Table 2. Potential use of abatement technologies by sectors and fuels.

Sector	Fuel type	Use of low sulfur fuel	Limestone injection	Wet FGD	Wellman-Lord process
Power plants	Hard coal	√	√	√	
	Brown coal		√	√	
	Oil	√		√	
Conversion	Hard coal	√		√	
	Oil	√		√	√
Domestic	Hard coal	√			
	Derived coal	√			
	Oil	√			
Industry	Hard coal	√	√	√	√
	Brown coal		√	√	√
	Derived coal	√	√	√	√
	Oil	√		√	√
Transportation	Oil	√			

Table 3. Variables used in computing costs of control technologies.

Generic variables
Technology-specific investment cost functions (FRG)
Lifetime (30 years)
Share of investments to fixed O&M costs
Real interest rate for CPE's (4%)
Boiler capacity in industry (50 MW_{el})
No retrofit
Sulfur removal efficiency (90 % wet/dry, 98 % Wellman-Lord)
Stoichiometric ratios
Thermal efficiency of combustion
Electricity price
Absorbent price
By-product price
Disposal cost
Additional energy demand
Country-specific variables
Real interest rate for market economies
Boiler size in power plants
Sulfur content by fuels (at plant site)
Heat value by fuels
Capacity utilization

Investment costs represent the total direct costs of the investment (materials, construction related labour, etc.). The boiler size is used as an indicator to estimate investment costs. Due to the relatively poor country specific data on the size distribution of industrial boilers we assume a uniform size of 50 MW_{el}. For power plants investment costs are calculated using the national average boiler size.

Fixed O&M costs (including insurance, taxes etc.) are assumed to be proportional to investment costs. Typical average ratios from the literature (Schärer and Haug, 1986; OECD, 1986; Inaba, 1985; Rentz, 1984) are used for all countries.

Investment and fixed O&M costs are incorporated into *capacity related annual costs.* Annual investment costs are obtained assuming country-specific real rates of interest based on 1984 data (OECD, 1985) for the market economies and 4% for the centrally planned economies. We have not yet distinguished new and retrofit installations, but instead assume that all plants are new with an economic life-time of 30 years.

Variable O&M costs include the costs of additional energy demand, absorbents and waste disposal. Energy costs are related to electricity prices and combustion process efficiencies. Absorbent and disposal costs depend on sulfur contents and fuel heat values, observing constant ratios of sulfur to absorbent and absorbent to end-product. Potential benefits from selling the by-products are also considered. All prices presently used in the model are derived from data for the Federal Republic of Germany (Schärer and Haug, 1986).

Energy-specific total annual costs are obtained by relating the capacity related plus variable O&M costs to actual energy units. This calculus takes into account country-specific capacity utilization ratios, i.e., capacity factors, expressed in terms of annual operating hours, as well as the efficiencies of combustion processes.

Currently the basic currency of the cost submodel is Deutschmarks (DM). Since all prices have been derived from data of the FRG, exchange rates are not used. Because only a limited number of control technologies is considered and few country specific variables are introduced, the cost functions used in this paper are tentative. Consequently, in this paper results are presented using cost indices.

In summary, the above calculations provide country-, sector-, fuel- and control technology-specific values for the *cost* of abating a ton of sulfur per unit of energy, and the sulfur removing *potential*, corresponding to the structure of a given energy pathway. These values may be computed for any time period and energy pathway. The model user may alter technologies, fuel choices and capacities using a menu in the RAINS model. Energy flows and mass balances are conserved in the computations.

4.1.4. National Cost Curves

The national cost function is defined as the minimal cost envelope encompassing the entire range of sulfur abatement options for a given country, energy pathway and time period. Consequently we have assumed that all national abatements are cost minimizing, which permits international comparison of costs. Legislation introduced by some countries (e.g. the

Ordinance on Large Firing Installations in the FRG) is neglected.

The cost curves are derived by minimizing total costs subject to various sulfur reduction requirements, which range up to the maximum technological feasible removal. The resulting national cost curve consists of piecewise linear approximations, typically containing 20 to 30 segments. Typical shapes are shown in Figure 4. These curves were estimated using the official energy forecast of the governments for the year 2000 (IEA, 1985; ECE, 1983). The arrows indicate emission levels corresponding to a 30% reduction from 1980 emissions. Due to the non fossil fuel based energy pathway country A has no cost in meeting a 30% reduction; country B must spend 400 million DM.

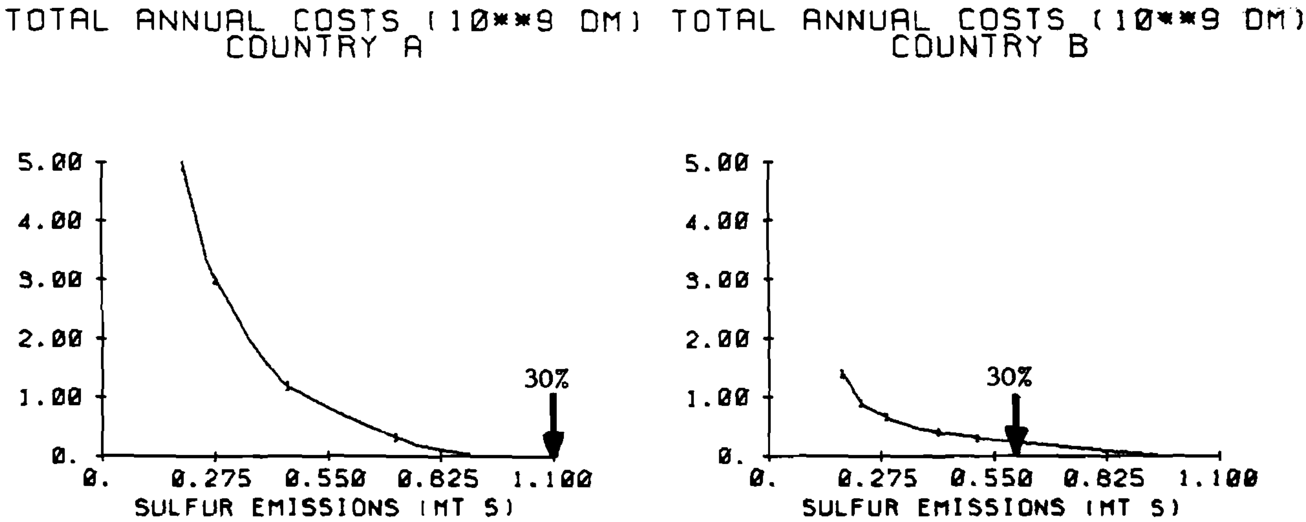


Figure 4. Two national total cost curves.

4.2. Optimization

This section reviews the formalization and use of the optimization submodel of RAINS as applied to targetted emission control strategies. First, the general framework is developed, including a discussion of targets and indicators. Second, the current status of the optimization submodel is described. Lastly, limitations of targetted strategies are discussed.

4.2.1. Targetted emission control strategies

The optimization submodel of the RAINS model permits the generation and analysis of *targetted* emission control strategies based on *indicators*. Indicators represent environmental impacts, economic factors, and/or other policy objectives. In targetted strategies, the sulfur (and perhaps NO_x) reductions of each European country are determined in a manner which meets the goals or constraints implied by the indicators in an economical or efficient fashion. Some targetted strategies of interest might include.

- Th country-by-country emission reductions required to achieve a specified S deposition criteria at the least cost.
- The emission reductions required to achieve a specified deposition criteria by removing the least amount of sulfur.
- The emission reductions which yield a low probability of environmental damage at the minimum cost.

These and other targetted strategies can be evaluated using the optimization submodel of RAINS.

Indicators in targetted strategies fall into three general classes:

1. *Environmental* indicators measure impacts or the risk of such impacts to 1) forests; 2) surface and groundwater; 3) agricultural production; 4) materials; and 5) human health. Useful indicators may include ambient concentration, deposition, lake acidity, change in soil pH, and forest damage. Environmental indicators may apply to some or all of the receptors in the model.
2. *Economic* indicators estimate the cost of emission controls and fuel substitution.
3. *Policy* indicators are related to equity and the feasibility of the control strategies. These indicators might represent the ability of the various countries to implement control strategies, the desirability of achieving similar environmental impacts on a per capita basis, minimum reductions for countries, or other goals.

Indicators may be used separately or jointly. For example, the targetted control strategy might be a cost minimizing solution satisfying both environmental and policy indicators. The interpretation of model results becomes more complex with multiple indicators.

The choice of indicators may crucially affect the outcome of the targetted control strategy. Consider, for example, indicators representing environmental effects. Indicators related to lake acidification would tend to affect depositions and emissions in northern Europe, while indicators related to forest impacts would influence areas in central Europe. Ideally, deposition or concentration thresholds should correspond to the sensitivity of land and water areas over Europe. However, the specification of deposition or concentration thresholds is difficult given the state-of-the-art of present ecological modeling and the available information. In addition, the specification of such targets may be highly controversial. Some components in the RAINS model may be used to derive environmental targets, e.g., the lake acidification submodel, forest impacts and ground water acidity. However, the latter two of these submodels are under development; and the lake submodel has been applied to only a portion of Europe. Consequently several alternative and simpler approaches are used to specify deposition targets, as described below.

4.2.2. Current status of the optimization submodel

At present, the optimization submodel employs a single objective, linear program operated in a quasi-interactive fashion on a mainframe computer. (A smaller scale version has been developed for use on a personal computer.) Mathematically, goals or targets are specified as constraints in the linear program. Constraints are equations which define the "feasible region" of possible solutions, which is then searched for the optimum. This formulation is conceptually equal to work by Ellis et al. (1985), Fortin and McBean (1983) and Morrison and Rubin (1985), although the application differs in numerous ways. The extension to non-linear problems, e.g., using soil or lake acidity as targets, is a relatively straightforward modification of the current approach.

