Optimal acid rain abatement policy in Europe

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June 1994

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By

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Abstract

Acid rain causes greater environmental damage than would occur if countries act cooperatively. Based on new estimates of sulphur abatement cost functions, the potential gains from cooperation are calculated for Europe. Various cooperative abatement rates are compared with the rates implied by recent international agreements. The distinction is made between primary and secondary abatement, and their respective roles are discussed.

Keywords: Environmental Management; abatement; acid rain; cooperation.

JEL Classification: C71, C72, Q50, Q52.

An earlier version of this paper has been presented as:

Optimal acid rain abatement policy for Europe: An analysis for the year 2000. University of York, Department of Environmental Economics and Environmental Management, Discussion Paper Series **94-03**.

1. The search for agreement on acid rain policy

In 1990, Britain's power plants and industrial boilers emitted 1,436 thousand tones of sulphur dioxide, of which 477 thousand tones fell as acid rain in Britain, and the rest fell on neighboring countries on the sea or is unidentified; and 543 thousand tones, emitted by its neighbors, fell on Britain [See EMEP, (6)]. In 1994, a £700m (US $1050m) enhancement of a single British power station (Drax) became operative, as part of a £8 billion programme with the objective of significantly reducing SO_2 emissions by the year 2000. In this paper we examine how much each country in Europe should spend for this purpose and in particular how much should be spent on cleaning up dirty emissions.

The damage caused by Britain's emissions was borne both by the people of Britain and the other countries, each of which also spread SO_2 on itself and its neighbors. This is a classic instance of economic inefficiency, since policies to reduce emissions - abatement policies - will be operated at less than optimal levels because countries and, more narrowly, power generating companies, do not bear the full costs of the damage they themselves cause. Economic theory can predict the "rational" level of abatement under a variety of assumptions, ranging from complete non-cooperation, through bargaining in the absence of sanctions or transfers, to the utopian cases of fully cooperative optimization at the regional or even world level.

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 signatories to reduce sulphur emissions by at least 30% by 1993 as compared with their 1980 emission levels (the "30% Club"). And in 1994, a "New Protocol" has been announced which modifies the 30% Club targets in a manner intended to yield a more equitable distribution of the burden of abatement (Klaasen [14]). Figure 1 shows the substantial nature of these revisions:

