Optimal sulphur emissions abatement in Europe

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ABSTRACT

This study presents a mathematical model for determining cost-effective emissions' control strategies in Europe, by minimizing sulphur abatement costs subject to different pollution control targets. The purpose is to compare the efficiency of a uniform percentage emissions reduction with a scenario that takes variation in environmental conditions into account. Some alternative criteria for re-allocating abatement costs between countries are considered, to see which countries are penalized and which are favoured by the proposed approaches, and which approaches should be "preferred" on efficiency grounds. Underlying the proposed model is the belief that a full cost-benefit analysis of acid rain abatement is infeasible. The model focuses on the costs of abatement and provides an estimation of the gains (or losses) that countries could achieve if they co-operate in their policies rather than act independently.

Keywords: Sulphur emissions; abatement; mathematical programming.

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INTRODUCTION

The industrial age brought scientific and technological progress in our society, but it also brought "acid rain". The vastly increased burning of fossil fuels to generate heat and electricity and a growing reliance on motor vehicles are principally to blame. Fossil fuels contain chemical elements, including carbon (C), hydrogen (H), oxygen (O), sulphur (S) and nitrogen (N). When fuels (such as coal, oil, petroleum and gas) are burned, different chemicals are released into the atmosphere as waste products. Oxygen, which is present in air anyway, combines with the chemicals to produce oxides - such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x) - which are the main pollutants causing acid rain. NO_x (NO, N_2O, NO_2) is emitted by both stationary sources - power stations for instance - and by vehicles. SO_2 is emitted by power stations and industrial and commercial installations, when burning oil and coal, and by metal smelters, when burning iron and other metallic ores.

Once emitted, some of the oxides fall directly onto surfaces of plants, trees, soils, lakes and buildings and this phenomenon is known as **dry deposition**. If dry deposition falls onto a dry surface, dew or rain will later convert it into acid droplets. If it falls into water then it will dissolve. Oxygen in the atmosphere transforms the remaining oxides into sulphuric and nitric acids (H_2SO_4 and HNO_3) and these are deposited with rain, snow, hail and dew, which is known as **wet deposition**. Dry deposition generally occurs close to the point of emission. Wet deposition often occurs up to thousands of kilometres downwind of emission sources. In other words, acid rain can be "exported" by one country and "imported" by another: emissions from one country cause depositions also in the territory of its neighbours and beyond. This limits the ability of individual countries to reduce environmental damage through their own actions.

2

The analysis here will be limited to sulphur as the polluting substance to control. The chemical transformation products of SO_2 are transported over long distances and environmental quality in any one European country is significantly affected by the actions of others. It is thus a classic case of externality: the user-country may have little reason to concern itself with the sulphur content of the fuels it uses, except to the extent that legislation or "moral" incentives force it to take account of sulphur dioxide emissions. Costs imposed on receptors (e.g. reduced income or utility, or both, outlay of money) are not borne totally by those emitting the pollutants. In economic terms, the purpose of an acid rain abatement strategy is to internalize the externalities cost-effectively and equitably. Given that the assimilative capacity of the atmosphere has been used by emitters at no direct cost, emission reductions are likely to be accomplished only through public intervention in the form of enforcement of edicts. Such edicts are synthesized from acid rain abatement strategies.

The recognition of these problems has led to political action in many countries on emission standards and other regulations. The transboundary nature of the problem and the need for international coordinated policy measures have been recognized by the 1979 Convention on Long-Range Transboundary Air Pollution, which was signed by 32 European countries (and the EEC), the USA and Canada. In 1985 a Protocol was added to the Convention committing the 21 signatories to reduce sulphur emissions by at least 30% by 1993 as compared with their 1980 emission levels (the "30% Club"). The cost of air pollution control is an important feature of the current international debate on whether and by how much to reduce emissions beyond this. Methods for estimating the costs of pollution abatement tend to differ from one country to another and from one organization to another. Therefore the optimization of air pollution abatement is a useful goal of public policy and is consistent with economic and social objectives.

This study describes a mathematical model, the purpose of which is to identify cost-effective acid-rain abatement strategies for 27 European countries. The model consists of a non-linear programme for minimizing sulphur abatement costs in all European countries simultaneously. Estimation of the model enables comparison of the efficiency of a uniform percentage reduction in emissions (as in the 30% Club) with a strategy of differentiated emission reductions.

BACKGROUND

Before introducing the model in more detail, it is useful to recall that the existing literature in the field distinguishes three types of single objective optimization approach:

(a) Emission driven approaches,

(b) Deposition constrained approaches and

(c) A combination of the two, termed deposition based optimal allocation.

Emission-driven strategies specify emission reductions to be achieved by specific sources. When the relationships between source location and receptor location are taken into account (case (b)), the problem is then to minimize emission control costs subject to meeting predetermined maximum allowable deposition (or concentration) targets at all receptors. A number of important air and water pollutants such as total suspended particulates and sulphur dioxide belong to this category. Most policy action in Europe has previously been in terms of emission targets only. Although in principle the two policies are equivalent the main reason in justifying the setting of targeted depositions is that in emission-driven strategies certain fundamental aspects of acid rain are ignored, namely that pollutants, having been transported over potentially long distances and varying meteorological conditions, can result in acidic deposition which varies greatly by location and over time. Additionally, if the relationships between source location and receptor location are not taken into account then the fundamental aspect of externality (represented by transfer coefficients, explained later) is not taken under consideration.

The alternative approach of targeted levels of deposition is difficult because of uncertainty in defining the appropriate environmental targets. An optimal co-operative policy could be approximated by a policy that reduces emissions to levels consistent with critical loads. A critical load is the maximum amount of sulphur that the environment can assimilate without suffering severe damage (see Nilsson and Grennfelt, 1988, for exact definition; see also Hettelingh et al, 1991, for critical load values). In order to take critical loads into account, one can construct a model that makes the annual change in the accumulated sulphur in the environment equal to the annual deposition minus the assimilative capacity of the environment. The assimilative capacity of the environment is accordingly the same as the critical load. The "sensitivity" scenario proposed here does this.

Acid rain has been subject of considerable scientific and technological research in Europe and North America. In Europe studies of the environmental benefits of alternative abatement strategies and cost-optimization procedures were undertaken by the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria (which has produced the RAINS model, see Alcamo et al., 1990); by the Stockholm Environment Institute (SEI) at York, United Kingdom (which has produced the CASM model); by Cambridge Decision Analysts in Cambridge, United Kingdom (who have produced the ACIDRAIN model, see CDA/ERL, 1989; CDA, 1989) and Imperial College at London, United Kingdom (with the ASAM model). All these European integrated models deal with grids (squares); i.e. the

5

estimated sulphur dioxide emissions are translated into depositions in each square. Europe is divided into squares with grid lines of 150 km and with approximately 720 grid lines intersections.

In North America, much modelling work associated with the development and evaluation of efficient acid rain abatement strategies has been undertaken in recent years. Shaw and Young (1986) have studied and tested several schemes to reduce sulphate deposition in North America while minimizing sulphur removal (1). Sulphur emissions are reduced first in the highest ranking source regions, i.e. those that have the largest elements in the source receptor matrices i.e. the strongest atmospheric link to sensitive receptor regions. Shaw (1986) carried the ranking scheme one step further to include cost factors such that the cost of sulphur removal, rather than the amount of sulphur removed from emissions, is minimized. The final output of the model was found to be that the emission reductions selected by this method cost less than those indicated by an optimization procedure which minimizes only the amount of sulphur removed. The "ranking" method is, however, rather crude. The optimization methods described in Shaw and Young (1986) and Shaw (1986) do not guarantee a global optimum, unlike the standard linear programming techniques. This is because the methods in the above two papers look at one receptor point at a time by ranking the importance of source regions in contributing deposition to that particular receptor.

Other approaches have emphasized minimizing the cost of deposition reductions (McBean, Ellis & Farquhar, 1985; Morrison and Rubin, 1985; Streets, Hanson and Carter, 1984) and have shown that deposition targeted strategies can achieve environmental objectives at less cost than emission reduction strategies from each source separately. However, the question must be raised of how applicable to Europe such cost optimization schemes could be,

6

in view of various considerations such as the greater relative spatial homogeneity of emission sources in Europe compared with the "clustering" of strong source regions in North America and the reliance of some optimization methods on the recognition of single receptor points to establish a global optimum (as in Shaw and Young, 1986).

Shaw (1987), claims that the wide scatter of sources and receptors in Europe and high percentage deposition reductions required are such that the difference in efficiency between targeted deposition-oriented strategies and more simple emission-based strategies is not nearly as marked as for the North American studies. In North America, one could accomplish multi-receptor optimization by using just one or two receptor points. But in Europe, despite the relatively widespread emission pattern, the geographical distribution of optimized emission reductions is not widespread, and depends a lot on the choice of target receptor and target deposition rate (Chadwick and Cooke, 1988). If depositions were to be reduced in Austria, Germany and Switzerland, emission reduction would be confined to the central part of the continent and would not extent to Scandinavia, the Balkan countries, Spain, Portugal and the former USSR. If, on the other hand, Fennoscandinavia was to be chosen as a target receptor area, the optimised emission reductions would be confined to Fennoscandinavia and those areas of Europe bordering on the Baltic. If, for either of the above target receptor areas, a target deposition was chosen that could not be attained even with the maximum feasible emission reduction in this region, then the area where emission reductions are to take place would still not extend over Europe but only over those regions whose emissions affect the target receptor. If it is not feasible to meet the deposition targets, then the formal optimization problem has no solution. This problem can be relaxed only by dropping the insistence that all deposition targets are met and by defining a measure of progress towards the targets. One can

7

place a ceiling on total abatement expenditure and find the abatement strategy which optimized towards the target.