The user has the choice of objectives and constraints (or indicators), as discussed below. The existing implementation of objectives and targets is preliminary: work under development will greatly extend the capability of the submodel.

The objective functions currently implemented include (1) minimization of total European control costs, using the cost submodel discussed in Section 4.1; and (2) minimization of total European sulfur removal. Although European totals are used as objectives, the submodel calculates and displays costs and sulfur reductions for individual countries. Note that if control costs are constant and equal among countries, objectives (1) and (2) are equivalent. An "export" option allows those costs or removal quantities to be minimized which relate to sulfur transported across national boundaries. This option is used tc represent objectives expressed in fluxes, e.g. 50% reduction of transboundary fluxes at minimum cost.

Several simple constraints have been implemented. These include (1) upper and lower bounds on the removal fraction for each country; and (2) limits on the maximum sulfur deposition or SO_2 concentration at each receptor. Removal fractions are based on emissions from a base year, selected as 1980. For example, specifying a minimum removal of 30% and a maximum removal of 60% ensures that emissions of each country will be between 40 and 70% of the 1980 emissions.

Due to the difficulty of determining sensitive areas and establishing deposition goals, several alternative approaches were used to specify deposition targets. These approaches may not produce target levels which correspond to the environmental or ecological sensitivity. However, they demonstrate the flexibility of the method and provide a preliminary indication of the implications of targetted policies.

Currently there are three options for determining deposition limits. In option 1, a *maximum deposition* limit is specified for all of Europe, e.g., 5 g/m^2-yr at all receptors. With this target, for example, the optimization submodel could determine the lowest cost country-by-country emission reductions which result in calculated depositions of 5 g/m^2-yr or less at all receptors. However, receptors which already experience deposition below 5 g/m^2-yr may not obtain further reductions. In option 2, deposition limits are determined as the deposition resulting from a specified *reduction in emissions* for a base year, selected as 1980. For example, the depositions obtained by a 50% reduction in 1980 emissions can be used as maximum depositions. This option tends to preserve the 1980 deposition and/or concentration pattern over Europe, however, the absolute level of deposition is decreased from 1980 levels. In option 3, a *reduction function* is used to specify the deposition target at each receptor. In the present submodel, reductions for each receptor are specified as a function of calculated deposition levels in a base year (1980). Figure 5 shows two possible functions specifying the fraction by which deposition must be reduced. Line (a) shows deposition decreases which are proportional to the 1980 depositions. For example, deposition would be reduced by 75% at a receptor with a high (1980) deposition level of 20 g/m^2-yr; a receptor with a deposition of 5 g/m^2-yr would require only a 25% decrease in deposition. Curve (b) contains a threshold, implying a deposition level below which no reductions are necessary. In comparison to option 1, which may not achieve lower depositions at receptors which are already below the target, reduction functions may be specified which require reductions at all receptors.

The principal outputs of the optimization submodel are country-by-country emission reductions and costs. The environmental impacts of the targetted strategies, e.g., deposition levels, can be obtained using the scenario analysis mode of RAINS. Additional outputs of the optimization submodel include (1) amount of emissions per control classification reduced by each country; (2) marginal costs of the control strategy (e.g., maximum cost/ton of SO_2 reductions), and (3) shadow prices indicating the value of changing constraints, e.g. cost of control/amount sulfur deposition.

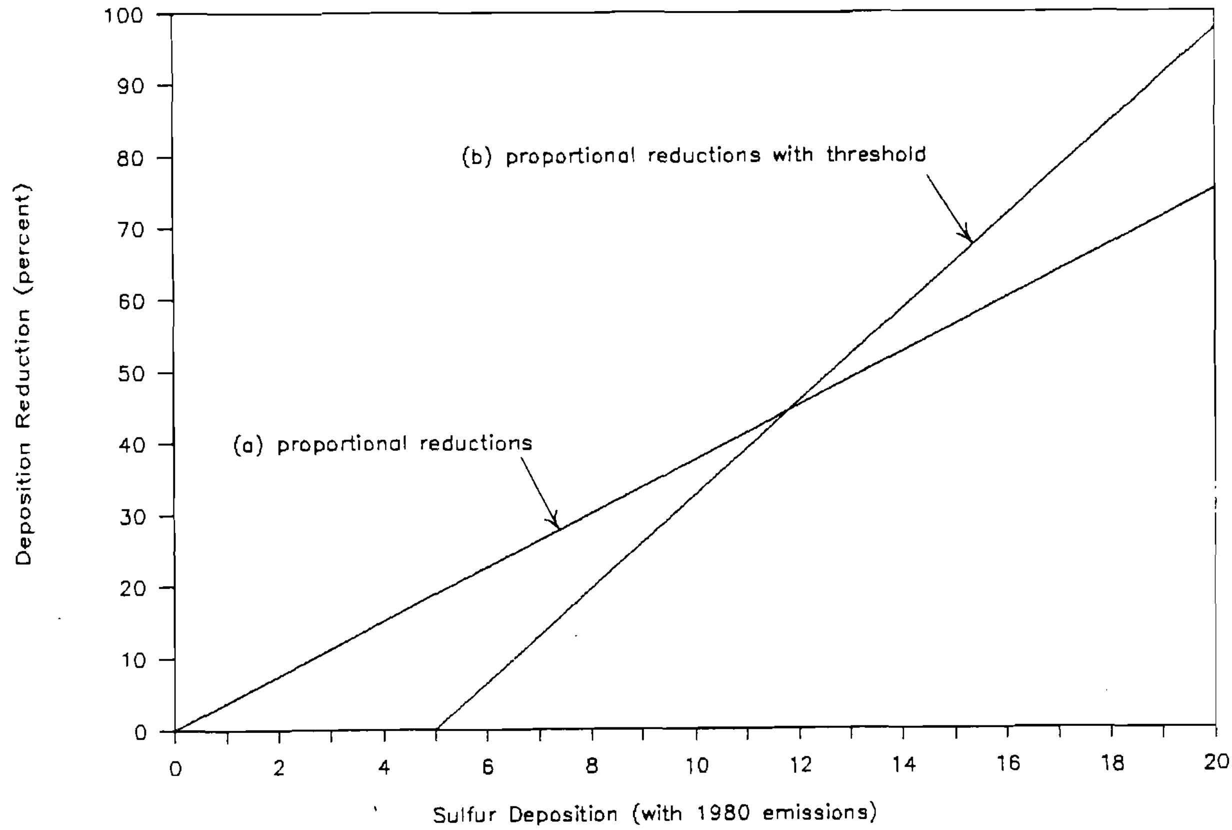


Figure 5. Two reduction functions.

4.2.3. Limitations

Models which formulate targetted strategies may be useful as policy tools if the model is credible. To enhance the usefulness of the model, results are presented in a comparative fashion, and a high degree of flexibility in targets is permitted. However, several shortcomings of targetted emission control approaches should be pointed out. These include the multi-objective nature of the problem; the uncertainty of the variables and models; and the inadequacy or irrelevance of expected or average performance given that decision makers may be sensitive to poor or even catastrophic outcomes which are not modeled. These ideas are further developed below.

In general, targetted emission control strategies are multiple objective optimization problems. We present results from the optimization submodel in a manner which shows the trade-offs entailed by single objective policies. Future versions of the model may permit a more interactive approach so that model users can interpret policy implications, alter their assumptions and objectives, and thus refine their goals to obtain satisfactory results. In addition, techniques which consider multiple and (usually) conflicting objectives of several decision makers are applicable. We have entered discussions with researchers who may use these techniques with the RAINS model (Witmuess et al., 1984).

At present, the optimization submodel is a deterministic formulation which does not consider model and data uncertainty. Moreover, nonlinearities and dynamic effects of the environmental impact models are highly simplified. Nonlinear and dynamic effects can be modeled using a multistage stochastic optimization based in part on past efforts to quantify the uncertainty and sensitivity of the atmospheric transport and lake acidity components in the RAINS model (e.g., Alcamo and Bartnicki, 1985). Comparative use of the model provides a heuristic consideration of uncertainty.

5. OPTIMIZED REDUCTIONS OF SO_2 EMISSIONS: SOME EXAMPLES

5.1. Introduction

This chapter presents several examples of optimal reduction strategies for Europe, which demonstrate the formulation and use of the new cost and optimization submodels of the RAINS model. Because these submodels are still under development, the results should be considered as preliminary, possibly, but not necessarily representative of optimal strategies.

Results of optimal policies, in terms of European control costs and sulfur reductions are given for the following examples:

1. Development of European control cost curves
2. Reduction of peak sulfur deposition
3. Reductions function for sulfur deposition
4. Flat rate deposition reductions
5. Reduction of sulfur deposition in southern Fenno-Scandia
6. Reductions of transboundary fluxes

These examples, including their objectives and a summary of results, are described in the following six sections. Examples 2-5, which employ sulfur deposition constraints, are used largely because there is no international consensus on deposition targets for Europe. Targetted policies using environmental indicators such as impacts on forests or water quality might not resemble any of these examples. Our intention in using these examples is to demonstrate the use of the cost and optimization submodels as tools for policymakers. We neither recommend nor suggest that these examples should be implemented.

All examples have several common features, including (1) the maximum emissions of each country are the 1980 levels; (2) costs are referenced to the control costs of a flat rate 30% reduction in 1980 emission levels, which is assigned an index of 100; (3) the year 2000 cost curves and emissions projections are employed, based on the fuel mix in the single energy pathway considered (derived from IEA (1985)) as explained earlier; (4) sulfur transport is based on a four-year meteorological period; (5) only aggregate European-wide control costs and sulfur reductions are presented, although country-by-country quantities are calculated; and (6) background deposition is assumed to be derived from entirely natural or uncontrollable emissions. With respect to the sixth point, "background" contributions in the EMEP model include both natural emissions and some anthropogenic emissions, the latter which are not attributed to emissions from specific countries. We have assumed that the background deposition is from only natural sources. In most cases this will not greatly alter results since the background fraction is usually small. However, where it is large, other assumptions might change results significantly.