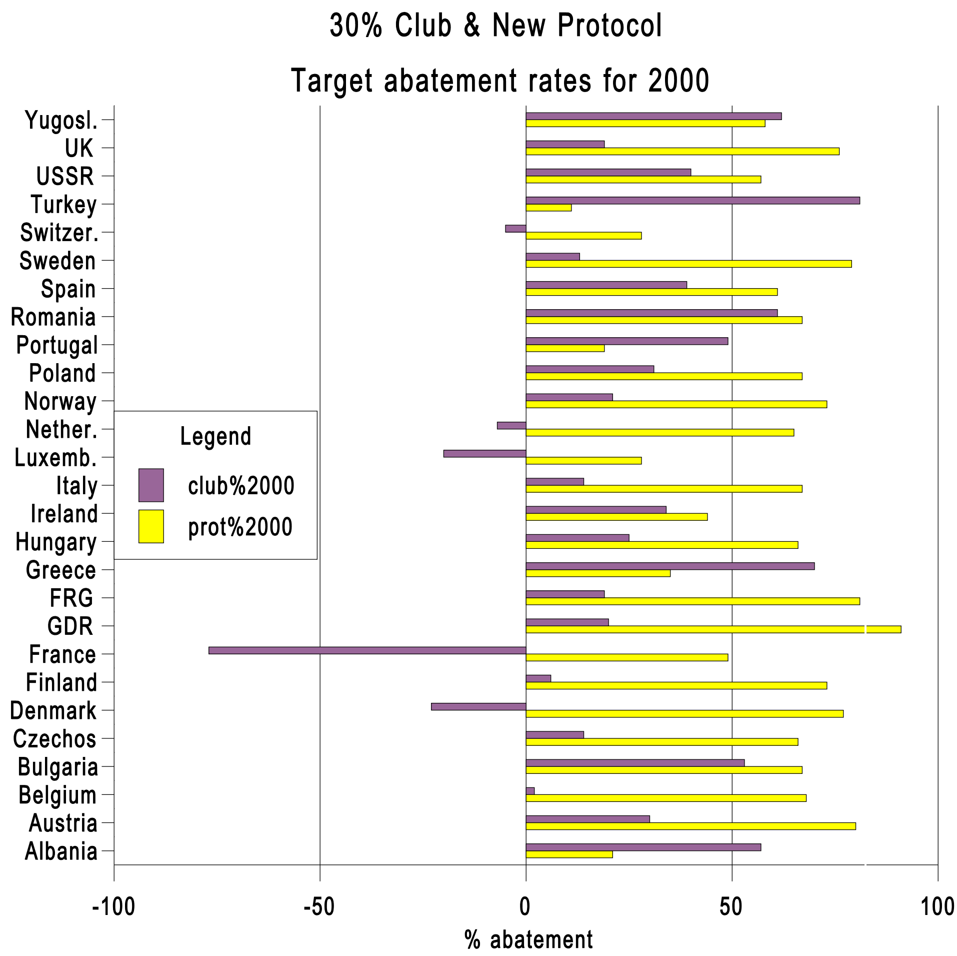

Figure 1: 30% Club and New Protocol target abatement rates

note that negative 30% Club targets mean that by 1990 the original 30% target had already been over-fulfilled. Uniform percentage reductions in emissions by each country are potentially inefficient for a number of reasons: (1) the characteristics of emitting sources vary from country to country, so that emissions control opportunities and costs vary between countries; (2) environmental objectives are not explicitly taken into account in setting emissions reduction goals - these objectives may vary spatially because ecosystems are not uniformly assimilative of SO_2 and NO_x; (3) SO_2 and NO_x are non-uniformly mixing pollutants, i.e. the spatial pattern of depositions varies with the locational pattern of sources; (4) evaluation of damage caused by depositions varies across countries.

In discussing emission reduction, it is necessary to make a distinction between primary and secondary abatement. By primary abatement, we mean the reduction of sulphur emissions by such means as: switching to low- or sulphur-free fuel; reduced use of sulphurous fuel as a result of improved fuel efficiency in power stations; improved energy-efficiency in the rest of the economy; or any other measure reducing the output of electricity. Secondary abatement involves the removal of sulphur from emissions during (e.g. by Fluidised Bed Combustion) or after (e.g. by Flue Gas Desulphurisation) burning the fuel, or removal (e.g. by washing) of sulphur before burning. The targets of the New Protocol and the 30% Club do not specify which means should be adopted. In this paper we are primarily concerned with the optimal pattern of secondary abatement, whose potential contribution to the targets can then be assessed and the role of primary abatement thus exposed. The choice between primary and secondary abatement has recently been discussed in detail by Newbery [18], and may involve, for example, the choice between using locally mined high calorific but sulphurous coal, combined with retrofitted abatement equipment as in the Drax case cited, and building new gas-burning power stations.

Mäler [16] and Halkos [8] have shown that for the costs of implementing the 30% Club target by secondary abatement, a 40% reduction in total emissions by allocating abatement expenditure to equalize marginal costs across the countries of Europe is possible. This "cost-effectiveness" approach, however, runs into the same problems as the 30% Club in securing agreement and implementation, since the net benefits are unequally distributed, and could be negative for some countries like Britain where reduced depositions may be valued less than their increased abatement costs. Nevertheless, the fact of the 30% Club Agreement points to the possibility of a more efficient agreement, which should be seen in the context of a wider set of issues on which countries seek agreement. These other issues include trade policy, fisheries, river and coastal pollution, military expenditure and foreign aid; for example, recent discussions within GATT have included the possibility of trade sanctions against countries with low abatement expenditure on the grounds of "unfair competition" (see [21]). These countries may agree to cooperate to their own disadvantage over a single issue, so long as this helps achieve advantageous agreement over other issues. In turn, such multi-issue agreements may provide countries with the means to punish deviation by others by in turn deviating from individually disadvantageous agreements.