This paper compares two well- tried scenarios. The first scenario is based on the use of critical loads and so is in line with the second (deposition constraint) approach outlined above. It considers sensitivity classes in each country by using the map of the relative sensitivity ecosystems applied to the indirect effects of acidic depositions after Chadwick and Kuylenstierna (1990). It is therefore an ecologically appealing scenario**.** The second scenario is somewhat more "realistic", in so far as countries are already committed to it, and is based on the "30% Club". In this scenario the cost of achieving this standard sets the available European budget constraint; and emissions abatement is then maximized subject to the budget constraint and an aggregate level of emission abatement no less than 30% of 1980 levels. An alternative formulation of this, involves the maximization of the sum of reductions in all countries under two constraints. The first constraint sets upper bounds on deposition levels in every European country. The second constraint represents a European fund for acid rain abatement. In order to fix the maximum available fund for a European abatement control effort and the deposition targets in this case, an emission driven strategy is used first. Mäler (1990) uses an approach similar to the second scenario here with the difference that Mäler does not consider the available fund constraint. Although he did not implement the idea, Mäler suggests that critical loads might provide more suitable targets in this sort of analysis.

The paper finds that differentiated deposition targets defined according to critical loads are costly, but more efficient in some aspects than a uniform percentage reduction from each country. Given that costs are a crucial characteristic, and given that grid-based analysis is more appropriate for big integrated models like the CASM and the RAINS models , it would

8

be interesting to see what results are obtained by fitting the cost-data to an individual country based study like the one proposed here. At the national level it is generally easier to reach a target level of deposition than if the areas are highly dispersed (squares, grids, as in the integrated models), since the country is also the unit of political action (e.g. for intergovernmental transfers). Also, it is reasonable that highly dispersed targets (squares, grids) would make it more costly (e.g. from the point of view of information) to implement these targets. However, the cost allocation resulting from the model is not always the most ‘equitable’ one, in the sense that some countries find themselves sustaining too high (or too low) a cost burden with respect to their real responsibility, or contribution, to total emissions and depositions. Therefore, the paper considers the possibility of establishing a new distribution of abatement costs across countries on the basis of ‘alternative’ cost allocation principles, which would take into account various elements suitable for evaluating each country’s responsibility in Europe’s total pollution level.

The constraints to the optimization problem vary according to which scenario is adopted. Section 1 presents the principles of cost calculation as well as the proposed mathematical model and its pollution control targets. In section 2, some alternative criteria for re-allocating the optimal level of total abatement costs in Europe (given by the non- linear programming model) between the countries are discussed. Section 3 reports the empirical results obtained from both the optimization problem and the alternative cost allocation principles. Finally, section 4 presents some concluding remarks.

1. THE MODEL

Sub-section 1.1 presents the principles followed in the abatement cost calculation used here. In sub-section 1.2 a mathematical programming model for minimizing sulphur abatement

9

costs in all European countries subject to basic deposition constraints is presented. Finally, the "scenarios" adopted for fixing the bounds to the depositions' variable are presented in sub-section 1.3.

1.1 Principles of cost calculation

For controlling sulphur-emissions the following abatement technologies, involving different levels of costs and applicability (depending on the physical and chemical characteristics of the fuel used), exist in most industrialized countries:

(a) gas oil desulphurization,

(b) heavy fuel oil desulphurization,

(c) hard coal washing,

(d) in furnace direct limestone injection,

(e) flue gas desulphurization and

(f) fluidized bed combustion.

The actual control costs of each abatement technology are defined by national circumstances and the abatement cost curves depend on the energy scenario adopted. Abatement costs differ considerably among countries even for the same technology, mainly due to country-specific factors such as sulphur content of fuels used, capacity utilization, size of installations and labour, electricity and construction cost factors. These cost input data were obtained country by country, sector by sector and fuel by fuel, where 27 countries (i.e. all Europe), 5 sectors and 10 fuels were considered, for the year 2000(2).

The important initial assumptions for the derivation of these national abatement cost curves are the following. First, control costs are independent of order of introduction. Second, each abatement technology has a fixed coefficient of abatement when operating at its defined

10

capacity. For example, an FGD unit has an abatement efficiency of 90% (i.e. removes 90% of the sulphur content of the fuel in use) at the efficient plant size, while a sorbent limestone injection unit has an abatement efficiency of 50% at the efficient plant size. Third, it is assumed that the objective of private users is to minimize the costs of abating a given level of emissions. Further, fuel use and costs are assumed given independently of abatement policy. For the purposes of this exercise, then, abatement by means of reducing the output of electricity or other industrial output is ruled out. Finally, another basic assumption of the cost module is that there is a competitive market for sulphur abatement technologies accessible to all European countries.

Let us now turn to the construction of the abatement cost curves. In each sector and for each plant size and fuel there are a number of competing potentially efficient technologies. For instance, combinations of reductions of sulphur emissions from coal combustion would probably include the use of natural low-sulphur and/or washed coals, as well as the application of technologies like sorbent limestone injection, fluidized bed combustion and FGD. Given the generic engineering capital and operating control cost functions for each efficient abatement technology, total and marginal costs of different levels of emission reduction at each individual source (power plant, industrial boiler, petroleum refinery) and in the national (country) level can be constructed. The total abatement cost (TAC) of an abatement option, including capital and operating cost components, is given by:

$$TAC = (TCC) * CRF(r) + (AOC) \qquad (1)$$

where TCC is the total capital cost ($), AOC is the full capacity annual operating and maintenance cost ($) and CRF(r) is the capital recovery factor at the real discount rate, r, given by

$$CRF(r) = r / (1-(1+r)^{-n}) \qquad (2)$$

11

CRF(r) converts a capital cost to an equivalent stream of equal annual future payments, considering the time value of money (represented by the discount rate, r). n represents the economic life of asset (in years). For simplicity we have used a real discount rate of 5% per annum for all countries. Resulting annualized costs are expressed in United States $ at their 1985 levels.

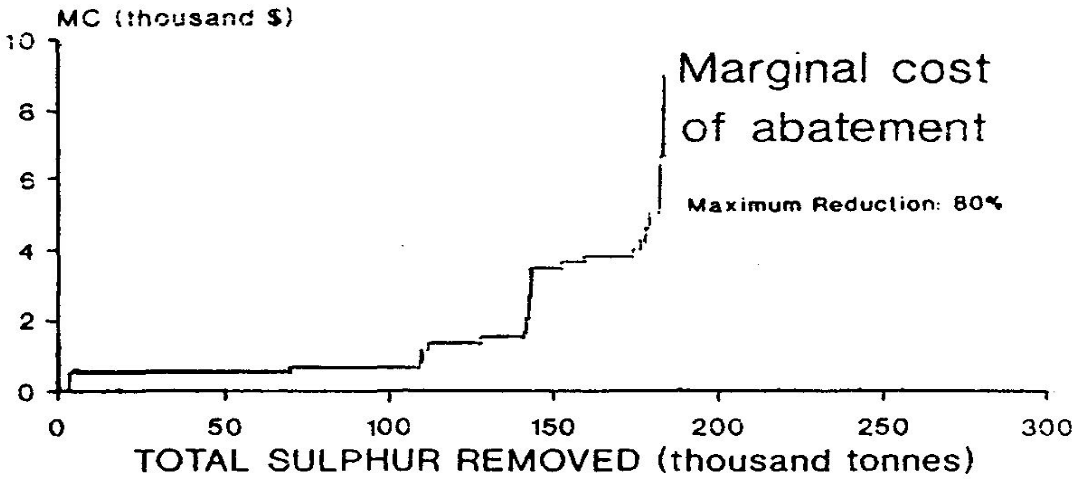
The economic efficiency of alternative abatement options (expressed as $ per tonne pollutant removed) depends on site specific conditions, and a least cost emission control function for each source can be estimated by ranking alternative options in order of increasing marginal cost of control. To do so, technologies are sorted so that marginal abatement costs increase with the level of abatement sought. Marginal costs increases are due to the effect of switching between technologies as the scale or level of abatement rises. The marginal cost curve has a staircase shape (i.e. it is a discontinuous step function) with each step representing the incremental effect of a particular discrete abatement technology. The level of each step indicates the incremental cost of a technology, and the range of each step the maximum incremental amount of sulphur removed by introducing that technology. The sequence of efficient technologies gives us the long run marginal cost of abatement. If an abatement technology is introduced which has a lower marginal cost at some level of abatement than the technology applied before, then this technology should have been applied first. The control methods applied before are not taken into consideration. The most cost – effective techniques are the proper abatement techniques for the national decision maker**.**

It is assumed that the regulatory authority seeks to maximize abatement subject to a budget constraint: a cheaper option will always be preferred over a more costly one. It would be economically inefficient to introduce relatively costly control options unless opportunities

12

for using cheaper alternatives had already been exhausted. The relative economic efficiency of alternative options is compared by reference to "cost-effectiveness" which, for a given option at a given site, is the total annualized cost divided by the annual tonnes of pollutant removed. This type of cost function is potentially useful to policy-makers because it indicates the maximum level of emission abatement that can be achieved with a given budget constraint. That is, we look for an efficient frontier or a minimal cost envelope, which will give us the optimal total cost function; i.e. the corresponding point on the marginal cost curve specifies the set of country control options which minimize total abatement costs (Rubin et al., 1986; Baumol & Oates, 1979; Kneese & Schultze, 1975; Mäler, 1990).

Figure 1
Netherlands (year 2000)



It is important to point out that building up cost curves for individual sources, by simply seeking the maximum abatement for any arbitrary budget constraint, may not yield satisfactory outcomes. This is because a slight relaxation of the source budget constraint may allow adoption of a more efficient technology. The result could be the occurrence of non-convexities in the cost function, with falling marginal costs over certain relatively small

13

abatement ranges. At the national level, however, of such ranges would be eliminated as the regulatory authority will, we assume, always be able to choose the most cost-effective technology at the source level while still satisfying the national aggregate budget constraint. For the same reason, since the average cost of abatement falls with the degree of utilization of that technology the regulatory authority will only select fully utilized technologies. Our procedure, therefore, is to build up the source cost functions by eliminating any technology choices which yield non-convex regions of the cost curve. National cost curves therefore will exhibit non-decreasing marginal costs.