5.2. Development of European control cost curves

This section presents cost functions which display aggregate European costs for several emission reduction policies. These policies, which are independent of sulfur transport and deposition levels, compare the following objectives:

a. *Flat rate reductions.* In this case, all countries reduce emissions by the same fraction, based on 1980 emissions. For example, in a 50% flat rate reduction, all countries have emissions from their 1980 levels.

b. *Maximum reductions with a total European-wide budget.* These results indicate the maximum sulfur removal obtainable for a given budget. Here, the optimization maximizes the total sulfur removed, subject to a budget constraint. Sulfur emissions from each country are permitted to vary from 1980 levels (the maximum) to a minimum level implied by the country specific cost curves.

c. *Maximum reductions with a total European-wide budget and a 30% minimum reduction.* This case is similar to (b) above, except all countries must reduce emissions from 1980 levels by at least 30%.

In summary, policy (a) provides an indication of costs for flat rate policies, and policy (b) maximizes sulfur removal over Europe subject to a budget constraint.

Figure 6 shows costs and removal quantities of the three policies. Costs are displayed using a cost index, where 100 references the cost of a 30% flat rate reduction in emissions from 1980 levels. Removals are displayed using emissions in year 1980 as a base. The European-wide 1980 emissions are equal to 29.8 million tons/yr. According to the energy pathway used, most countries would increase their year 2000 emissions from 1980 levels without pollution abatement to a total of 34.9 million tons/yr. Emissions from Denmark, F.R.G., Italy, and the USSR increase by less than 5% from 1980 levels while four countries reduce emissions i.e., Belgium, Finland, France and Sweden.

Emission reductions are calculated using 1980 as a base. As an example, a 50% removal from 1980 levels reduces emissions to 14.9 million tons/yr (one-half of 1980 emissions). As the energy pathway shows that year 2000 emissions would total 34.9 million tons/yr, a reduction in year 2000 emissions of 20 million tons/yr would be required. When expressed in terms of year 2000 emissions, the 50% reduction in 1980 emission requires a larger percentage reduction (57.3%) from the unabated year 2000 emissions.

Returning to Figure 6, the cost curves show strongly increasing costs beyond 60 to 70% removal. This results as the highest removal rates can only be accomplished using the most expensive control options; the potential of inexpensive control options has been exhausted. (Similar results were shown in Section 4.1 for individual country cost curves.) The maximum removal possible in year 2000 using the current cost curves is 29 million tons/yr, resulting in sulfur emissions of 5.6 million tons/yr. Thus, the fully abated emissions in year 2000 corresponds to 81% decrease in 1980 emissions. The maximum reduction costs 4.7 times as much as a 30% flat rate reduction, although only 2.1 times as much sulfur is removed.

The upper line in Figure 6 shows the flat rate policy (a). With the current cost curves, all countries were able to reduce emissions from 1980 levels by at least 50%. However, additional reductions were not possible for several countries. The maximal removal for each country varied between 50 and 91% of 1980 levels. The flat rate curve continues to 80%, however, by permitting countries to "drop out" as their control options were exhausted. This operation may tend to decrease the difference between the three policies.

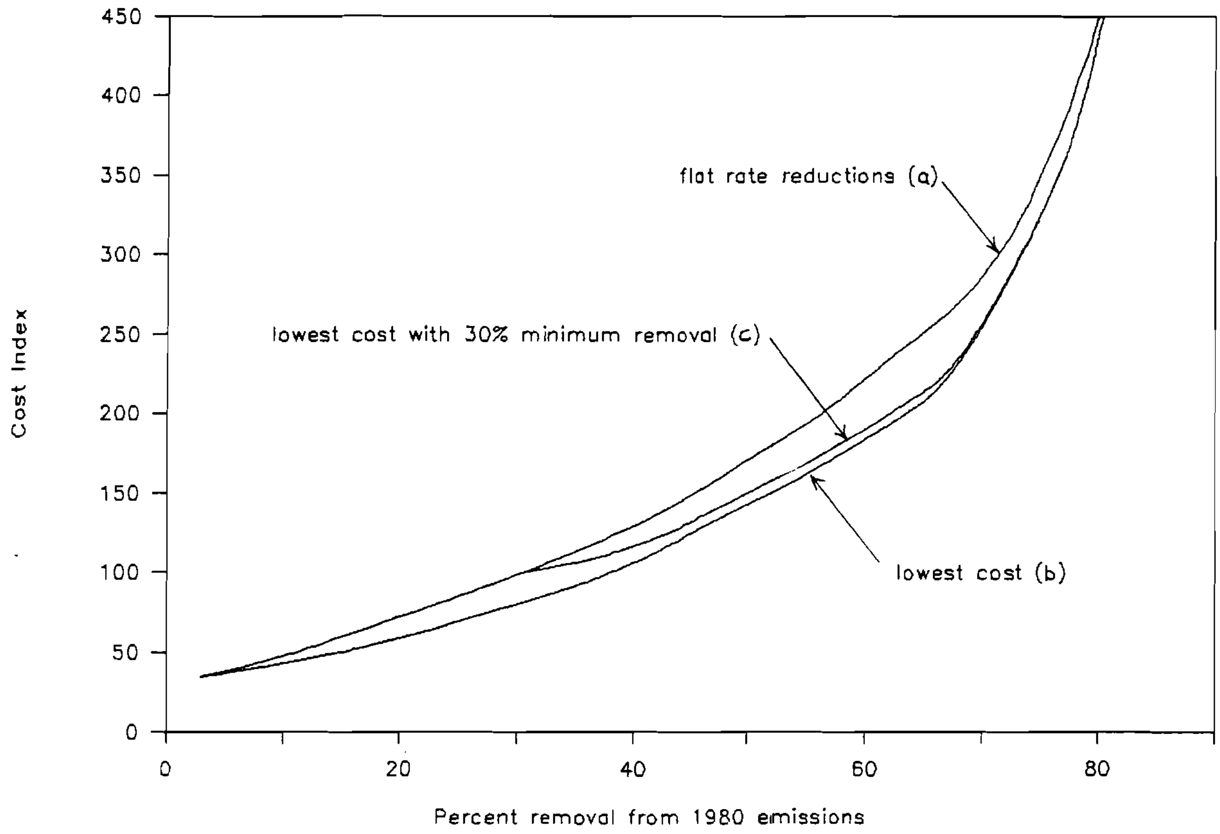


Figure 6. Total European costs vs. sulfur reductions for three policies.

The maximal removal policy (b) forms the lowest cost "envelope" in Figure 6. For example, 30% sulfur removal (14.1 million tons/yr of year 2000 sulfur removed) may be accomplished for only 80% of the cost of the flat rate policy. For 50% removal, the cost is 88% of the flat rate policy. The cost savings are achieved by maximizing removal in countries with low removal costs. This changes the *spatial pattern* of the emission reductions, however the total European sulfur reduction remains constant.

The current cost curves do not include the least expensive control options, e.g. fuel switching. Incorporation of such control options in the cost curves would increase the difference between costs of flat rate and maximal removal policies. Thus, cost savings above may be regarded as a lower bound on cost differentials. Cost savings of the policies discussed in the following sections may also be underestimated for similar reasons.

The third policy (c), maximum removal with a minimum 30% reduction by all countries, has costs between flat rate (a) and maximum removal (b) policies. At high removal levels, this policy is similar to policy (b).

In summary, the European costs curves show increasing costs with additional sulfur removal, especially above 60-70% removal. This increase would be more dramatic if additional control options, such as fuel substitution, were considered. There is about a 20% difference between flat rate and reduction maximizing policies for moderate sulfur removal levels (30-60% of 1980 emissions). Because of the preliminary nature of the cost curves, this differential may be regarded as a lower bound.

5.3. Reduction of peak sulfur deposition

The severity of some impacts of sulfur deposition, including materials damage such as corrosion and discoloration, is directly related to deposition level. Thus, a possible objective for optimized emission control policies is the reduction of the *maximum deposition* levels for all land areas of Europe. For this objective, a maximum deposition level is selected. Then, the optimal country-by-country emission reductions which most efficiently achieve the specified deposition levels are determined. With these reductions, deposition at all European sites will be at or below the specified deposition level.

Three policies were examined to investigate the effects of reducing the peak deposition. The policies had different objectives, namely:

a. *Minimizing total European cost.* This case obtains the minimum cost approach which achieves the specified deposition level.

b. *Minimizing reductions in total European emissions with technological constraints.* Here, the reduction effort, in terms of sulfur removal, is minimized. The reductions from each country are limited to the control options discussed in Chapter 4.

c. *Minimizing reduction in total European emissions without technological constraints.* This differs from policy (b) in that the technological constraints imposed by the cost curves are ignored. Reductions of each country may range up to 100% of 1980 emissions. Thus, a country may completely eliminate its emissions. While unrealistic, this assumption helps to illustrate the sensitivity of the solution to the cost curves.

A range of deposition targets are used to identify the sensitivity of the optimal solutions to deposition level. Costs and removal quantities are computed for policies (a) and (b); because policy (c) ignores the technological constraints imposed by the cost curves, only reductions can be computed for this case. (Costs of the minimum reduction policy were computed using the least expensive technologies.)

Figure 7 shows the European costs vs. maximum European deposition for policies (a) and (b). As in the previous section, the cost index refers to the cost of a 30% flat rate reduction. For both policies, costs increase rapidly as the maximum deposition level is decreased below 5-6 g/m^2-yr. This occurs as more expensive technologies must be used to reduce peak depositions to low levels, and because the number of affected receptors increases as the deposition limit is lowered. The lowest peak deposition that can be achieved over Europe is about 4.7 g/m^2-yr, due to both limits on the maximum removal for each country and the background component of the EMEP model. Cost differences between the minimum cost (a) and minimum removal (b) policies are negligible.