In this paper we distinguish between two types of cooperative agreement. The "social welfare" (henceforth SW) agreement can be viewed as an efficient version of the 30% Club, in that it seeks to achieve maximum aggregate net benefits, although these may be distributed unevenly and even yield negative net benefits for some countries. In this latter event, "side-payments" to induce agreement are needed: such side-payments may not be financial, but could be in the form of compensating net benefits from agreement on other issues. The complexity of such multinational/multi-issue bargaining need hardly be emphasized, however, which serves to demonstrate their utopian character (for discussion, see Andersson [4], Mäler [15, 16], Newbery [17] and Welsch [25]). The second type of cooperative agreement we consider is more restrictive, but should be easier to achieve, since it requires that all countries achieve non-negative net benefits: this is the Pareto-dominant (PD), or "no-loser" solution. An objective of this paper is to quantify the costs of restricting the form of agreement to this second type, thus eliminating the need for side-payments or collateral agreements.

The benchmark against which to judge the benefits of cooperation is, of course, the status quo, which we take to be the "naive" non-cooperative Nash equilibrium, in which each country takes the policies of its neighbors as given, optimizing within that context. The general principles of game theory in this sort of context are set out in [11], but there have been few empirical applications so far reported. Mäler [15] provides a clear analysis of the "acid rain game" and some estimates of the gains from cooperation for European countries; Kaitala et al. [13] and Tahvonen et al. [20] model a dynamic game between Finland and four regions of the former USSR. We take Mäler's study as our point of departure, and based on different data and model specification provide further numerical estimates of the potential benefits from cooperation and the potential role of secondary abatement in particular.

The essential steps in this form of study are as follows. First, for each country, one must determine abatement cost functions: these measure the cost of eliminating tones of SO_2 from power stations' emissions, and will vary between countries depending on the existing power generation technology, and on the local costs of implementing best practice abatement techniques. Full details of the abatement cost functions used here are reported in [7, 9] and summarized below in section 1. These control functions are based on research conducted by the Stockholm Environment Institute at York (SEIY) using information at the level of the individual power station; the International Institute for Applied System Analysis (IIASA, Austria) estimates are based on more aggregate data. The IIASA functions are the basis of Mäler 's study, while Kaitala et al. [13] and Tahvonen et al. [20] use their own cost estimates, details of which are not known but which they compare with IIASA values.

Second, one needs a matrix of transfer coefficients, indicating what proportions of emissions from any source country is ultimately deposited (in the form of acid rain) in any receiving country. For this purpose, we use the international matrix of 27x27 countries derived by the European Monitoring and Evaluation Program (Norwegian Meteorological Institute), using 1990 as our base year (see [6]).

Third, damage functions are necessary. The existing applied literature assumes that damage is a linear function of deposition (see [15, 16]). The evidence of sensitivity maps (see [1, 5]), however, strongly indicates that this is not valid, and that the damage function should be convex: depending on the local ecology, a succession of thresholds of tolerance to acidity results in increases in the marginal damage as the level of acidity increases. Thus doubling the rate of deposition will more than double the damage caused. In common with other studies, we do not directly estimate the damage functions, but infer their parameters by assuming that countries currently equate national marginal damage cost with national marginal abatement cost, the latter being obtained from the cost functions described above. The assumed form of the damage function has quite far-reaching implications for the analysis, as we shall show.