Using this procedure for every European country and for every plant in every sector an abatement cost curve may be derived which shows the least cost emission control function for each source. This means that for a country with 100 power plants, industrial boilers and petroleum refineries there would be 100 abatement cost curves. To produce a least cost curve for a country these curves are aggregated. This is done by finding the technology on the plant with the lowest marginal cost per tonne of sulphur removed in the country and the amount of sulphur removed by that technology on that plant. This is the first step on the country curve. Iteratively the next highest marginal cost is found and is added on the country curve with the amount of sulphur removed on the X-axis. In the final national cost curve each step represents an abatement measure that achieves an emission reduction of an extra unit at the least cost. The national cost curve consists of a large number of very small steps.

1.2 A Non-Linear Programming Approach

In the non-linear programming approach, an attempt is made to determine an optimal "aggregate" level of the abatement coefficient (i.e. of the total emissions' reduction) for each of the 27 existing European countries and for Europe as a whole. A complete analysis would be to optimize both emissions and abatement across all European countries. This could in principle be done within the following framework:

$$\underset{SE_i,\ SA_i}{\text{maximize}}\ \Sigma_i\ [BE_i(SE_i)-C_i(SA_i)-Q_i(\Sigma_j d_{ji}(SE_j-SA_j)]\qquad (3)$$

where SE_i is the quantity of S emitted in country i, called unconstrained emissions and which are assumed to be exogenous in the mathematical problem; $BE_i(SE_i)$ is net benefits from activities generating emissions associated with electricity production and/or other industrial activities; SA_i is the quantity of sulphur (in tonnes per year) to be abated in country i, i.e. the decision variable; Q_i represents damage done by depositions in country i; C_i is the cost of abatement in country i; and d_{ji} is the proportion of country j's emissions deposited ("exported") at receptor-country i, called transfer coefficient $(0 \leq d_{ji} \leq 1)$[3]. The first order conditions of (3) are:

$$BE_k'(SE_k) - \Sigma_i Q_i'\ (\Sigma_j d_{ji}(SE_j-SA_j)\ d_{ki} \leq 0 \qquad SE_k \geq 0 \qquad (4)$$

$$-C_k'(SA_k) + \Sigma_i Q_i'\ (\Sigma_j d_{ji}(SE_j-SA_j)\ d_{ki} \leq 0 \qquad SA_k \geq 0 \qquad (5)$$

However, there is unsatisfactory and limited information regarding $Q_i(.)$ and $BE_i(SE_i)$ for all European countries; therefore a full cost-benefit analysis is not feasible. At this stage optimization exercises will analyze the minimum cost of achieving any given level of depositions. With Q unknown a variety of cost-effectiveness exercises can be carried out. A more complete model for each European economy is also required in order to analyze the trade off between reducing, say, electricity output and introducing abatement methods. Therefore, SE_i is assumed to be fixed, i.e. the analysis will be conditional on SE_i.

Underlying the proposed model is the belief that a full cost-benefit analysis of acid rain abatement is not feasible. The model focuses on the costs of abatement and provides an estimation of the benefits (or losses) that countries could achieve if they co-operate their policies rather than act independently. That is, the model seeks to identify a global

15

optimization programme for the whole of Europe considering both the cases of co-operative and non co-operative solutions. Clearly the focus on nations is to some extent artificial. Within a nation the ecological sensitivity to acid rain varies considerably, so the specification of pollution standards D_j is likely to be somewhat arbitrary. Furthermore, the receipt of sulphur depositions is unlikely to be evenly spread across a country. However, it is at the national level that abatement policies must be implemented. Although the modelling of pollution flows here is to some extent crude, the crucial feature of this model is that it acknowledges the political environment in which abatement measures must be implemented. In requiring specifications for the country depositions' variable, this study will encourage decision-makers to address a key environmental issue: namely, what deposition or emission standards should be applied, and how those standards should be secured. For those purpose, a more accurate modelling of flows of acid rain would be superfluous (as well as being infeasible).

For this purpose, the knowledge of the following data set is required for each country: (a) the total amount of sulphur emitted from each plant of each sector mentioned above, (b) the associated abatement costs per unit of sulphur removed, (c) the total amount of S-depositions, (d) the proportion of these depositions due to the country's own emissions, (e) the proportion due to the country's natural (geologic and biologic) sources and (f) the proportion due to the other countries' emissions. Knowledge of the above allows a mathematical programming problem, for determining the cost-effective abatement strategies in Europe, to be written in its simplest form as follows:

$$\text{Minimize} \quad \sum_{i=1}^{27} C_i(SA_i) \qquad (6)$$

$$\text{Subject to} \quad \sum_{i=1}^{27} d_{ij}(SE_i - SA_i) \leq \bar{D}_j - B_j \qquad j=1,2,\ldots,27$$

$$SA_i \geq 0 \quad SE_i \geq 0 \qquad i=1,2,\ldots,27$$

16

where the 27 European countries are considered simultaneously, and where $\overline{D}_j$ is the maximum allowance of depositions in country j, called targeted or constrained depositions (whose evaluation forms the subject of sub-section 1.2) and B_j is the outstanding level of depositions caused by natural sources in receptor-country j, called background pollution (4). The fact that pollution may remain in the atmosphere for long periods of time is addressed in the background deposition coefficient. SA_i, SE_i, $\overline{D}_j$ and B_j are expressed in tonnes (t). The function $C_i(SA_i)$, which is the objective function in (6), is the non-linear cost function (convex upward-sloping curve implying marginal costs increasing with removal level), giving the cost in country i of achieving any level of emissions' reduction SA_i by means of the abatement technologies mentioned above. Each of the 27 constraints (one for each European country) indicates the minimum annual abatement of sulphur depositions D_j to be secured in country j. These reductions are to be achieved by abating the sulphur emitted in each of the 27 European countries under consideration. Table 1 presents the value of the unconstrained sulphur emissions and the corresponding deposition levels in the year 2000 (5).

The model solves for the optimal values of: (a) the decision variable (SA_i^*), i.e. the emissions reduction achieved when countries act either independently or in co-operation, (b) the depositions reduction achieved independently or in co-operation, (c) the corresponding total abatement costs ($C_i(SA_i)$) and (d) the gains (or losses) that can be achieved by each country in terms of co-operation with the others rather than acting independently. These results are given country by country and for Europe as a whole.

17

Table 1: Unconstrained emissions in the year 2000 (EM), actual depositions (Dep), and targeted deposition reductions under scenarios 1 - 2 (Tar dep1 and Tar dep2). All in thousand tonnes of sulphur.

Countries	EM	DEP	Tar dep1	Tar dep2
Albania	200.00	154.00	84.40	89.74
Austria	187.00	376.00	226.70	115.70
Belgium	329.00	180.00	77.75	27.08
Bulgaria	961.00	702.00	217.53	283.80
Czechoslovakia	1216.00	1450.00	1128.80	281.06
Denmark	143.00	109.00	5.10	11.23
Finland	270.00	423.00	282.30	112.96
France	765.00	1183.00	194.95	288.53
GDR	2099.00	952.00	572.10	191.86
FRG	1556.00	1235.00	463.35	254.01
Greece	450.00	594.00	300.66	299.91
Hungary	467.00	436.00	22.94	123.89
Ireland	83.00	71.00	7.82	21.83
Italy	1715.00	1342.00	463.40	477.83
Luxembourg	15.00	7.00	1.00	0.62
Netherlands	242.00	199.00	48.00	37.60
Norway	69.00	247.00	82.00	49.34
Poland	2182.00	1859.00	685.70	507.23
Portugal	218.00	232.00	94.50	140.04
Romania	1374.00	1331.00	315.40	563.46
Spain	2573.00	2012.00	738.50	1179.93
Sweden	248.00	534.00	319.30	123.41
Switzerland	50.00	134.00	58.30	38.42
Turkey	2203.00	1976.00	305.60	1089.60
USSR	10890.00	13921.00	3531.80	4260.07
UK	1844.00	1117.00	458.96	134.36
Yugoslavia	1891.00	1466.00	635.07	775.32
Total	34240.00	34242.00	11321.93	11478.84

18

1.3 Pollution control targets

Most of the data required by the model are readily available. The country-specific abatement cost functions have been described in section 1 and are presented in Halkos (1992). EMEP (1989) gives estimates of the flows of sulphur depositions between countries and these are used to compute the transfer coefficients d_{ji}. The major difficulty in making the model operational is to construct plausible pollution standards for each country. In this section we examine two alternative strategies: a "sensitivity" scenario based on a country's current damage from sulphur depositions; and a scenario concerning the "30% Club". In the constraint of problem (6), $_j$ indicates the maximum level of depositions allowed in receptor-country j, on the basis of some environmental criteria, or, as they are called in the introduction, "scenarios". In this sub-section, the scenarios expose the methods for evaluating $\overline{D}_j$**.** The values obtained are shown in table 1.

This model is not seeking to model benefits of abatement with any precision. However, it is sensible to consider benefits in developing abatement standards, so as to ensure that the costs of abatement are imposed in the most cost-effective way. In effect, the analysis seeks to secure a cost-effective pattern of pollution abatement, so it is important to direct sulphur reduction strategies so as to secure pollution improvements in the areas that would benefit most. As a result a deposition constrained abatement scenario is proposed.