Figure 8 shows the emission reductions required to achieve the specified deposition limit for the three policies. Emission reductions are plotted as sulfur removed from year 2000 emissions. For example, the upper line shows the reductions corresponding to the minimal cost policy (a). With this policy, a 6 g/m^2-yr deposition limit requires a removal of 18.3 million tons/yr of sulfur. As with the costs, the required sulfur reductions increase rapidly as deposition levels are reduced below 5 or 6 g/m^2-yr, and differences between cost-minimal and reduction minimal policies (a) and (b) are minor.

The minimal removal policy *without* technological constraints (c) requires less sulfur removal than policies (a) and (b), most markedly at high removal levels. For example, at 5 g/m^2-yr, policy (c) requires 15% less sulfur removal than policy (a). This results as policy (c) permits complete reductions from each country, while policies (a) and (b) are constrained by capacity constraints on removal quantities in the cost curves. At low deposition levels, the maximum removal rates for countries strongly affect results by forcing reductions in neighboring countries. In contrast, without technical constraints the same or even lower deposition levels may be achieved by reductions entirely within the countries where deposition maxima occur.

It is possible to compare the maximum depositions resulting from flat rate reductions to the optimized policies. For example, a flat rate reduction of 50% reduces the maximum deposition (considering only the anthropogenic contribution) to about 9 g/m^2-yr; the same level may be achieved at only 57% of the cost by the cost optimal policy. Of course, the resulting deposition patterns of the two cases may be dramatically different: the optimized solution primarily reduces the peak depositions while the flat rate reduction achieves proportionally equal decreases in the deposition. Figure 9 contrasts isolines resulting from these two policies. Differences between the two policies may be viewed as the movement of particular isolines.

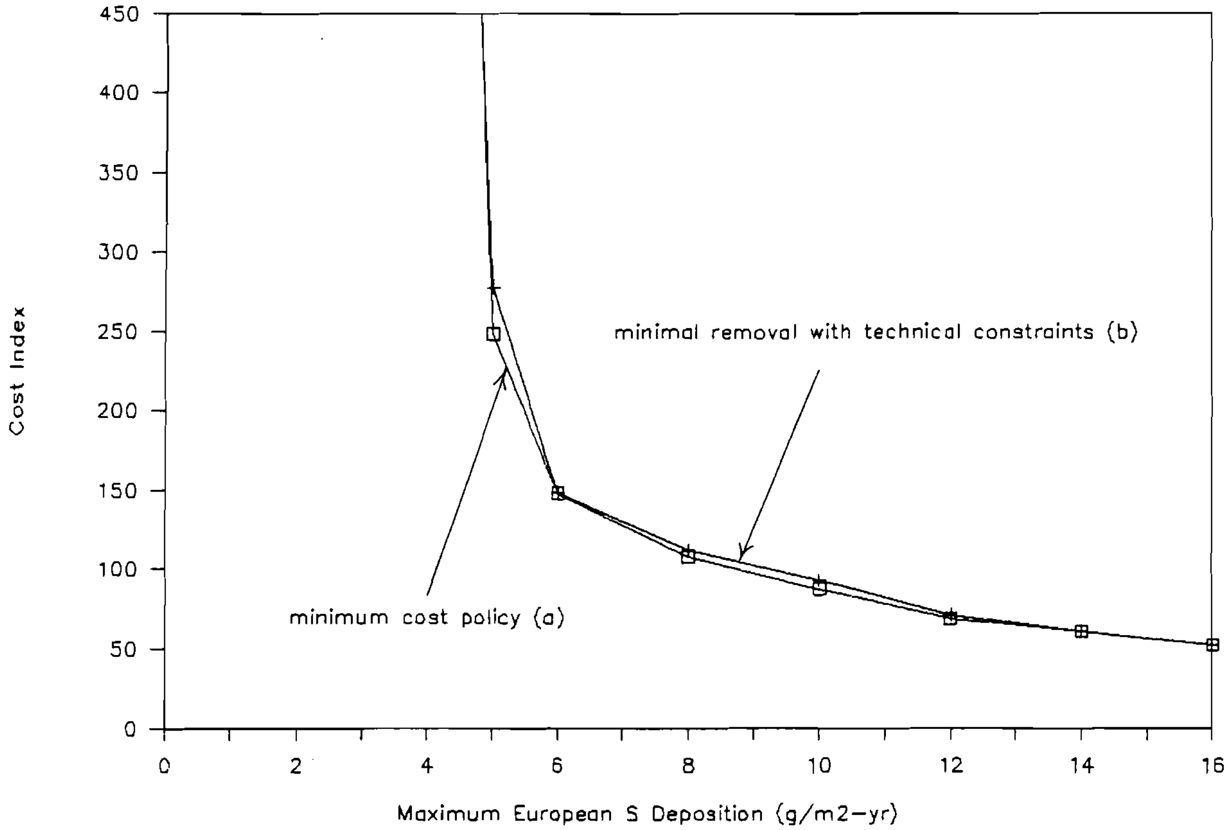


Figure 7. Total European costs vs. peak sulfur deposition.

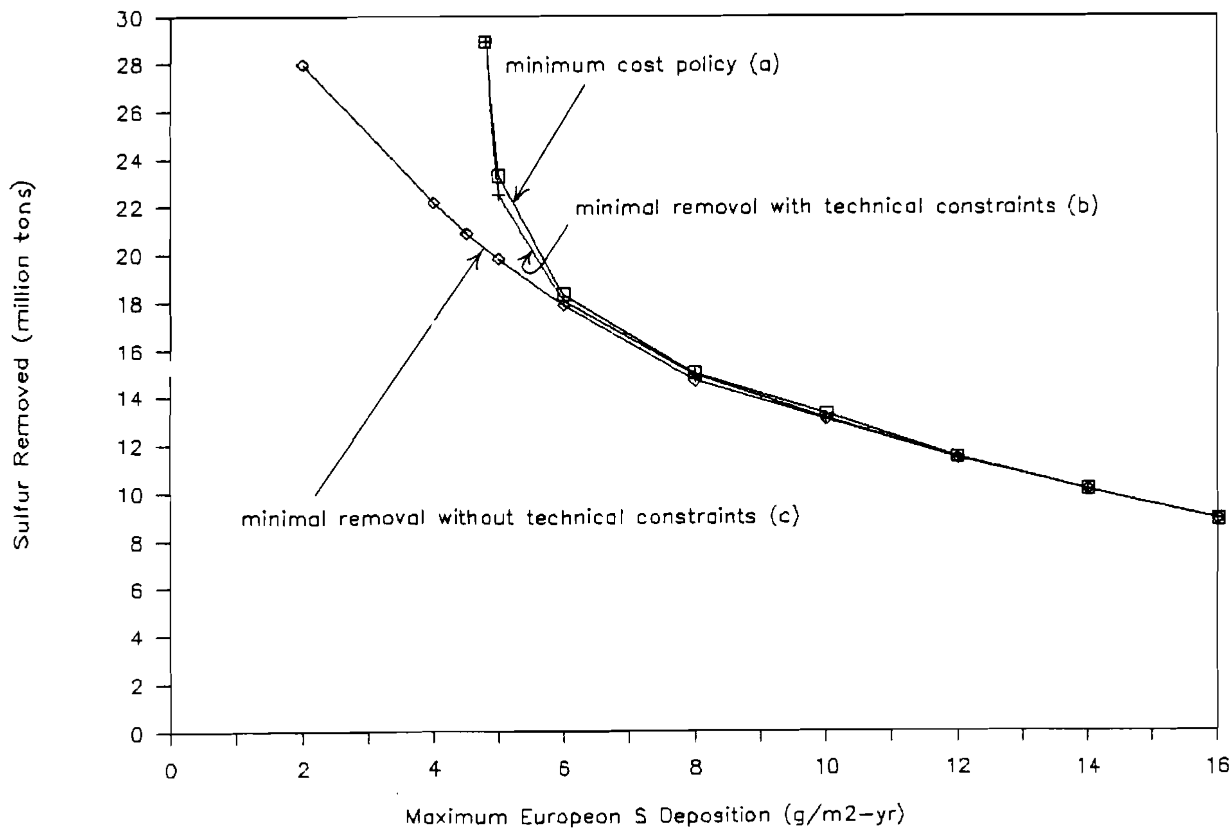
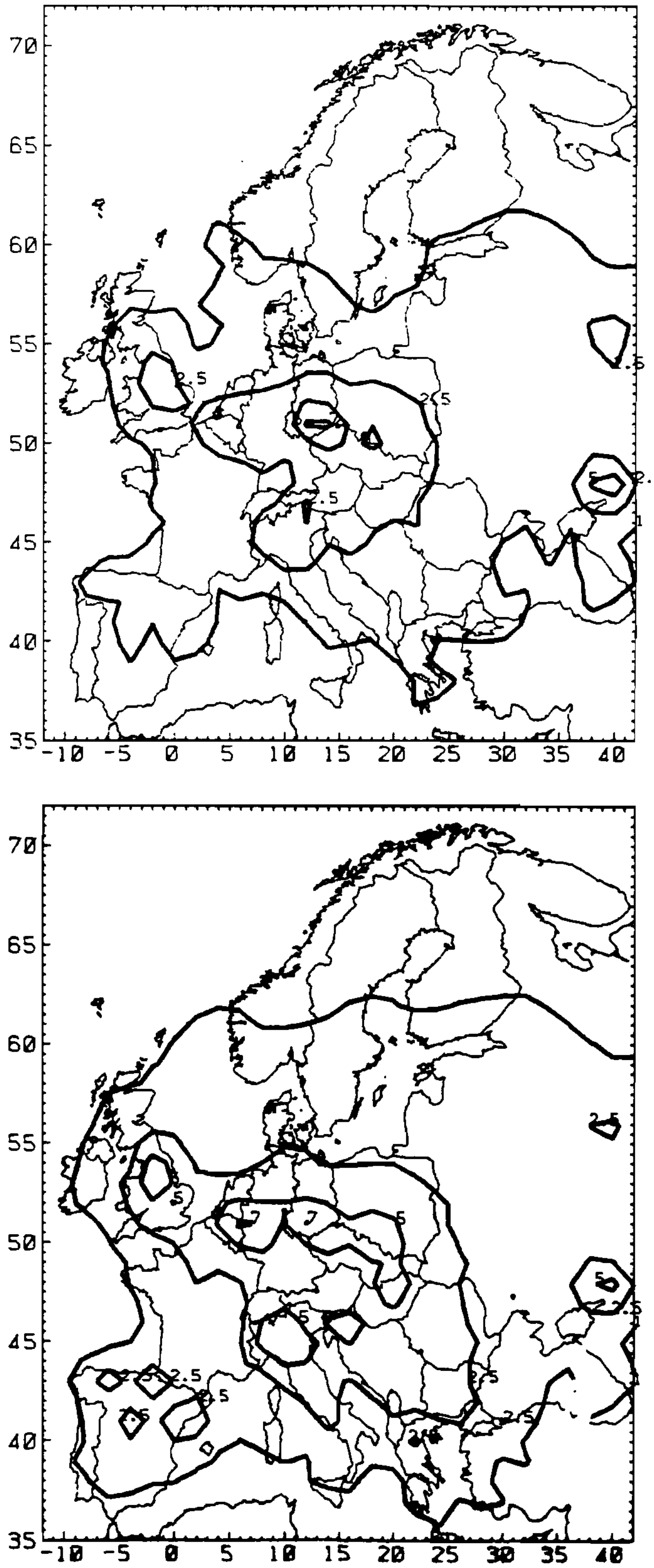