2. Modeling optimal abatement

We begin by defining the net benefit function for each country i as

$$NB_i = -(AC_i + DC_i),$$

where AC_i is abatement cost and DC_i is damage cost. The abatement cost function is

$$AC_i = AC_i(SR_i)$$

where SR_i is tones of sulphur removed from sulphur emissions E_i: net emissions from country i are therefore given by the difference $E_i - SR_i$. These emissions are the byproduct of power generation and other uses of fuel, which we take as exogenous. We later use empirical estimates of the AC_i functions: these functions are convex, with $AC_i' > 0$ and $AC_i'' > 0 \ \forall$ i.

The damage cost function depends on sulphur deposits, and is also country-specific:

$$DC_i = DC_i(D_i),$$

where D_i is tones of sulphur deposited in country i, and with $DC_i' > 0$. It is often assumed for empirical purposes that the damage function is linear (see e.g. Mäler [15,16] and Newbery [17]), while theoretical work assumes convexity i.e. $DC_i'' > 0$ (see e.g. Welsch (op. cit.)). We will use the convex assumption both for realism and because it permits policy interdependence, as discussed below.

Deposits of sulphur in each country depend on the international transfer matrix H, where h_{ij} is the proportion of net emissions from country j which are deposited in i: these proportions are assumed fixed. Country i also receives D_{iB}, other background deposits (from the rest of the world, volcanos, etc). Thus

$$D_i = \Sigma_j h_{ij}(E_j - SR_j) + D_{iB}.$$

The damage function is therefore also convex in SR, and the net benefit function NB_i concave in SR_i.

The *status quo* is modeled as the laissez-faire case of multilateral Nash equilibrium, with SR as the choice variable. The i'th country maximizes NB_i by choosing SR_i to set marginal private net benefit to zero: $\partial NB_i/\partial SR_i = 0,$

giving the reaction function discussed further below.

In the SW maximization case, aggregate net benefit is maximized when each country sets marginal social net benefit to zero:

$$\Sigma_j \partial NB_j/\partial SR_i = 0 \qquad \forall i.$$

Since $\partial AC_j/\partial SR_i = 0 \ \forall \ i \neq j$, marginal social net benefit is given by

$$\partial NB_i/\partial SR_i = -(\partial AC_i/\partial SR_i + \Sigma_j \partial DC_j/\partial SR_i)$$

hence the optimum is achieved by equating the individual marginal abatement cost to the aggregate marginal benefit. Since marginal benefits are non-negative and marginal abatement costs increasing, it is clear that abatement is higher under SW maximization. This is illustrated in the demand and supply diagram in Figure 2 below, in which marginal benefit (MB) is the negative of marginal damage cost, NSR is "Nash sulphur removed" and SWSR is "SW sulphur removed": with a linear damage function yielding constant marginal benefit (MB(L)), the SW outcome (SWSR(L)) is shown to be greater than that with diminishing marginal benefit.

An increase in sulphur emissions in the rest of the world would shift the sloping MB lines to the right, resulting in more domestic abatement, while the horizontal MB(L) lines would not be affected: this illustrates how nonlinear damage functions are necessary to generate interdependent abatement policy. Strict equalities in the above argument imply the assumptions that in the *status quo* all countries choose to incur some abatement cost ($SR_i > 0$) and that the feasible upper limit of abatement is less than 100%, so that $AC \rightarrow \infty$ as $SR \rightarrow E$: an interior solution follows. Welsch (op. cit.) discusses the possibility that the non-negativity constraint binds at the optimum, but dismisses that case as a practical problem.

Welsch establishes that the conditions for a SW equilibrium to exist are quite favorable, provided agreement on monitoring and on the measurement of abatement and damage costs can first be reached. In such equilibrium cost-sharing would be essential since side-payments would be required to ensure that no country is a net loser relative to the Nash *status quo*. As pointed out above, these side-payments might take the form of commitments on other issues also requiring multilateral agreement.