1) **A "sensitivity" scenario:** This scenario is an "index number" approach. From a relative sensitivity map of ecosystems applied to the indirect effects of acidic depositions in Europe constructed by Chadwick and Kuylenstierna (1990) it is possible for each country to calculate the area of land in each of five "sensitivity" categories. To each class corresponds a maximum deposition allowance, or ecosystem sensitivity threshold, which represents the maximum

19

acceptable level of sulphur deposition on these points, denoted by β_k (k=1,2,3,4,5), and is expressed in tonnes of sulphur per square kilometre (t/km^2) per year. These are:

$$
\begin{array}{ll}
\text{class 1} & \beta_1 \geq 5.12 \ t/km^2 \text{ per year} \\
\text{class 2} & \beta_2 = 2.56 \ t/km^2 \text{ per year} \\
\text{class 3} & \beta_3 = 1.28 \ t/km^2 \text{ per year} \\
\text{class 4} & \beta_4 = 0.64 \ t/km^2 \text{ per year} \\
\text{class 5} & \beta_5 = 0.32 \ t/km^2 \text{ per year}
\end{array}
\qquad (7)
$$

These critical loads are based on ecological criteria for which data for the entire continent are available, like geology, soil type, vegetation and amount of rainfall (for more details regarding the way that these factors are weighted to give these classes of relative sensitivity to acidic depositions, see Chadwick and Kuylenstierna, 1990). The authors of this categorization estimate that the most sensitive type of terrain (class 5) is able to tolerate at most 0.32 tonnes of sulphur depositions per square kilometre per annum without suffering ecological damage. At the other extreme, class 1 terrain is assumed to be capable of tolerating 5.12 tonnes per square kilometre per annum. Therefore, the classes are ranked in order of increasing sensitivity: class 1 refers to the least sensitive regions and class 5 to the most sensitive regions of each country. Let us call these regions "sensitivity areas". Accordingly, we construct the following sensitivity index:

$$\overline{D}_i = D_i - \sum_{i=1}^{5} (D_{ik} - a_{ik}\beta_{ik}) \qquad (8)$$

Where a_{ik} is the area in nation i lying in sensitivity category k, and s_{ik} is an index, such that

$$s_{ik} = \min(D_i / A_i, \beta_k) \qquad (9)$$

Where A_i is the total area (in $1000km^2$) of country i and β_k the critical load for each sensitivity class k(k=1,2,3,4,5) given by expression (7). The abatement requirement of achieving $\overline{D_i}$ therefore reflects current annual depositions in excess of te environmental sensitivity limits proposed by Chadwick and Kuylestierna. It is an index of severity of current pollution in the country in excess of some uniform benchmark.

Of course the abatement of sulphur pollution cannot be directed to specific geographical areas Thus, although the scheme described above gives a realistic measure of levels of depositions harmful to the environment, it does not necessarily reflect a realistic level of abatement required to eliminate ecological damage. It implicitly assumes that abatement can be directed in the precise quantities to those areas suffering environmental harm from sulphur depositions. In practice, of course, acid rain is indiscriminate in the areas it pollutes. Therefore, an important assumption in expression (8) is that air pollutants fall uniformly on the country's territory, i.e. that climatic factors which could determine a higher concentration of depositions in some regions rather than others such as rain, prevailing winds, variability in the level of precipitations and other atmospheric phenomena do not have any effect here. This assumption is made for simplicity, because of the obvious difficulty of measuring such effects and because the analysis needs to be made practicable.

A drawback of the targeted deposition reduction approach is that for some participating countries the costs of control policies will be much higher than the benefits and therefore, such countries might be unwilling to contribute to better environmental conditions in other countries if this implies high costs to them. In reality, there are countries where the economic circumstances are such that one cannot expect substantial investments in pollution control over the next years. Furthermore, one has to consider technological constraints. A country might argue that the structure of its electricity producing sector does not allow a rapid implementation of new abatement technologies. These economic, technical and political observations indicate a difficult environment in which to negotiate a common European policy for reducing adverse effects of acid rain. A way out of this situation could be an agreement

21

that allows for cost sharing via a European fund for the abatement of air pollution. Such a policy would imply abandoning the Polluter Pays Principle currently generally accepted throughout the continent.

In practice, the targeted deposition reduction approach produces prohibitively expensive abatement costs (see section 3), since it tries to provide a severe constraint to (6), on the basis of a "disaggregate" sensitivity analysis, which tries to take into account all possible reasons and elements for imposing a given depositions' reduction on each country. Scenario 2 relies on the "30% Club" and is therefore a more realistic one, for countries that have already reached an agreement and it tries to optimize emissions reduction subject to a budget constraint. This formulation of the optimization problem can also be seen as a way to reflect budget constraints in addition to emission or deposition targets.

2) **A "budget-constraint" scenario:** Ecologists and environmental policy makers now accept that there is a relationship between sulphur emissions and depositions. The recognition of this relationship has led to efforts to reduce emission levels and the consequent depositions. As long-range transport of sulphur compounds in the atmosphere is a well-established phenomenon, efforts to reduce emissions have sought international agreement on abatement as well as purely national actions like the 30% Club. But as mentioned already, emission-driven strategies ignore the transboundary nature of acid rain. Before this scenario is presented, it is better to give an idea of the tasks to be achieved. Table 2 explains how this scenario operates. The first two columns present the unconstrained emissions in 1980 and 2000 respectively, while the third column presents the level of emissions in 1980 after a 30% reduction[6]. The last two columns show the sulphur removed in 2000 (in thousand tonnes and percentages respectively) in order to achieve a 30% reduction in the year 2000 but in 1980 emission levels.

22

Table 2: The "30 percent Club" Protocol

Countries	Emissions (in 000 t) 1980	Emissions (in 000 t) 2000	Emissions in 1980 according to a 30% reduction	Sulphur removed in the year 2000 to achieve 30% reduction in 1980 emission levels: Levels	(%)
Albania	97	200	68.0	132.1	66.0
Austria	177	187	124.0	63.1	33.7
Belgium	392	329	274.4	54.6	16.6
Bulgaria	874	961	611.8	349.2	36.4
Czechoslovakia	1679	1216	1175.3	40.9	3.4
Denmark	200	143	140.0	3.0	2.1
Finland	275	270	192.5	77.5	28.7
France	1520	765	1064.0	-	
FRG	1755	1556	1228.5	327.5	21.1
GDR	2367	2099	1656.9	442.1	21.1
Greece	248	450	173.6	276.4	61.4
Hungary	666	467	466.2	0.8	0.2
Ireland	73	83	51.1	31.9	38.4
Italy	1637	1715	1145.9	569.1	33.2
Luxembourg	20	15	14.0	1.0	7.0
Netherlands	255	242	178.5	63.5	26.3
Norway	71	69	49.7	19.3	28.0
Poland	2130	2182	1491.0	691.0	31.7
Portugal	124	218	86.8	131.2	60.2
Romania	1040	1374	728.0	646.0	47.0
Spain	1446	2573	1012.2	1560.8	60.7
Sweden	266	248	186.2	61.8	24.9
Switzerland	55	50	38.5	11.5	23.0
Turkey	513	2203	359.1	1843.9	83.7
UK	2365	1844	1655.5	188.5	10.2
USSR	11036	10890	7725.2	3164.8	29.1
Yugoslavia	816	1891	571.2	1319.8	69.8

23

In this second scenario, it is important to bear in mind a drawback of the targeted deposition reduction approach is that, as mentioned above, for some countries the abatement control cost may be higher than the benefits. Additionally, there may exist technological constraints of achieving these targets. Therefore, there is a need for international transfers in order to motivate all countries to reduce their emissions. A way out of this problem is by considering a European fund for the abatement of acid rain pollution. The following optimization problem deals with this issue:

$$\text{Maximize} \quad \sum_{i=1}^{I} SA_i \tag{10}$$

$$\text{Subject to} \quad \sum_{j=1}^{27} d_{ji}(SE_j - SA_j) \leq \bar{D}_i \quad (i=1,...,I)$$

$$\sum_{i=1}^{I} C_i(SA_i) \leq \overline{AF}$$

$$SA_i \geq 0, \quad SA_i \geq PSA_i \quad \text{and} \quad SA_i \leq SE_i$$

where $\overline{AF}$ is the available fund and **PSA** the planned reductions already agreed upon (e.g. as of the 30% emission reduction in our case). The amount of the fund in this formulation, and for our third scenario, is determined as follows. We first solve the following emission-driven optimization problem of each single European country taking the decision at a national level, i.e.:

$$\text{Minimize} \quad C_i\,(SA_i)$$

$$\text{Subject to} \quad (SE_i - SA_i) \leq \overline{SE_i} \tag{11}$$

$$SA_i \geq 0$$

where $\overline{SE_i}$ is the sulphur emission standard representing, for instance, the 30% reduction agreed to by many countries in 1985. The solution to problem (11) gives us the individual costs of achieving these emission targets and therefore, the corresponding deposition levels after achieving these emission reductions. The sum of these individual costs will give us the

24

maximum European available budget for emissions abatement of 30% of 1980 emission levels in the year 2000. This is then used as the available fund (AF) variable in problem (10), while the targeted depositions of the first constraint have to be less or equal to the depositions achieved in problem (11).

As mentioned, the values of $\overline{D}_j$ obtained under scenarios 1 and 2 are shown in table 1. The next section introduces some alternative criteria for re-allocating between the countries the optimal total abatement costs given by the non – linear programming model.