Figure 8. Total European sulfur removal vs. peak sulfur deposition.

In summary, optimal policies may be used to reduce peak depositions in Europe at considerable savings compared to flat rate reductions. Little sensitivity to the cost curves was observed, although the constraints on the maximum possible removal from each country appear influential at low deposition levels. These conclusions must be tempered by the preliminary nature of the cost curves and the single energy pathway considered.



(a)

(b)

Figure 9. Sulfur deposition isolines for (a) 50% flat rate removal policy and (b) cost minimal reduction of peak deposition to 9 g/m^2-yr. Isopleths for 1, 2.5, 5 and 7.5 g/m^2-yr are shown.

5.4. Reduction functions

As a third example of optimized control strategies, several reduction functions are used to specify the decrease in deposition at each receptor, as discussed in Section 4.2.2. In contrast to policies aimed at reducing the peak depositions at a subset of receptors (as in the previous section), the reduction function ensures that *all* receptors obtain lower deposition levels. Ideally, reduction functions would consider the sensitivity of the receptor, the time history of pollution, and other aspects important for environmental effects. In the present example, a simple function is used to specify the maximum sulfur depositions at all receptors. The optimal solution finds the country-by-country sulfur reductions which minimize the total European control costs *and* satisfy the deposition constraints.

Target depositions at each receptor are determined by requiring a percentage reduction in deposition at each receptor which is proportional to the calculated 1980 deposition. Line (a) in Figure 5 shown earlier illustrates the nature of the reduction functions considered. These functions require the greatest percentage decrease in deposition at receptors with high concentrations. The proportionality constants are called "reduction multipliers." The percentage decrease in deposition is obtained as the product of the reduction multiplier and the 1980 sulfur deposition, in g/m^2-yr. The reduction multipliers range from 1 to 4. As the peak deposition in Europe is about 20 g/m^2-yr, the maximum reduction in depositions from 1980 levels ranges from 20 to 80%. Receptors with 1980 concentrations of 9 g/m^2-yr would require exactly half as much reduction.

Figure 10 shows total European costs as a function of the reduction multiplier, where costs are displayed using the cost index (100 corresponds to the costs of a 30% flat rate reduction). Figure 11 shows total European sulfur removal as a function of the reduction multiplier. These figures indicate, for example, that a reduction multiplier of 3.5 costs 46% more than a 30% flat rate reduction and requires a total removal of 18.6 million tons/yr. The maximum deposition at any receptor resulting under this policy is about 7 g/m^2-yr. Some costs and sulfur removal are required for a zero multiplier since the maximum emissions permitted in this examples (as well as the others) cannot exceed 1980 levels and most countries increase their unabated emissions from 1980 to 2000.

Figures 10 and 11 indicate that costs and removal quantities increase quickly for multipliers above 3.5. The rates of increase are not as fast as found for the reduction of the maximum sulfur depositions (Figures 7 and 8) since the reduction function requires decreases in deposition and thus emissions at all locations, even for low values of the multiplier. In contrast, the reduction of peak depositions focuses control efforts in countries which experience the highest depositions.

The maximum depositions resulting using reduction multipliers can be compared to the policies of the previous section which reduce maximum depositions. For example, the multiplier of 3.5 results in a maximum sulfur deposition of 7 g/m^2-yr. The same maximum deposition could be achieved with a cost savings of approximately 15% using the minimal cost solution reducing the maximum European deposition.

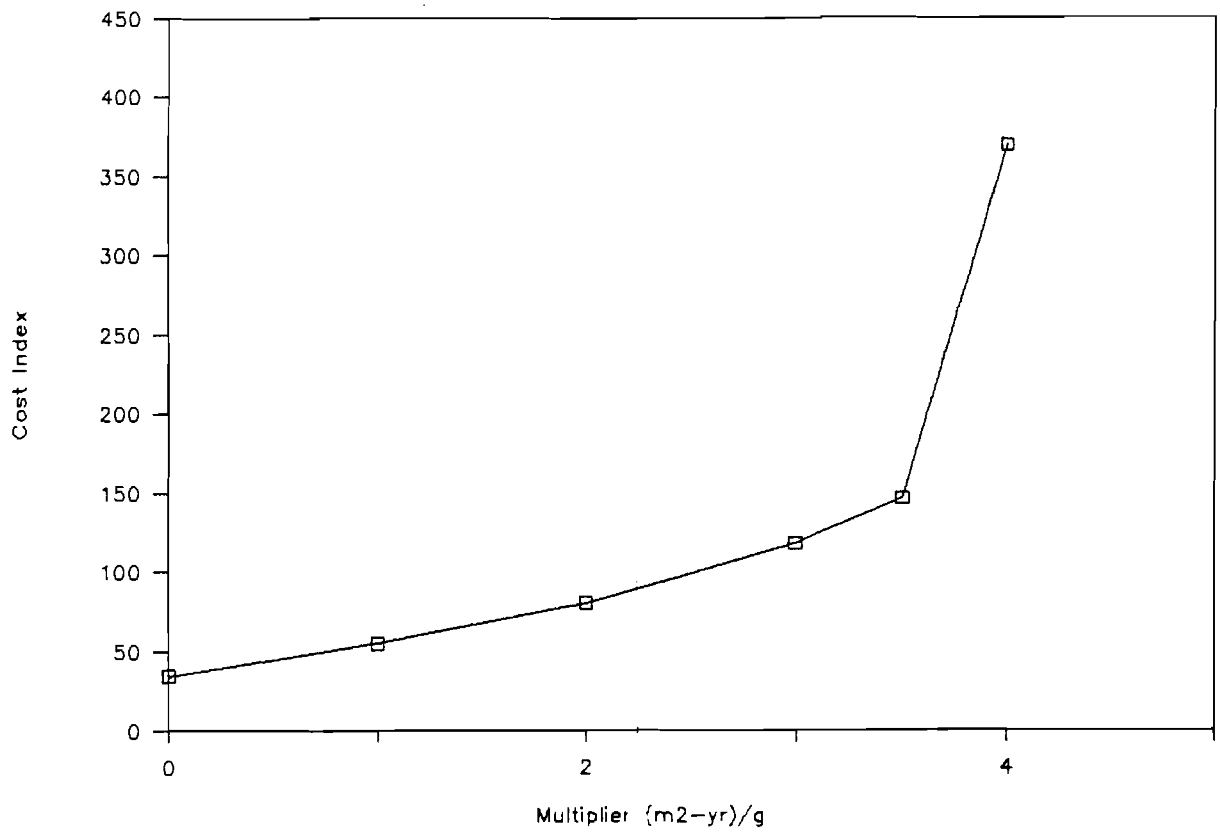


Figure 10. Total European sulfur control costs as function of reduction multiplier for variable reduction policies.