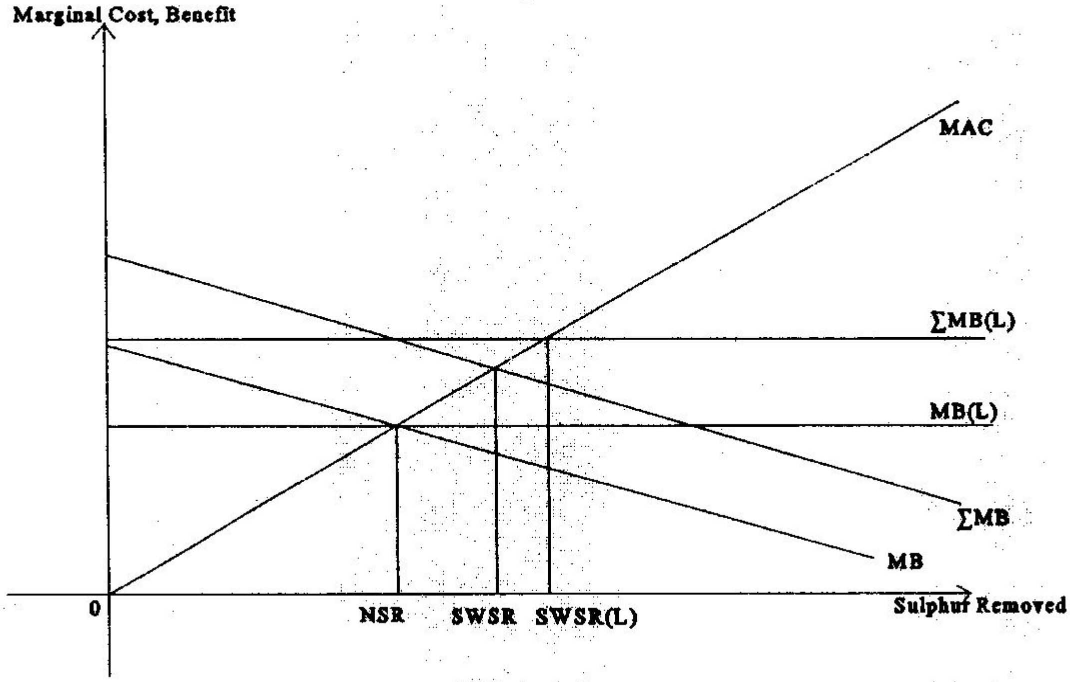

Figure 2 : **Nash and SW Outcomes with Linear and Nonlinear Damage Functions**

We wish to consider the case, however, where side-payments are ruled out: the reason for this is that the conditions for a SW equilibrium may be considered impossibly utopian, particularly since the damage costs of acid rain are highly uncertain and contentious (see [3, 17, 19, 22, 23]). A more reasonable objective is an agreement under which each country achieves at least the Nash benefit level, without having to agree levels of monetary compensation with all its neighbors to offset abatement and damage costs. Monitoring would still be necessary to ensure physical emission limits were not exceeded, but this is relatively easy to establish. Such equilibrium is the Pareto-dominant or "no-loser" case given by:

$$\text{Maximize } \Sigma_i NB_i(SR)$$

$$\text{subject to } NB_i \geq NB_i^* \quad \forall\, i$$

where NB_i^* is the initial Nash benefit level, and $SR = \{SR_1, SR_2, ...SR_i, ...\}$ the set of abatement levels. The aggregate benefits achieved in this case will be less than in the SW case, and it is of interest to measure the potential gains relative to the polar Nash and SW cases. We report our estimates below.