2. ALTERNATIVE COST ALLOCATION PRINCIPLES

It can be seen that our mathematical programming model determines the optimal total abatement costs for each country and for Europe as a whole under the two scenarios examined in sub-section 1.3. However, some countries could find themselves reaching the required target with a greater (lesser) effort than their planned policies in this respect: then the rational behaviour solution to the cost distribution problem in (6), i.e. the set of costs ($C_i(SA_i^*)$, i=1,2,...27), may not correspond to the cost distribution that the countries are effectively willing to pay, given their contribution to total emissions and depositions. In other words, the effective abatement strategies may not be the equitable ones. In this section, the optimal total abatement cost in all Europe given by the solution of (6) is taken for granted, i.e. $C^* = \Sigma_i C_i(SA_i^*)$, and six alternative criteria, or "principles", for re-allocating C^* equitably between the countries by taxes or subsidies are examined[(7)]. An attempt is made to establish cost-sharing arrangements between countries and to create a form of European fund for air pollution control, which could raise subsidies from member countries in proportion to some indicator (such as the gross national product, national emissions, etc) and then distribute these subsidies to countries in such a way as to promote cost-effective emissions' or depositions' reduction measures. The corresponding results are shown in tables 5 to 10. Consider the suggested principles in turn.

i) The first principle is called "polluter pays principle (PPP)" and relies on the idea that one who is causing an environmental problem has the responsibility to take the necessary measures to eliminate the problem and bear the full cost of the measures. The PPP was adopted by the OECD countries in 1972 (OECD, 1975). According to this principle, each country's share of total abatement costs (here called **"scaling factor"**) is determined as follows:

$$SF_i = SE_i / \Sigma_i SE_i \quad \text{and} \quad \Sigma_i SF_i = 1 \qquad (12)$$

where $\mathbf{SE_i}$ denotes country i's unconstrained emissions (defined in section 1) and $\mathbf{SF_i}$ is the scaling factor, on the basis of which country i's total abatement cost will be:

$$C_i = SF_i C^* \qquad (13)$$

where, as we mentioned, $C^* = \Sigma_i C_i (SA_i^*)$. Therefore, the polluter-pays principle redistributes costs according to each country's share of total unconstrained emissions. This principle is incomplete as an efficiency principle as it requires only the control costs and not residual damages be paid. It is clear from expressions (12) and (13) that the term "polluter pays" is in some sense misleading, because what really happens is that the polluting country bears the cost of abating its own pollution (emissions). However, we have preferred to keep in use the term "polluter pays" because this was introduced extensively in OECD terminology (OECD, 1975). Indeed, this would seem a fairly equitable principle, even when the country's emissions deposit mainly on its own territory. Some interpretation problems arise, however, with the "polluter pays principle"; particularly concerning what is to be effectively paid: only control costs (standard PPP) or also the physical damage (extended PPP)? The latter is hardly measurable in monetary terms; moreover, it is often impossible to identify the particular polluters responsible for damage, especially if damage becomes visible only after a long period (in general ecosystems need a long time to recover, assuming that they can). Therefore, for the purpose of this work we define this principle only on control costs.

ii) Looking for a procedure that will lead to a reduction in waste emissions in such a way that social welfare rises in both countries, the "Polluter Pays Principle" is inconsistent with a Pareto improvement, as a program of pollution abatement in a polluting country would impose costs on this country with no offsetting benefits. Moreover, the PPP is difficult to apply in international context as there is not a European Authority to attribute environmental costs to the polluter via taxation or regulation. International spillovers constitute a game theoretic problem in which the non co-operative solution is inefficient, because each country does not take into account the effects of its action on the welfare of other countries when it seeks to minimize the costs of pollution net of abatement costs. In a co-operative solution the net costs are minimized for all countries together. But this implies that there may be countries that are worse off in the co-operative than in the non co-operative solution, in the absence of any kind of compensation (e.g. in the form of side payments). The need for side payments means, therefore, that the Victim Pays Principle is more appropriate for solving international problems. The requirement that the process yields a Pareto-improvement implies a "Victim Pays Principle (VPP)" according to which the pollutee country (countries) should bear the abatement costs and the residual damage. This principle is the closest one to our non-linear programming model. In this case:

$$S_i = (D_i - \bar{D}_i)/ \Sigma_i \bar{D}_i \qquad SF_i = (S_i / \Sigma S_i) \text{ and } \quad \Sigma_i SF_i = 1 \qquad (14)$$

27

where D_i and $\overline{D}_i$ are the actual and constrained depositions respectively (defined in section 1). Then, if $SF_i < 0$, the country lies beneath its target and doesn't sustain any cost, i.e. we set $C_i = 0$ in (13): a negative cost $C_i < 0$ would not, in fact, make any sense. However, for this reason, the countries for which $SF_i > 0$ will sustain a higher cost burden (unless C^* is shortened by the amounts corresponding to the negative scaling factors) and because depositions are not always due to internal emissions, this explains why the principle is called "victim pays".

The applications of the VPP are rare in reality. This is because where a country has to deal with other countries (or country in a bilateral level) on transboundary pollution issues, and then an acceptance of the VPP in the negotiations of these issues may give the country a reputation of a "weak" negotiator. Mäler (1990) gives another reason: countries with a transboundary pollution problem develop a "web of international relations" i.e. they may have a large number of links other than the flow of pollutants from one of the countries to the other (e.g. trade, capital markets, tourism etc). Therefore, one country may want to make concessions in order to improve friendly neighbourhood relations and thereby to achieve advantages in other areas of mutual interest.

iii) Another way of negotiating is by sharing equally the responsibilities. In this case the abatement costs and the residual damage are borne equally by the polluter and the victim countries. This third principle is called "equal share of responsibility" and the scaling factor is simply the average of the scaling factors given by the polluter pays and the victim pays principles.

iv) In general it would not be appropriate to expect a poor country to choose to devote as high a proportion of its scarce resources to abate pollution as do its rich neighbours. The European countries are not equally rich and therefore the poor countries would tend to want

28

to abate less than the rich countries. An indicator of the economic situation of countries is given by the Gross National Product (GNP). Therefore, the fourth principle is called "gross national product principle", and considers the most global indicator of the countries' economic activity, to which emissions are implicitly assumed to be proportional. In this case:

$$SF_i = GNP_i / \Sigma_i GNP_i \quad \text{and} \quad \Sigma_i SF_i = 1 \qquad (15)$$

where **GNP$_i$** is the real gross national product of country i ($ million, 1985). This principle favours the "poor" countries.

v) Strictly related to the preceding one is the fifth principle, called "emissions intensity". In this case:

$$S_i = SE_i / GNP_i \qquad SF_i=(S_i / \Sigma S_i) \qquad \Sigma_i SF_i = 1 \qquad (16)$$

i.e. emissions are considered explicitly, but the other countries' influence disappears from the scaling factor. In other words, only country i's emissions' "weight" on country i's gross national product matters to evaluate the country's responsibility on pollution. There is no explicit consideration of the other countries' emissions, or gross national products, like in expressions (14) and (15).

vi) It is notable that different countries are likely to value differently the damage which pollution causes them. It is not possible to draw general conclusions about the likely variations in valuation of damage. In most analyses the aim of defining "'damage cost" is to find the total amount that victims of (or sufferers from) pollution would pay to be free of the pollution at a given time and place. This "willingness to pay" is then assumed to stem from the victim's valuation of the "damage" or harm that the unabated pollution imposes on him. In this thesis (as many authors have) the "damage cost" terminology is avoided by referring instead to the value of "benefits" of pollution abatement. Therefore, the sixth principle is called "willingness

29

to pay" and it is based on a standard economic theory approach of rational agents (in our case, countries) attempting to maximize their utility by maximizing the net benefits of pollution control. These are defined as the benefits of an improved environment minus the costs of pollution control: each country reduces emissions up to the point where its marginal benefits equal the marginal abatement costs. Here the marginal benefits are identified with the quantity of depositions "avoided" per unit of marginal abatement undertaken by the country.

Assuming that countries behave rationally, each country reduces emissions up to the point at which the countries' net benefits are maximized, which is also the point at which the country's marginal benefit equals its marginal abatement cost. So:

$$MB_i = MC_i \qquad (17)$$

The scaling factor for this principle is given by:

$$S_i = MB_i(D_i - \bar{D}_i) \qquad SF_i=(S_i / \Sigma S_i) \quad \text{and} \quad \Sigma_i\, SF_i = 1 \qquad (18)$$

where $\mathbf{MB_i}$ is the marginal benefit of country i from the abatement of one extra unit of emissions in country i, equal to the pre-reform marginal abatement cost; i.e. we extend the victim pays principle and expression (12) and instead of considering only tonnes of sulphur depositions we weight such tonnes by the value of the marginal benefits as shown by (18). Defining $D_i - \bar{D}_i = \delta_i$ as the country's required depositions' reduction, then from (18), the countries for which $\delta_i > 0$ must "repay" the corresponding benefit under the form of a total costs' share. However, given the sensible range of variation in sensitivity existing not only across countries, but also, as seen, across different areas (Chadwick and Kuylenstierna assume the existence of five different sensitivity classes, as shown in scenario 1), the quantity of depositions is a very general and imprecise approximation for "true" benefit.

As mentioned, the values of SF_i and C_i obtained with the above principles are shown in tables 5 to 10. In the next section, these results as well as the overall empirical results of the non-linear programming model, under each of the scenarios defined in sub-section 1.3, are commented on. An attempt is made to see which countries are favoured and which, on the contrary, are penalized by the approaches proposed; and which scenarios and/or which cost allocation criteria must be "preferred" from an environmental point of view. Some concluding remarks will follow.

3. EMPIRICAL RESULTS

In this section the results obtained from the mathematical programming model are interpreted. Using tables 3-4 it is possible to answer the following questions: i) which scenario is to be 'preferred' and ii) which cost allocation principle is the most 'equitable' one across countries. Consider the first question. Having presented the two scenarios in section 1, it is now possible to show the results of the non – linear programming model under each scenario in table 3-4. Looking at the total numbers for Europe, i.e. ($SA^*=\Sigma_{i=1}^{27}$ (SA_i^*) and $C^*=\Sigma_{i=1}^{27}$ $C_i(SA_i^*)$), it is tempting to say (as was in section 1) that scenario 1 is the most "severe" one, since it is the most expensive (C^* = 9,634 million $) and also the one leading to the highest required emissions' reduction (SA^* = 17,072 thousand tonnes), according to the discussion which was explaining the nature of the depositions' target under scenario 1. Looking at table 1, it can be seen that scenario 2 requires the largest depositions reduction. However, if countries co-operate then scenario 1 achieves the highest depositions reduction.