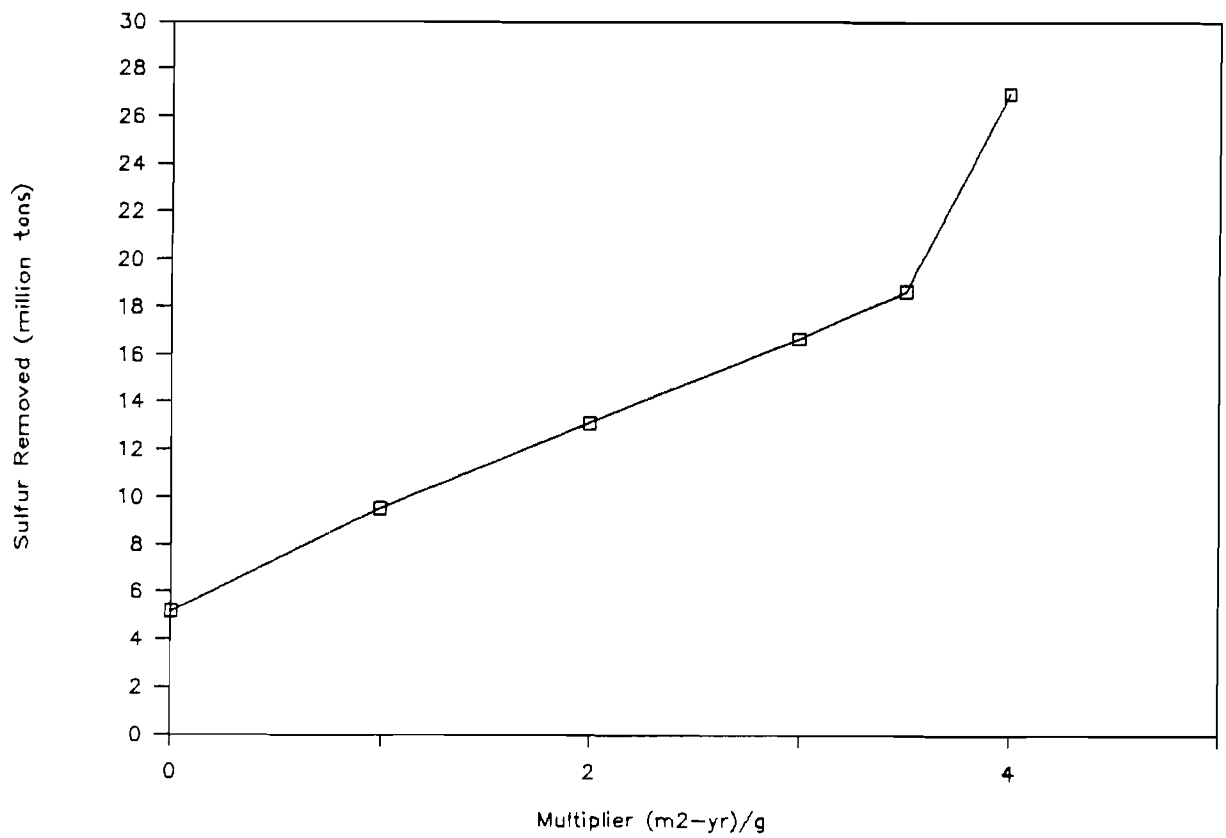


Figure 11. Total European sulfur removal vs. reduction multiplier.

In summary, the deposition function provides a flexible approach for specifying deposition goals. In fact, flat rate reductions and reductions of the peak deposition levels provided in Sections 5.2 and 5.3, respectively, are subsets of this approach. With additional data specifying receptor sensitivities related to environmental indicators, reduction functions may be used to derive targetted policies aimed at minimizing environmental impacts.

5.5. Flat rate deposition reduction

As another example of optimal policies, some alternatives to flat rate emission reductions are explored. Flat rate reductions achieve a uniform percentage decrease in the anthropogenic component of sulfur deposition at all receptors. There may be more cost-effective ways of reducing sulfur deposition to these or lower levels by increasing the sulfur removal in countries with low control costs, and conversely, by decreasing removal in countries with high control costs. Thus, flat rate deposition reductions result in similar environmental impacts, as measured by sulfur deposition, but at lower total expenditures than flat rate policies.

The potential cost savings of such policies was estimated by finding the cost optimal solution which achieved sulfur deposition at each receptor equal to or below that obtained by a 50% flat rate reduction in sulfur emissions from 1980 levels. A second example found the cost optimal solution for a 30% flat rate reduction in emissions. Results for both policies were similar. In brief, the cost optimal policies reduced total European costs by less than 1%. This cost savings is certainly within the error range of the calculations. For most countries, the sulfur removal and costs of flat rate and cost-effective strategies were similar. These results indicate that the problem is highly constrained and little potential for large cost savings exists. Similar results were obtained when sulfur removal (rather than costs) was minimized. Consequently, these conclusions do not appear dependent on the cost curves.

In summary, this example indicates relatively little opportunity for emissions "trading" between countries when "flat rate deposition" reductions are required. Such deposition reductions can be accomplished by flat rate *emission* reductions with nearly equal efficiency. These conclusions do not necessarily hold for other deposition targets or policies. Earlier examples, such as the reduction of the maximum deposition levels (Section 5.3) indicate that some deposition targets other than flat rate reductions may be achieved at considerable cost savings.

5.6. Reduction of sulfur deposition in southern Fenno-Scandia

This section presents examples of optimal emission policies related to lake acidification in southern Fenno-Scandia (Finland and Sweden). Acidification of lakes in this area was one of the first impacts attributed to sulfur deposition. Deposition levels in Scandinavia are low, typically in the order of 2 or 3 g/m^2-yr in Finland, Sweden and Norway. Consequently, the examples of optimal control policies related to peak depositions (Sections 5.3 and 5.4) have little direct bearing to deposition levels in these regions. Due to the very different geographical focus, the examples in this section provide a strong contrast to the preceding examples.

Four receptors in southern Sweden, and three receptors in southern Finland were selected for analysis. Using 1980 emissions, the calculated sulfur depositions at these receptors are between 2.5 and 3 g/m^2-yr. Costs and removal quantities for the 27 countries modeled are calculated using the optimization submodel with various deposition targets and the three objectives used in Section 5.3, namely:

(a) Minimizing total European costs;

(b) Minimizing reductions in total European emissions, subject to technological constraints inherent in the cost functions; and

(c) Minimizing reductions in total European emissions, without technological constraints (thus permitting complete removals and zero emissions from a country).

Optimizations were performed separately for receptors in Sweden and Finland.

Figure 12 displays the costs (using the same cost index as before) required to attain various deposition levels in the two regions. Results of the minimum cost policy (a) are plotted. To achieve 1.5 g/m^2-yr in southern Finland requires 1.14 times the cost of the 30% flat rate reduction policy; this level may be achieved in southern Sweden for 0.59 times the cost of the reference scenario. Depositions below 1.8 and 1.2 g/m^2-yr can be achieved in Finland and Sweden, respectively, for the cost of the 30% flat rate policy. However, the flat rate policy would decrease deposition levels to only about 2 g/m^2-yr.

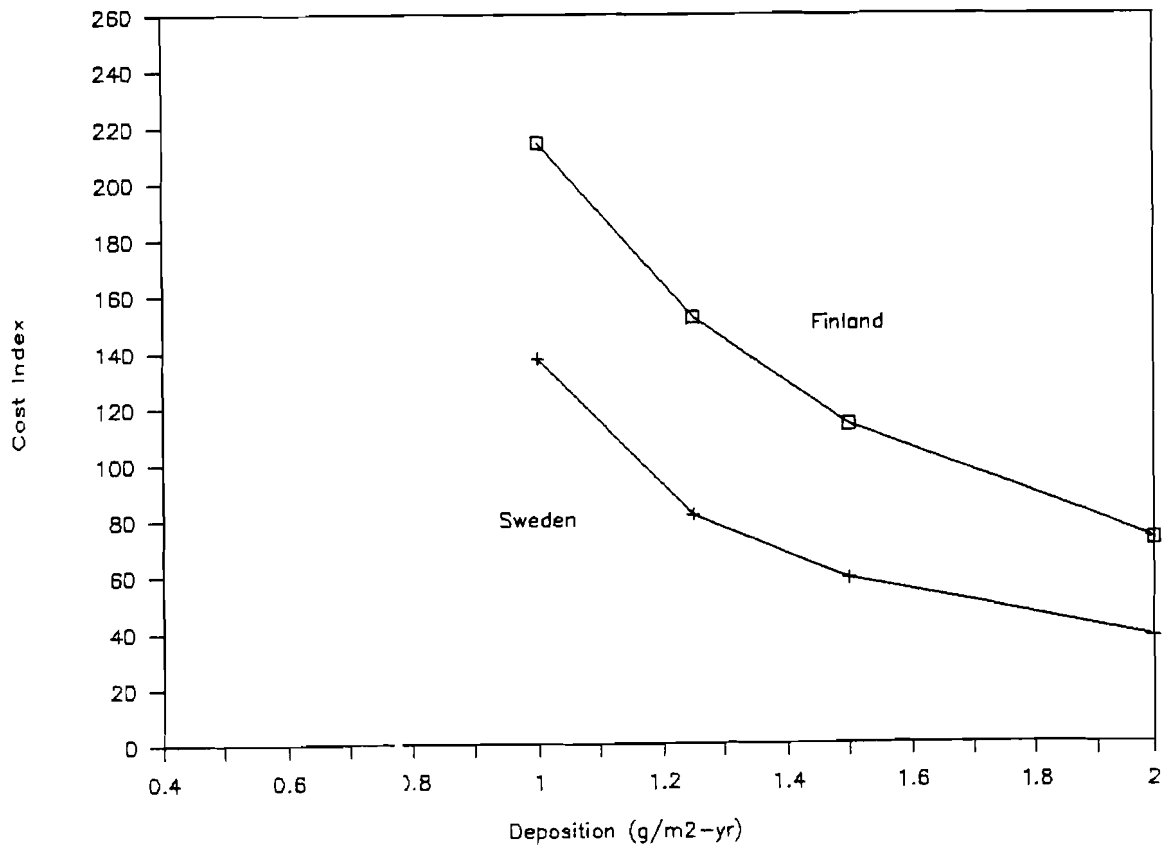


Figure 12. Cost of deposition reductions in southern Finland and Sweden.

Figures 13 and 14 show the removal quantities associated with the three objectives for Finland and Sweden, respectively. The cost minimizing and removal minimizing policies have larger differences compared to the removal curve shown earlier (Figure 6). For example, to attain a deposition level of 1.5 g/m^2-yr in Finland, the minimum removal policy (b) requires 13.6 million tons/yr, or 13% less than the minimum cost policy (a). In addition, the country-by-country reductions required by policies (a) and (b) are very different for several countries. This sensitivity to the cost curves occurs as the selected receptors are roughly equidistant to several countries. The transfer coefficients for these countries are of similar magnitude, however, several of the countries have large differences in the cost of sulfur removal. For these countries, the difference between the cost and removal minimizing policies is large.

In summary, the example indicates that policies targetted for specific regions may provide considerable savings in comparison to flat rate policies. In contrast to earlier examples, considerable sensitivity to differences between the national cost curves is observed.