The bilateral case

Bilateral analysis allows a simple graphical representation of the different equilibrium concepts and the importance of nonlinear damage function. Solution of the bilateral case will permit empirical comparison of partial cooperative gains with fully multilateral SW gains. Graphically, the different equilibrium outcomes are shown in Figure 3, in an Edgeworth box. The proportional abatement coefficients α_1 and α_2 are plotted on the horizontal and vertical axes respectively: α_i is defined as SR_i/E_i. The isobenefit curves are the locuses of all points (α_1, α_2) that ensure different given levels of net benefits NB_1 and NB_2. Since damage and abatement costs are convex in α_1, α_2 and in the deposits D_1, D_2, the isobenefit curves are represented as convex functions. R_1 and R_2 are the reaction functions and their intersection point N is the market or Nash equilibrium. B_1 and B_2 are the best achievable points. The curve joining B_1 and B_2 is the contract curve and in the region Nab both countries gain relative to the Nash solution. The SW solution lies somewhere on the contract curve, and the Pareto dominant solution on the ab segment (at a or b if the SW solution would require side-payment).

It is notable that the reaction functions are both negatively sloped, illustrating the interdependence of abatement levels: the more country A abates, the less country B abates. This interdependence occurs because $\partial^2 NB_i/\partial SR_i \partial SR_j = -\partial^2 DC_i/\partial SR_i \partial SR_j < 0$: with linear damage functions the reaction functions are also linear and cross at a right angle.

In this case, with negatively sloped reaction functions, the Von Stackelberg solution is another non-cooperative case that may be obtained from the problem:

$$\begin{aligned} &\underset{SR_1, SR_2}{\text{Maximize}}\ NB_1(SR_1, SR_2, D_{B1}) \\ &\text{subject to } (\partial/\partial SR_2) NB_2(SR_1, SR_2, D_{B2}) = 0 \\ &\qquad SR_i \geq 0 \end{aligned}$$

if country 1 is the Stackelberg leader, choosing α_1 such that country 2, behaving in a Nash manner, chooses α_2. In general, the Stackelberg leader thereby improves net benefits relative to the Nash solution. The Stackelberg case is of some interest in the context of abatement control, modeling the situation where one country induces its neighbor to adopt higher abatement rates to reduce pollution imported from the first country: the first country benefits both from the lower abatement cost and from lower levels of pollution imported from the second. In Figure 2, S_{12} and S_{21} show the Stackelberg solutions, with 1 and 2 respectively as leaders.