Table 3: A "sensitivity" scenario (emissions and depositions in 1000 tons S; costs and benefits in m $)

Countries	Emissions reduction IND	Emissions reduction CO-OP	Depositions reduction IND	Depositions reduction CO-OP	Total costs IND	Total costs CO-OP	Benefits
Albania	120.57	118.97	84.40	92.31	180.81	134.06	+46.75
Austria	588.79	116.82	226.70	234.19	324.18	36.04	+288.13
Belgium	258.38	236.55	77.75	125.69	342.41	213.22	+124.19
Bulgaria	500.11	634.60	217.53	429.47	134.80	207.42	-72.62
Czechoslovakia	2761.8	749.38	1128.8	903.00	604.70	348.11	+256.59
Denmark	14.30	109.50	5.10	77.02	0.29	141.44	-141.15
Finland	511.55	189.05	282.30	245.32	893.23	400.60	+492.63
France	366.49	473.77	194.95	669.65	275.09	434.80	-159.71
FRG	1800.4	1336.4	572.10	616.19	2514.9	1228.3	+1286.65
GDR	1193.7	1209.6	463.35	855.78	1562.2	1625.3	-63.06
Greece	491.99	365.80	300.66	401.12	501.11	260.69	+240.42
Hungary	79.95	262.02	22.94	261.72	21.04	89.66	-68.61
Ireland	12.48	8.92	7.82	17.10	0.24	0.17	+0.07
Italy	785.31	979.24	463.40	765.56	460.16	657.66	-197.50
Luxembourg	5.00	3.50	1.00	3.49	0.14	0.06	+0.08
Netherlands	170.82	167.44	48.00	137.61	184.98	173.17	+11.81
Norway	145.08	35.47	82.00	148.62	257.59	14.11	+243.48
Poland	1523.6	1384.2	685.70	1156.22	1375.4	831.94	+543.47
Portugal	141.10	140.77	94.50	128.72	136.94	136.05	+0.89
Romania	684.61	713.79	315.40	719.99	182.70	192.56	-9.86
Spain	1023.8	1030.5	738.50	845.41	239.70	241.15	-1.45
Sweden	569.69	154.88	319.30	324.02	1032.1	94.11	+937.98
Switzerland	182.19	9.34	58.30	73.40	274.19	0.46	+273.73
Turkey	403.86	390.09	305.60	483.64	124.83	121.12	+3.71
UK	3753.1	3881.4	3531.8	5762.22	627.47	671.95	-44.48
USSR	849.72	1115.8	458.96	668.99	520.63	906.43	-385.79
Yugoslavia	1466.3	1254.4	635.07	925.71	896.85	468.53	+428.31
TOTAL	20405	17072[(a)]	11322	17072[(a)]	13669	9634.1	+4103.27

32

Table 4: The "30% Club" scenario (30% emissions reduction in 1980 emission levels)
(emissions and depositions are in 1000 tonnes S; costs and benefits in m $)

Countries	Emissions reduction		Depositions reduction		Total costs		Benefits
	IND	CO-OP	IND	CO-OP	IND	CO-OP	
Albania	120.17	117.59	89.74	89.74	180.81	114.15	+66.7
Austria	63.10	81.77	115.70	145.32	3.36	8.77	-5.41
Belgium	54.60	89.81	27.08	39.00	1.63	11.95	-10.27
Bulgaria	349.20	621.27	283.80	429.72	87.68	193.85	-106.17
Czechoslovakia	40.90	570.29	281.06	564.48	14.67	205.42	-190.75
Denmark	3.00	25.91	11.23	23.19	0.06	2.94	-2.88
Finland	77.50	32.85	112.96	112.96	41.09	17.36	+23.73
France	0.00	12.58	288.53	317.77	0.00	2.10	-2.10
FRG	442.10	810.62	191.86	335.67	155.35	292.98	-137.63
GDR	327.50	403.11	254.01	336.00	78.93	107.85	-28.92
Greece	276.40	337.75	299.91	384.49	149.01	212.80	-63.79
Hungary	0.80	254.08	123.89	225.73	0.39	82.91	-82.53
Ireland	31.90	38.95	21.83	26.13	5.21	8.35	-3.14
Italy	569.10	547.51	477.83	477.83	302.11	288.87	+13.25
Luxembourg	1.00	4.94	0.62	1.54	0.02	0.09	-0.07
Netherlands	63.50	38.78	37.60	37.60	21.77	9.92	+11.85
Norway	19.30	26.71	49.34	66.11	0.59	0.81	-0.23
Poland	691.00	379.77	507.23	517.85	263.21	122.77	+140.43
Portugal	131.20	128.11	140.04	140.04	115.25	109.57	+5.68
Romania	646.00	953.95	563.46	777.17	170.03	284.43	-114.39
Spain	1560.8	1622.7	1179.9	1225.6	408.00	437.11	-29.11
Sweden	61.80	91.53	123.41	163.57	1.98	8.91	-6.93
Switzerland	11.50	9.85	38.42	39.54	1.63	0.64	+0.99
Turkey	1263.4	1204.1	1089.6	1089.6	1385.2	776.28	+608.88
UK	3164.8	4380.8	4260.1	5665.0	430.21	858.17	-427.96
USSR	188.50	175.26	134.36	134.36	98.17	90.85	+7.32
Yugoslavia	1319.8	1232.2	775.32	826.67	784.58	451.13	+333.45
TOTAL	11479	14193[(a)]	11479	14193[(a)]	4701	4701	0

33

These results should be expected for the following reasons: the "30% Club" scenario relies on the idea that countries act independently trying a certain emissions target in the first stage, and trying to see if they can achieve better emission and deposition levels if they co-operate by spending the same total amount of money. Conversely, scenario 1 incorporates a more detailed analysis, taking into account both dimensional factors (i.e. the areas of the countries) and the different sensitivity levels (despite the implicit, restrictive assumption of a uniform depositions' concentration on land: see section 1). Indeed, the comparison provided above shows the existence of a trade-off between emission reductions, on one hand, and both control costs and deposition targets on the other hand. Hence, it is useful to calculate for these scenarios the quantity of depositions avoided per unit of cost incurred (i.e. the ratio $(D-)/C^*$, where $D=\Sigma_j D_j=34{,}242$ thousand tonnes and indicates Europe's actual depositions, see table 1). Doing so, scenario 2 gives the best ratio and scenario 1 the most expensive. Using tables 1 and 3-4, these ratios are 1.68 and 4.84 thousand tonnes deposition reduction per million $ in the non-cooperative case and 2.4 and 4.26 in the co-operative one for scenarios 1 and 2 respectively. Therefore, scenario 2, is the most convenient one, since it "minimizes" total abatement costs, as a consequence of "maximizing" depositions' reductions per unit of cost in all Europe simultaneously. However, scenario 1, i.e. the "sensitivity" depositions' reduction in each country, minimizes the total depositions in Europe, while scenario 2 presents the lowest total costs (which is logical according to the aim of this scenario). But, it could be argued that a higher abatement cost (4,663=9,364-4,701 million $) is worth sustaining if it leads to a much higher cut in the depositions' target (2,879=17,072-14,193 thousand tonnes).

Finally, considering the benefits that can be achieved if countries co-operate instead of acting independently, it can be seen that these benefits are negative for some countries and

34

these countries should be compensated. Scenario 1 is in favour of more countries, although it makes Bulgaria, Denmark, France, FRG, Hungary, Italy, Romania, USSR and UK worse off. Also, the gains for Ireland and Luxembourg and the loss for Spain are negligible. Romania experiences a moderate loss and the UK a substantial loss. Obviously the UK would have no incentives to participate in a co-operation to reduce sulphur emissions. Regarding scenario 2, we must bear in mind that it redistributes the costs: countries first achieve independently their targets and then try to see how could they optimize their efforts by achieving the same or higher deposition target reductions by spending the same amount of money; i.e. we have a re-allocation of the abatement costs in an optimized way as far as countries where control cost is cheaper should undertake more abatement. This leads to a more than 40% emissions reduction across Europe compared to the case where countries act independently. Therefore, a cost of achieving a 30% reduction could in fact achieve a 40% average reduction if an efficient cost allocation were adopted. Mäler (1990) also finds that 40% is achievable, although there are differences within countries due to the fact that Mäler uses the unconstrained emissions in the year 1984, different transfer matrix and different abatement cost estimates (he uses IIASA's control cost data). By acting co-operatively rather than independently Albania, Finland, Italy, Netherlands, Poland, Portugal, Switzerland, Turkey, UK and Yugoslavia get a better cost allocation, while all the other countries are worse off. It is worth mentioning that according to this scenario UK enjoys a positive benefit of $7.32 million, while under scenario 1 UK has a negative benefit of $385.8 million. Finally, the following table presents a summary of all the comparisons presented above regarding the results of the non linear model under the two scenarios.

35

Summary of the main results

		Scenario 1	Scenario 2
Total abatement costs (in $ million)	INDEPENDENTLY	13,669	4,701
	CO-OPERATIVELY	9,634	4,701
Total sulphur abated (in 1000 tonnes)	INDEPENDENTLY	20,405	11,479
	CO-OPERATIVELY	17,072	14,193
Depositions reduction (in 1000 tonnes)	INDEPENDENTLY	11,322	11,479
	CO-OPERATIVELY	17,072	14,193
(D-)/C* (1000 t/$ m)	INDEPENDENTLY	1.68	4.84
	CO-OPERATIVELY	2.4	4.26

A country by country analysis is perhaps necessary before deciding which scenario is the "best" one, and this leads us immediately to the second question. The first step for a country by country analysis is to look at table 1, from which the **major emitters** are the following: Bulgaria, Czechoslovakia, France, East Germany, West Germany, Hungary, Italy, Poland, Romania, Spain, Turkey, Soviet Union, United Kingdom and Yugoslavia (i.e. the "Eastern block" and the major EU members plus Turkey). Now, from tables 5-10, which show the non-linear programming model's cost allocation according to different principles, both scaling factors and required emission reductions do reflect, under each scenario, the importance of these countries' contribution to total emissions. Of course, the same conclusion can be drawn for the polluter pays principle (see Table 5 and expression (12), which defines the polluter pays principle’s scaling factor). The victim pays principle shows also the relative importance of the 14 major emitters mentioned above for each scenario (see table 6).