4.5. Reduction of transboundary fluxes

The final example of optimal emission strategies considers the deposition which is attributable to only transboundary fluxes of pollutants, i.e., that deposition which arises from sulfur exports between countries. The deposition at receptors due to emissions in the "host" country which contains the receptor thus is not considered. The key concept of this policy is the separation of sulfur deposition which is due to "domestic" and "foreign" sources. For example, an optimal policy (which would involve international negotiations) might reduce exports to all other receptors by a certain amount, say 30 or 50%. Further deposition reductions, if desired, could be accomplished by decreasing emissions in the host country, a purely national action. The deposition which is attributable to the host is often very significant (sometimes half or more of the total).

Using a cost minimizing objective, a 30% reduction in transboundary fluxes could be achieved at 84% of the cost of the 30% emission flat rate policy which also results in a 30% reduction in exports. A 50% reduction in exports could be accomplished for 82% of the cost of the 50% flat policy. While the optimal and flat rate policies removed about the same amount of sulfur, the optimal policy obtains lower costs by decreasing sulfur emissions in centrally located countries which have low removal costs.

Since the receptor grid is relatively coarse and thus some countries have very few receptors, we should be cautious in interpreting these results. However, the example indicates that policies based on sulfur exchanges can be formulated and evaluated using the optimization submodel. The preliminary results indicate large cost savings compared to flat rate policies.

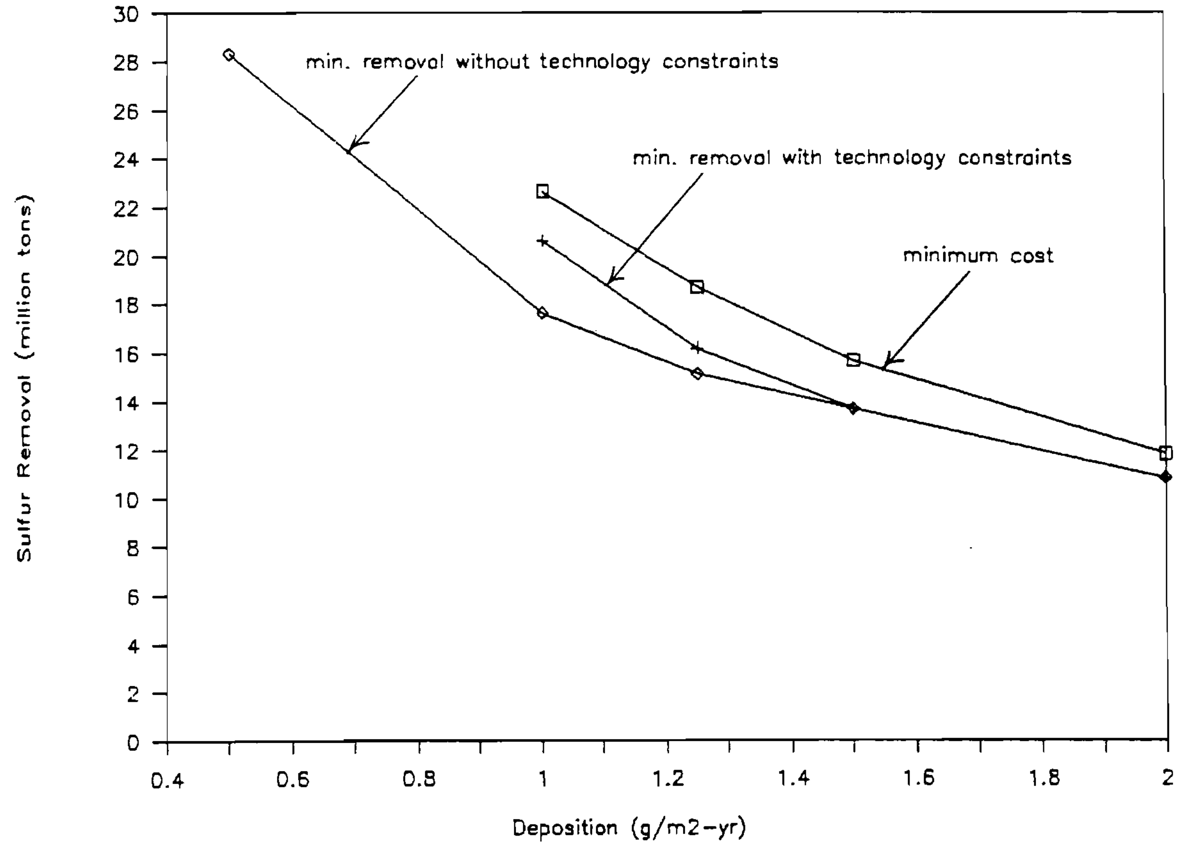


Figure 13. Sulfur removal vs. sulfur deposition in southern Finland.

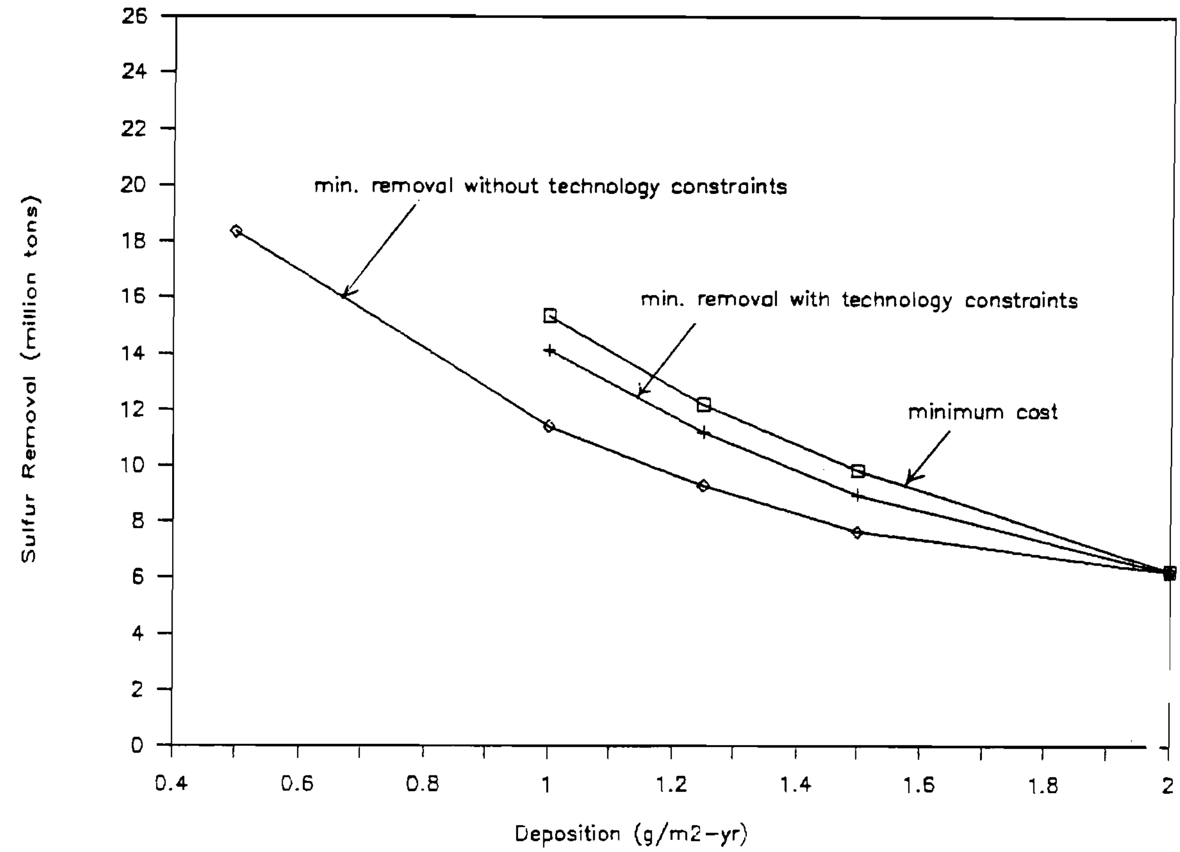


Figure 14. Sulfur removal vs. sulfur deposition in southern Sweden.

5.8. Comparison of policies

In this section the policies discussed above are compared using the cost per ton of sulfur removal, an indicator which might interest policymakers. This aggregate measure permits comparison of the cost penalties or advantages of the different policies. However, it neither indicates the country costs nor the environmental effects. Table 4 shows removal costs for the policies examined in this chapter. Total European costs are compared to total European removals. In the table, each column represents a fixed European budget, which varies from one to three times the cost of the 30% flat rate removal policy. Thus, the efficiency of the different policies, in terms of the costs per ton of sulfur removed, may be compared within each column. The lowest cost removal policy (1b) is always the cheapest; other policies may impose penalties up to about 25% higher, although differences are usually smaller. For example, with a budget twice as large as required by 30% flat rate removals, the lowest cost removal policy (1b) has removal costs 13% lower than the flat rate reduction policy (1a), while policies aimed at reducing peak depositions (2a, 2b) have costs 4-12% higher.

Table 4 also illustrates the increasing costs of sulfur removal, i.e., diminishing returns with higher budgets. The estimated costs per ton nearly double with a three-fold increase in the reference budget.

Table 4. Average European costs of sulfur removal (in 1000 DM/ton of sulfur) for the policies examined.