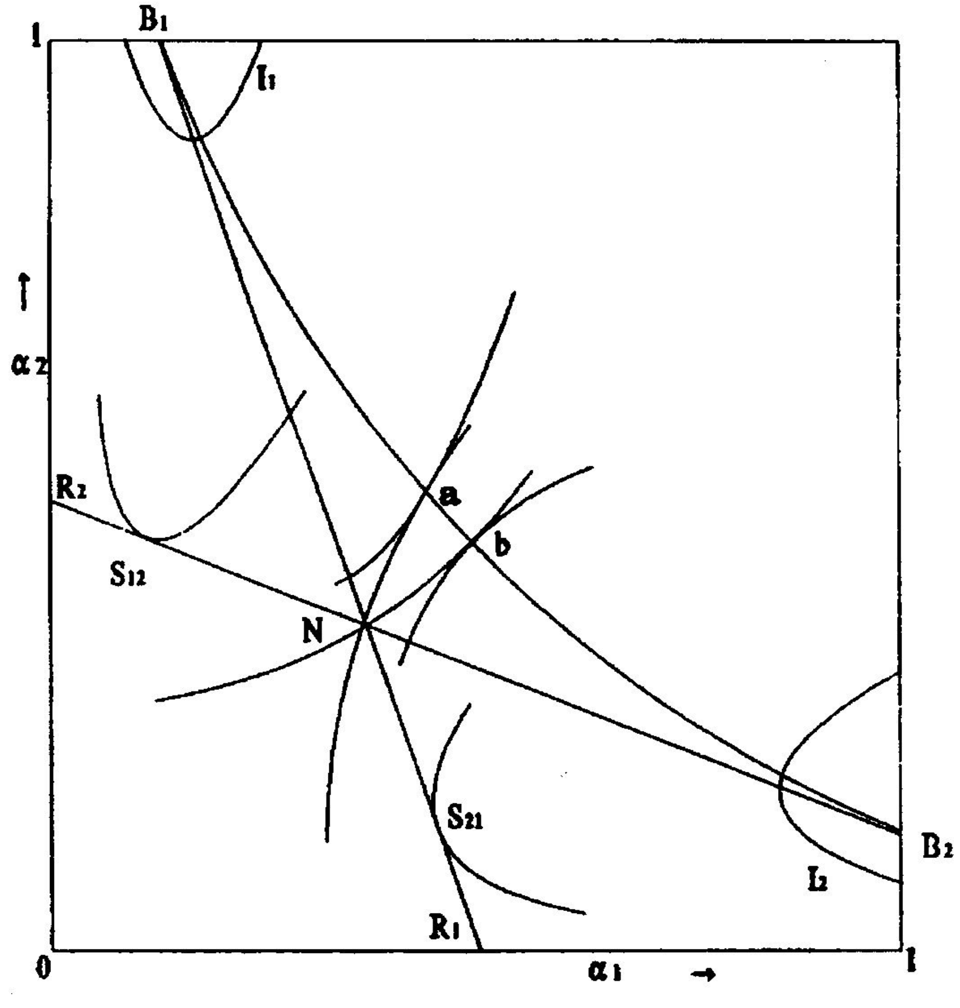

Figure 3 Two-Country Abatement Games

3. The empirical study of European abatement

Measurement and approximation of abatement cost functions

The basic idea behind the derivation of cost functions is to find the least-cost abatement technologies for each country for any given level of sulphur abatement. We here provide a brief account of the necessary procedures and assumptions[1].

To control sulphur-emissions the following abatement technologies, with 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. The abatement costs (per tone SO_2 removed) will vary among countries as a result of country-specific factors such as sulphur content of fuels used, capacity utilization, size of installations and labor, electricity and construction cost factors. In view of the differences between countries, with regard to both present and future energy demand, energy mix and fossil fuel qualities, the optimization must be carried out on a country-by-country basis.

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 n power plants, industrial boilers and petroleum refineries there would be n 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 tone 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 to 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. It should be noted that in a decentralised economy, the achievement of such minima may be prevented by the existence of taxes or by various forms of market failure, and intervention may be required to induce the private sector to minimize real resource costs.

For analytical purposes, it is necessary to approximate the national cost curves by a functional form, at least over a relevant range spanning the range between current abatement levels and those implied by the international agreements. We found that least squares equations of the form

$$AC_i = a_{0i} + a_{1i}SR_i + a_{2i}SR_i^2$$

yield satisfactory approximations for all the countries analyzed in this paper[2]. Mäler [15, 16] and Kaitala et al. [13] also use quadratic approximations of the abatement cost functions; and Tahvonen [20] uses a piece-wise linear approximation.

Damage cost function and its approximation

The problem of estimating benefit functions (or equivalently damage functions) is more difficult than the estimation of abatement costs, since the consequences of acidification cannot be identified with any certainty. Damage depends on deposits, which depend on the $[h_{ij}]$ matrix as shown above. This matrix is measured using the European Monitoring and Evaluation Programme (EMEP) transfer coefficient matrix, a basic instrument in all empirical models dealing with acid-rain problems [6].

As already pointed out, the choice of restrictions on the derivatives of $DC_i(.)$ is important. Mäler [15, 16] and Newbery [17], although stating a preference for a convex damage function, assume a linear damage function with DC_i' constant for all i, but we have chosen an alternative

[1] For more details on abatement cost function derivation, see Halkos [7,8,9] and Appendix III.
[2] Equations were fitted across the range 5-55% of maximum feasible abatement; constraining a_{1i} to zero helped avoid negative abatement solutions. See Appendix II charts illustrating typical maximum feasible abatement.