However, due to the different definition of the relevant scaling factor (given in expression (14)), some countries find themselves paying a higher cost share than they would in the polluter pays principle or in the present model's cost allocation. These countries are Austria, Czechoslovakia, Finland, France, Greece, Norway, Portugal, Sweden, Switzerland and USSR.

This result is not surprising, since, from Chadwick and Kuylenstierna (1990), such countries present very high levels of sensitivity in many parts of their territories, which means that depositions tend to concentrate on them. Conversely, some of the 14 major emitters, like Italy, Spain, FRG and GDR pay a lower cost share in the victim pays principle than in the polluter pays or the non linear programming model principle, due to the lowest depositions' sensitivity despite the high level of emissions. Therefore, the opinion presented here is that the equal share of responsibility principle is really the most "equitable" one, because it modifies the emissions/depositions' weight in total abatement costs in order to have the abatement costs borne equally by the polluter and the victim, for all the countries in all scenarios as shown by table 7. Conversely, the gross national product principle presents very low cost shares for all Eastern block countries (except the USSR), which are, however, included in the 14 major emitters; while countries like the Netherlands, Sweden or Switzerland (plus, of course, the main EU members) show a sensible increase in their scaling factors with respect to other principles, because of their sustained economic activity (represented by the gross national product). The emissions' intensity principle "overcorrects" this phenomenon, in the sense that the Eastern block countries register in this case too high cost shares with respect to all other principles: this is due to the joint influence of low gross national products and high emissions standards on the definition of the scaling factor (recall expression (16)), except for the Soviet Union, which registers a very low scaling factor in all scenarios. This is probably because the

37

elevated values of emissions, depositions and gross national product in this country are due to its large territory rather than anything else (including the emissions/gross national product ratio).

Finally, the "willingness to pay principle" is quite "variable" across scenarios, since the difference between actual and constrained depositions (D_i- $\bar{D}_i$) is considered explicitly in the scaling factor (see expressions (17) and (18)). However, the countries for which such a scaling factor is larger than the one given by our model (i.e. the countries which are not "willing to pay" the corresponding amount of abatement costs) are basically the following: for scenario 1 Albania, Austria, Czechoslovakia, Finland, France, Hungary, Luxembourg, Netherlands, Norway, Poland, Sweden and Switzerland; and for scenario 2 Albania, Austria, Belgium, Czechoslovakia, Denmark, Finland, France, FRG, Hungary, Norway, Poland, Switzerland, Turkey and the UK. Recalling (17) and (18), the conclusion is that such countries pay "more than they ought to" if the amount by which actual internal depositions exceed target depositions was also considered in the evaluation of the country's total abatement cost. Then, given that these countries present a high level of economic activity and given that they are not all included in the 14 major emitters, the willingness to pay principle may not be considered as the most "equitable" in redistributing total optimal abatement costs between European countries as it favours the major emitters (e.g. GDR, Italy, USSR, Yugoslavia, etc). In general, all these cost-allocation principles give a good indication of which countries could eventually be required to implement more consistent abatement strategies for reducing the acid rain impact over all Europe.

Table 5: Scaling factors and costs for the "polluter pays principle" (emissions are given in 1000 tonnes of S and total costs in m $)

	EM	SF	C Sc1	C Sc2
ALB	200	0.005841	56.27	27.46
AUS	187	0.005461	52.62	25.67
BEL	329	0.009609	92.57	45.17
BUL	961	0.028067	270.40	131.94
CZE	1216	0.035514	342.14	166.95
DEN	143	0.004176	40.24	19.63
FIN	270	0.007886	75.97	37.07
FRA	765	0.022342	215.25	105.03
GDR	2099	0.061303	590.59	288.18
FRG	1556	0.045444	437.81	213.63
GRE	450	0.013143	126.62	61.78
HUN	467	0.013639	131.40	64.12
IRE	83	0.002424	23.35	11.40
ITA	1715	0.050088	482.55	235.46
LUX	15	0.000438	4.22	2.06
NET	242	0.007068	68.09	33.23
NOR	69	0.002015	19.41	9.47
POL	2182	0.063727	613.95	299.58
POR	218	0.006367	61.34	29.93
ROM	1374	0.040129	386.60	188.64
SPA	2573	0.075146	723.96	353.26
SWE	248	0.007243	69.78	34.05
SWI	50	0.001460	14.07	6.86
TUR	2203	0.064340	619.85	302.46
SU	10890	0.318049	3064.10	1495.14
UK	1844	0.053855	518.84	253.17
YUG	1891	0.055228	532.07	259.62
TOTAL	34240	1.000000	9634.06	4700.97

where: **EM** stands for unconstrained sulphur emissions in the year 2000; **SF** is the scaling factors; **C Sc1 and C Sc2** are the total costs according to scenarios 1 and 2 respectively.

39

Table 6: Scaling factors and costs for the "victim pays principle" (total costs in million $)

	SF Sc1	SF Sc2	C Sc1	C Sc2
ALB	0.005207	0.002823	50.16	13.27
AUS	0.006500	0.011435	62.62	53.76
BEL	0.004451	0.006718	42.89	31.58
BUL	0.021091	0.018372	203.20	86.37
CZE	0.013983	0.051352	134.72	241.41
DEN	0.004523	0.004295	43.58	20.19
FIN	0.006125	0.013620	59.01	64.03
FRA	0.043015	0.039295	414.41	184.72
GDR	0.016539	0.033393	159.34	156.98
FRG	0.033594	0.043095	323.64	202.59
GRE	0.012771	0.012920	123.03	60.73
HUN	0.017983	0.013711	173.24	64.46
IRE	0.002751	0.002160	26.50	10.15
ITA	0.038250	0.037964	368.50	178.47
LUX	0.000261	0.000280	2.52	1.32
NET	0.006574	0.007090	63.33	33.33
NOR	0.007183	0.008683	69.20	40.82
POL	0.051080	0.059384	492.10	279.16
POR	0.005986	0.004040	57.67	18.99
ROM	0.044214	0.033719	425.96	158.51
SPA	0.055442	0.036553	534.13	171.84
SWE	0.009347	0.018037	90.05	84.79
SWI	0.003296	0.004199	31.75	19.74
TUR	0.072721	0.038940	700.60	183.06
SU	0.452293	0.424411	4357.42	1995.14
UK	0.028648	0.043168	275.99	202.93
YUG	0.036174	0.030342	348.51	142.64
TOTAL	1.000000	1.000000	9634.06	4700.97

where: **SF Sc1 and SF Sc2** are the scaling factors according to scenarios 1 and 2 respectively; **C Sc1** and **C Sc2** are the total costs according to our scenario 1 and 2 respectively.

Table 7: Scaling factors and costs for the "equal share of responsibility principle" (total costs in million $)

	SF Sc1	SF Sc2	C Sc1	C Sc2
ALB	0.005524	0.004332	53.22	20.36
AUS	0.005981	0.008448	57.62	39.72
BEL	0.007030	0.008163	67.73	38.38
BUL	0.024579	0.023219	236.80	109.15
CZE	0.024749	0.043433	238.43	204.18
DEN	0.004350	0.004236	41.91	19.91
FIN	0.007005	0.010753	67.49	50.55
FRA	0.032678	0.030818	314.83	144.88
GDR	0.038921	0.047348	374.96	222.58
FRG	0.039519	0.044270	380.73	208.11
GRE	0.012957	0.013031	124.82	61.26
HUN	0.015811	0.013675	152.32	64.29
IRE	0.002587	0.002292	24.93	10.77
ITA	0.044169	0.044026	425.52	206.96
LUX	0.000350	0.000359	3.37	1.69
NET	0.006821	0.007079	65.71	33.28
NOR	0.004599	0.005349	44.31	25.15
POL	0.057403	0.061555	553.02	289.37
POR	0.006176	0.005203	59.50	24.46
ROM	0.042171	0.036924	406.28	173.58
SPA	0.065294	0.055850	629.05	262.55
SWE	0.008295	0.012640	79.91	59.42
SWI	0.002378	0.002830	22.91	13.30
TUR	0.068530	0.051640	660.23	242.76
SU	0.385171	0.371230	3710.76	1745.14
UK	0.041251	0.048512	397.42	228.05
YUG	0.045701	0.042785	440.29	201.13
TOTAL	1.000000	1.000000	9634.06	4700.97

where: **SF Sc1 and SF Sc2** are the scaling factors according to scenarios 1 and 2 respectively; **C Sc**1 and **C Sc**2 are the total costs according to scenarios 1 and 2 respectively.

Table 8: Scaling factors and costs for the "gross national product principle" (GNP and total costs in million $)

	GNP	SF	C Sc1	C Sc2
ALB	2800	0.000514	4.95	2.42
AUS	69060	0.012678	122.14	59.60
BEL	83230	0.015280	147.21	71.83
BUL	25530	0.004687	45.15	22.03
CZE	85960	0.015781	152.03	74.19
DEN	57330	0.010525	101.40	49.48
FIN	53450	0.009813	94.53	46.13
FRA	526630	0.096681	931.43	454.49
GDR	93631	0.017189	165.60	80.81
FRG	667970	0.122629	1181.41	576.47
GRE	35250	0.006471	62.35	30.42
HUN	20720	0.003804	36.65	17.88
IRE	17250	0.003167	30.51	14.89
ITA	371050	0.068119	656.26	320.22
LUX	4900	0.000900	8.67	4.23
NET	132920	0.024402	235.09	114.71
NOR	57580	0.010571	101.84	49.69
POL	78960	0.014496	139.65	68.14
POR	20140	0.003697	35.62	17.38
ROM	45536	0.008360	80.54	39.30
SPA	168820	0.030993	298.58	145.70
SWE	99050	0.018184	175.19	85.48
SWI	105180	0.019309	186.03	90.77
TUR	56060	0.010292	99.15	48.38
SU	2046000	0.375613	3618.67	1765.75
UK	474190	0.087054	838.68	409.24
YUG	47900	0.008794	84.72	41.34
TOTAL	5447097	1.000000	9634.06	4700.97

where: **GNP** stands for gross national product; **SF** is the scaling factors; **C Sc1 and C Sc2** are the total costs according to scenarios 1 and 2 respectively.