	Control policy	European budget in terms of 30% flat rate policy				
		1.00	1.50	2.00	2.50	3.00
1.	Cost curves					
	a. Flat rate emission reductions	1.67	1.87	2.14	2.42	2.69
	b. Lowest cost removal	1.44	1.72	1.92	2.12	2.64
	c. Lowest cost & 30% min. removal	1.67	1.76	2.01	2.29	2.64
2.	Reduction of peak deposition					
	a. Lowest cost	1.64	1.92	2.25	2.52	2.86
	b. Minimum removal	1.70	1.95	2.37	2.73	3.03
3.	Variable reduction functions					
	a. Lowest cost	1.57	1.87	2.28	2.62	2.90
4.	Alternatives to flat rate reductions					
	a. Lowest cost	1.60	1.87	na	na	na
5.	Reductions for Fenno-Scandia					
	a. Lowest cost: Sweden	1.78	2.20	na	na	na
	b. Lowest cost: Finland	1.62	1.91	2.17	2.36	na
6.	Reductions of transboundary fluxes					
	a. Lowest cost	1.50	1.79	2.01	na	na

6. CONCLUSION

This paper describes two recent extensions of the RAINS model and sample results of these extensions. Optimal emission control policies have been determined by linking together submodels of RAINS describing emissions, costs, atmospheric transport, and environmental indicators. It is important to stress the tentative nature of the results. However, it is clear that optimal policies of acidification reduction can be formulated and evaluated with the RAINS model. These single objective policies are optimal either with regard to costs, total emission reduction, or maximum deposition levels. Solving multiple objective problems, e.g. optimality with regard to these three (or other) criteria, is a next step in the extension of RAINS.

The six examples presented in the previous chapter represent a spectrum of policies which range from focus on the *few* receptors which obtain the highest depositions to flat rate reductions in which *all* receptors are treated equally. In the next few years, work aimed at defining sensitive areas should produce an internationally accepted list of areas. Receptors corresponding to these sensitive areas could then be used in the formulation of targetted emission control policies. The examples indicate that significant costs savings may be possible in some cases. In general, the advantage of optimal policies increases as deposition targets are more narrowly defined. Although no internationally accepted list of ecologically sensitive areas exists, targetted policies can be evaluated using the RAINS model. As a first approximation we will use the forest soil submodel. For each of the examples in Chapter 5, an indicator of soil acidification could be calculated. A next step would use the soil submodel in a reversed way: formulate target values for soil impacts and obtain the optimal emission reductions. This approach would account for the fact that although deposition levels in Scandinavia are much lower than in central Europe, environmental effects in Scandinavia can be more severe.

The sensitivity and uncertainty of our results have not yet been established. As pointed out in Chapter 2, this type of analysis is being applied to other submodels of RAINS. The series of analyses reported in Chapter 5 have shown several major sources of uncertainty:

- Because the mix of abatement options depends on the energy structure of a country, the country cost functions are strongly dependent on the energy pathway. The results might change substantially if other energy pathways are assumed. In particular the maximum possible abatement, which in our current cost functions is as low as 50% for some countries, could change. This would imply that especially in cases where high emission reductions are assumed, optimization results will differ largely.
- The cost functions are also dependent on many assumptions as listed in Table 2. With additional information about country specific details, the cost functions might change drastically.
- So far we have not included abatement of process emissions in the cost functions. Although for most countries these emissions are relatively small, in some countries (e.g. Finland, Spain, Sweden) process emissions account for up to 25% of the totals.

- Some sensitivity to the cost curves has been noted. This occurs due to both limits on the maximum removal possible for each country and the cost differences between countries. Stated differently, the atmospheric transport model often appears to have a greater influence on optimal policies than cost curves. This may result since at any (land based) receptor, the transport coefficient for the "host" country containing the receptor is considerably larger than the transport coefficients for other countries. Consequently, to reduce deposition at any particular receptor, emission reductions should first take place in the host country. Exceptions occur when receptors are equidistant from several countries with different costs, and reductions in the "host" country do not achieve the target deposition.
- Results of optimization depend also on the atmospheric transfer matrix used. In Lehmhaus et al. (1986) a new version of the EMEP model is described. The country-to-country transfer matrix reported there indicates that results in this paper will change.

In recognition of model uncertainty we have presented results in a comparative fashion, illustrating the trade-offs between key indicators.

Further development of RAINS submodels for cost and optimization include the following:

- Improvement of cost functions
- Sensitivity and uncertainty analysis of the new submodels
- Error propagation
- Multi-objective optimization
- Development of transferable software for optimization.

Decision making in acidification abatement is a matter of international negotiations and agreements. The RAINS model enlarged with the submodels described in this paper provides a tool for analysis of a wide range of alternatives. Of course political factors also play a role in negotiations. No attempts are made to model the attitudes of decision makers, such as their behavior under uncertainty. However, interactive use of the model provides a technique which can accommodate the objectives and attitudes of decision makers.

REFERENCES

Alcamo, J., and J. Bartnicki (1985). An approach to uncertainty of a long range air pollutant transport model. IIASA Working Paper WP-85-88, Laxenburg.

Alcamo, J., L. Hordijk, J. Kämäri, P. Kauppi, M. Posch and E. Runca (1985). Integrated analysis of acidification in Europe. *Journal of Environmental Management* 21, 47-61.

Alcamo, J., J. Bartnicki and W. Schöpp (1986). Effect of non-linear sulfur removal coefficients on computed sulfur source-receptor relationships: some model experiments. Presented at EURASAP Symposium on Interregional Air Pollutant Transport, Budapest.

Dovland, H., and J. Saltbones (1986). Emissions of sulphur dioxide in Europe in 1980 and 1983. EMEP/CCC-Report 1/86, Lillestrøm, Norway.

Economic Commission for Europe (ECE) (1983). *An Energy Efficient Future*. Butterworths, London.

Economic Commission for Europe (ECE) (1985). Report of the third session of the Executive Body. ECE/EB.AIR/7. Geneva.

Eliassen, A., and J. Saltbones (1983). Modelling of long-range transport of sulphur over Europe: a two-year model run and some model experiments, *Atmospheric Environment* 17, 1457-1473.

Ellis, J.H., E.A. McBean and G.J. Farquhar (1985). Deterministic linear programming model for acid rain abatement. *J. of Environmental Engineering* 111, 119-139.

Fortin, M., and E.A. McBean (1983). A management model for acid rain abatement. *Atmospheric Environment* 17, 2331-2336.

Hettelingh, J.P., and L. Hordijk (1986). Environmental conflicts: the case of acid rain in Europe. *Annals of Regional Science* (in press).

Holmberg, M. (1986). The impact of acid deposition on groundwater: a review. IIASA Working Paper, WP-86-31, Laxenburg.

Hordijk, L. (1985). A model for evaluation of acid deposition in Europe, in: A. Sydow et al. (eds.), *Systems Analysis and Simulation* 1985 II, Akademie Verlag, Berlin.

Hordijk, L. (1986). Towards a targetted emission reduction in Europe. *Atmospheric Environment* (in press).

Inaba, Y. (1985). Costs of meeting stricter environmental standards for stationary sources of emissions: the electricity sector. International Energy Agency, 2676D/14.6.85.

International Energy Agency (IEA) (1985). *Coal Information Report*, OECD, Paris.

Kämäri, J., P. Kauppi, E. Matzner and M. Posch (1985a). A dynamic model for estimating acidification of forest soils on a regional scale, in: C. Troyanowski (ed.), *Air Pollution and Plants*, Verlag Chemie, Weinheim.

Kämäri, J., M. Posch and L. Kauppi (1985b). Development of a model analyzing surface water acidification on a regional scale: application to individual basins in Southern Finland, in: I. Johansson (ed.), *Hydrological and Hydrogeochemical Mechanisms and Model Approaches to the Acidification of Ecological Systems,* Nordic Hydrological Program, Report 10, Stockholm.

Kämäri, J., M. Posch and L. Kauppi (1985c), A model for analyzing lake water acidification on a large regional scale - Part 1: Model structure. IIASA Collaborative Paper CP-85-48, Laxenburg.

Kämäri, J., M. Posch, R.H. Gardner and J.-P. Hettelingh (1986). A model for analyzing lake water acidification on a large regional scale. Part 2: Regional application. IIASA Collaborative Paper, Laxenburg (in preparation).

Kauppi, P., J. Kämäri, M. Posch, L. Kauppi and E. Matzner (1985). Acidification of forest soils: a model for analyzing impacts of acidic deposition in Europe - Version II, IIASA Collaborative Paper CP-85-27, Laxenburg.

Lehmhaus, J., J. Saltbones and A. Eliassen (1986). A modified sulphur budget for Europe for 1980, EMEP/MSC-W Report 1/86, Norwegian Meteorological Institute, Oslo.

Mäkelä, A. (1986). Stress phenomena and growth models. Proceedings of the 18th IUFRO Congress, Ljubljana (in press).

Morrison, M.B., and E.S. Rubin (1985). A linear programming model for acid rain policy analysis. *Journal of the Air Pollution Control Association* 35, 1137-1148.

Organisation for Economic Cooperation and Development (OECD), (1985). Main economic indicators, several issues 1985 and 1986. Department of Economics and Statistics, OECD, Paris.

Organisation for Economic Cooperation and Development (OECD), (1986). Understanding pollution abatement cost estimates. Environment Monographs No. 1, Environment Directorate, OECD, Paris.

Posch, M., L. Kauppi and J. Kämäri (1985). Sensitivity analysis of a regional scale soil acidification model. IIASA Collaborative Paper CP-85-45, Laxenburg.

Rentz, O. (ed.) (1984). Minderung von Stickoxidemissionen aus Kohlekraftwerken in Baden-Württemberg. Bericht der Kommission. Staatsministerium Baden-Württemberg, October 1984.

Schärer, B. and N. Haug (1986). The cost of flue gas desulphurization and denitrification in the Federal Republic of Germany. Economic Commission for Europe, Executive Body for the Convention on Long-Range transboundary Air Pollution. EB.AIR/SEM.1/R.25.

van Breemen, N., C.T. Driscoll and J. Mulder (1984). Acidic deposition and internal proton sources in acidification of soils and waters. *Nature* 307, 599-604.

Witmuess, A., R. Straubel and R. Rosenmueller (1984). Interactive multicriteria decision procedure for macro-economic planning. *Systems Analysis, Modelling Simulation* 1(5), 411-424.

World Meteorological Organization (1984). Final report of the expert meeting on the assessment of the meteorological aspects of the 2nd phase of EMEP, WMO/TD 11, WMO, Geneva.