Table 9: Scaling factors and costs for the "emissions intensity principle" (total costs in million $)

	SF	C Sc1	C Sc2
ALB	0.183489	1767.74	862.575
AUS	0.006956	67.01	32.699
BEL	0.010154	97.83	47.735
BUL	0.096696	931.58	454.566
CZE	0.036339	350.09	170.829
DEN	0.006408	61.73	30.122
FIN	0.012976	125.02	61.002
FRA	0.003732	35.95	17.542
GDR	0.057588	554.80	270.718
FRG	0.005984	57.65	28.130
GRE	0.032794	315.94	154.162
HUN	0.057898	557.79	272.177
IRE	0.012360	119.08	58.105
ITA	0.011873	114.39	55.816
LUX	0.007864	75.76	36.967
NET	0.004677	45.06	21.986
NOR	0.003078	29.66	14.471
POL	0.070988	683.90	333.712
POR	0.027806	267.88	130.714
ROM	0.077512	746.76	364.382
SPA	0.039152	377.19	184.052
SWE	0.006432	61.96	30.236
SWI	0.001221	11.76	5.741
TUR	0.100948	972.54	474.555
SU	0.013673	131.73	64.276
UK	0.009990	96.24	46.961
YUG	0.101413	977.02	476.739
TOTAL	1.000000	9634.06	4700.97

where: **SF** is the scaling factors; **C Sc1 and C Sc2** are the total costs according to scenarios 1 and 2 respectively.

43

Table 10: Scaling factors and costs for the "willingness to pay principle" (total costs in million $)

	SF Sc1	SF Sc2	C Sc1	C Sc2
ALB	0.028336	0.036574	272.99	171.93
AUS	0.022795	0.023089	219.61	108.54
BEL	0.007717	0.005486	74.35	25.79
BUL	0.011567	0.029224	111.43	137.38
CZE	0.036852	0.057943	355.04	272.39
DEN	0.011498	0.004275	110.77	20.10
FIN	0.113153	0.018206	1090.12	85.59
FRA	0.087603	0.054071	843.97	254.19
GDR	0.127246	0.017409	1225.90	81.84
FRG	0.092496	0.043205	891.11	203.11
GRE	0.024411	0.034164	235.17	160.60
HUN	0.017469	0.034019	168.30	159.92
IRE	0.000017	0.001661	0.16	7.81
ITA	0.015415	0.029365	148.51	138.05
LUX	0.000083	0.000009	0.80	0.04
NET	0.019530	0.000371	188.15	1.74
NOR	0.039279	0.001117	378.41	5.25
POL	0.191068	0.041727	1840.76	196.16
POR	0.007571	0.011340	72.94	53.31
ROM	0.008150	0.042067	78.52	197.76
SPA	0.004107	0.018589	39.56	87.38
SWE	0.034258	0.001298	330.04	6.10
SWI	0.000140	0.000622	1.35	2.92
TUR	0.007612	0.238138	73.34	1119.48
SU	0.049712	0.173339	478.93	814.86
UK	0.015805	0.023373	152.27	109.88
YUG	0.026110	0.059317	251.55	278.85
TOTAL	1.000000	1.000000	9634.06	4700.97

where: **SF Sc1 and SF Sc2** are the scaling factors according to scenarios 1 and 2 respectively; **C Sc1 and C Sc2** are the total costs according to scenarios 1 and 2 respectively.

4. CONCLUDING REMARKS

A non-linear programming approach for minimizing pollution control costs in 27 European countries simultaneously or independently has been proposed. The analysis here has been developed using the example of sulphur as the polluting substance to control; and it has been assumed that there exists two possible "scenarios" of sulphur depositions or emissions in Europe in order to fix the constraints to the optimization problem. The results obtained lead to the following conclusions:

(1) The scenario maximizing the quantity of sulphur depositions avoided in receptor-countries per unit of cost incurred in emitting-countries is the "30% Club" one. However, the "30% Club" scenario requires the highest deposition reductions when countries act independently but the lowest reduction is achieved when countries co-operate. It can be seen that uniform percentage reductions in emissions by each country are potentially inefficient because these reductions do not take into account any environmental objectives, variation in control costs between countries as well as the fact that national control strategies have not been designed to maximize economic efficiency. On the other hand, scenario 1 leads to a much higher cut in the depositions' target but as it could be expected in a higher abatement cost.

(2) The cost of achieving a 30% uniform reduction could in fact achieve a 40% average reduction if an efficient cost allocation were adopted.

(3) The most 'equitable' principle for distributing the optimal total abatement cost in Europe between the countries, given their main characteristics such as 'unconstrained' emissions, sensitivity to depositions, total area and/or gross national product, was the one based on a simple average of each country's contribution to both total emissions and depositions. Therefore, the 'joint' application of the writer's 'sensitivity' depositions reduction scenario,

and an ‘equal share of responsibility’ principle in Europe’ s total sulphur emissions and depositions targets for determining each country’s cost share, should provide a good indication to planners for containing the ‘acid rain’ impact in Europe within reasonable limits. Co-operative solutions can achieve environmental targets in a more cost-effective way. But there is a need for a mechanism for international transfers in order to motivate countries to co-operate. There are a number of reasons why a country may not be willing to co-operate. First, the country may find the scientific evidence unconvincing and therefore either does not accept that there is an environmental problem or believes that the risks are exaggerated. Second, the country may accept that a particular environmental problem exists, but attach a lower priority to solving it than do countries backing the proposed international agreement. Levels of concern about environmental issues differ among countries due to differences in preferences, per capita income, environmental endowments, the degree of environmental concern for future generations, expectations about the pace of future technological innovations etc. Third, the country may be trying to free-ride on the efforts of other countries to solve the problem. Without a world government and with the number of countries increasing, the likelihood of free-riding rises. Fourth, poorer OECD countries and eastern European countries face problems due to the fact that in these countries individual plants are too old to be retrofitted and must be replaced; and governments whose people face poverty and deprivation or who are trying hard to catch up with their richer neighbours inevitably place lower priority on environmental measures. Finally, a government failure may result in too little protection of the environment as far as governments respond to political pressure rather than maximizing social welfare. Also, government failure in one country can reduce the desirable level of abatement in other countries.

46

At the same time, there is a series of options for promoting co-operation. The first step is to identify which of the reasons mentioned above is behind the cause of non co-operative behaviour. With the first two reasons, the solution relies on better scientific evidence and persuasion to change rankings. Sometimes the country may disagree with the proposed inter-country allocation of responsibility, for dealing with regional and global environmental problems. Responsibility may include modifying behaviour by consuming less fossil fuels and paying for cleaning-up existing problems. For the problem of free-riding a binding agreement which requires an incentive system in the form of side payments, cash or technology transfers to potential defectors is needed. In such side payments the victims pay polluters to reduce pollution. For the fourth reason, obviously there is a great potential for the richer countries of Europe, to provide assistance to poorer ones for environmental investments. Finally, governments should undertake pollution control strategies and should ideally maximize social welfare rather than responding simply to political pressure. To avoid a government failure that results in too little protection of the environment a supra-national institution needs to be established which should not be subject to the same pressure as national governments. This institution would identify conflicts, evaluate them on social terms, and resolve them. Also, such an institution would facilitate transfer payments between countries in order to promote co-operation.

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47

NOTES

(1) These schemes utilize the source-receptor linkages, as described by the source-receptor matrices produced by long range atmospheric transport models (like the EMEP model), to select the source areas where emission reduction should take place. For the purpose of estimating changes in concentration and depositions due to emission changes, Shaw and Young assume that the deposition at a receptor location is the sum of the partial contributions, each of which is proportional to the emissions from a source or from a group of sources. If E_j is the emission rate in source region j and T_{AJ} is a coefficient of proportionality connecting the source region with the receptor A, then the deposition D_A at receptor A is of the form

$$D_A = T_{A1}E_1 + T_{A2}E_2 + ... + T_{AJ}E_J + T_{AN}E_N$$

(2) Other types of abatement options that are omitted in this approach are abatement through energy conservation in its broadest sense (energy demand suppression, fuel switching, and efficiency measures), fuel substitution and use of low sulphur fuels. Bach (1984) suggested that these measures may provide a source of cheap abatement options in addition to technologies under consideration.

(3) The estimates of the flows of sulphur emissions and the subsequent depositions between countries are based on the EMEP model (European Monitoring and Evaluation Program, Norwegian Meteorological Institute) from which the cross-country "transfer coefficients" d_{ji} and d_{ii} which measure the trade-off of sulphur (total dry and wet deposition of sulphur) between all single European countries can be obtained. The proportional transfer coefficients of the EMEP's transfer matrices have been used with early and provisional unconstrained sulphur emission estimates from SEIY, since modified, to derive a transfer matrix of a closed system of 27 countries. There is obviously an uncertainty, regarding the elements of this matrix, because of weather variability and different meteorological conditions year by year and so on. This means that actual transport matrix coefficients will vary from year to year due to these meteorological variations

(4) This background depositions have been excluded in our model, as far as they are attributable to natural sources (such as volcanoes, forest fires, etc) but also to emissions whose origin cannot be determined and therefore it is impossible to be tracked by our model. Of course, if the background depositions are included, then actual depositions in each European country will become even larger.

(5) The estimates of the unconstrained sulphur emissions used in this paper are based on early work undertaken by the Stockholm Environment Institute (SEI) at York. They should, however, be regarded as indicative only. Obviously, subsequent revision to estimate of energy balances and fuel sulphur content for the year 2000 will lead to revisions of the cost estimates. Later estimates by the SEI, to be published shortly, may be more realistic.

(6) See note 5.

(7) On the mainstream of Klaasen and Jansen (1989), who provide a critical review and some numeric examples, also related to Europe, of most existing pollution control allocation criteria.

48

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49

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50