approach. The total cost arising from a given level of sulphur emissions is, for country i,

$$TC_i = \text{abatement cost} + \text{damage cost} = AC_i + DC_{i.}$$

Cost of abatement is estimated by quadratic functions of sulphur removed, and we assume damage costs are also quadratic in deposits:

$$TC_i = [a_{0i} + a_{1i}\, SR_i + a_{2i}\, SR_i^2] + [c_{1i}\, D_i + c_{2i}\, D_i^2].$$

It follows easily that total cost is minimized when

$$c_{2i} = [(a_{1i}+2a_{2i}SR_i)/2h_{ii}D_i]\text{- } (c_{1i}/2D_i)$$

This is the only information available to "calibrate" the damage function, on the assumption that national authorities act as Nash partners in a non-cooperative game with the rest of the world, taking as given deposits originating in the rest of the world. If, like Mäler [15, 16] and Newbery [17], we set c_{2i}=0, then c_{1i}=$(a_{1i}+2a_{2i}SR_i)/h_{ii}$, and total cost becomes

$$TC_i = [a_{0i} + a_{1i}\, SR_i + a_{1i}\, SR_i^2] + [(a_{1i}+2a_{2i}SR_i)/h_{ii}]D_i \qquad \text{(i).}$$

We prefer to restrict c_{1i} to zero and calibrate c_{2i} as $c_{2i}=(a_{1i}+2a_{2i}SR_i)/2h_{ii}D_i$

yielding total costs of

$$TC_i = [a_{0i} + a_{1i}\, SR_i + a_{1i}\, SR_i^2] + [(a_{1i}+2a_{2i}SR_i)/2h_{ii}]D_i \qquad \text{(ii)}$$

Comparing (i) and (ii), this choice obviously halves the implied total damage costs at the optimum; the positive second derivative means that the benefits from reductions in deposits will also be less than implied by a linear damage function, while the costs of additional deposits will be greater. The quadratic damage function also yields interdependence of policies, as discussed for the bilateral case above.

This "revealed preference" calibration procedure rests on strong assumptions: in each country it is assumed that abatement policy has been optimized so that marginal abatement cost equals marginal damage cost, the latter being somehow evaluated according to local conditions and attitudes. Such evaluations will depend as much on political and social considerations as on objective measures of physical damage. In this paper the importance of political change in Germany for damage function calibration is accordingly recognized.

The results of this paper depend on EMEP data, based on the old European boundaries. It is useful to work with this 'old data'. It does not make much sense to aggregate FRG and GDR simply for the sake of using current boundaries for the reason that policies in the two areas have historically been so different. In our model, we have used different damage coefficients for FRG and GDR for the year 1990 and the FRG's damage coefficient for both countries for the year 2000 in an attempt to model their political union. Similarly, the political evolution in the old USSR and Czechoslovakia is a political issue: as our calibration is based on the year 1990 it is necessary to treat these areas as political units even in 2000.

Finally, the total annual sulphur emissions used here are based on research and projections conducted by IIASA for the years 1990 and 2000. The emissions for the year 1990 are net (i.e. after secondary abatement) while for the year 2000 are gross [2]. For 1990, we have estimated gross emissions using the current sulphur abatement level of European countries in 1990 (see Appendix III).

4. Numerical Results

The discussion below is largely in terms of graphs: the numerical details may be found in Table A1.

i. Initial vs SW Solutions for 1990

Figure 4 compares the initial (actual) and computed SW abatement rates for all 27 countries and the average for Europe, based on IIASA data on sulphur emissions in 1990. It is striking that both rates for FRG are quite similar, and very high, while for most other countries the SW rate considerably exceeds the actual, and in the cases of Belgium, Austria and Luxembourg very large increases are indicated. Overall, the average SW abatement rate would more than double. Aggregate costs for these scenarios are \$1553.3m for Nash and \$1527.0m for SW, the net gain of \$26.3m being distributed as a mixture of gains and losses. In terms of quantities of sulphur removed from the atmosphere, the figures are more impressive: 832.0 thousand tones under Nash and 2124.0 thousand tones under SW.

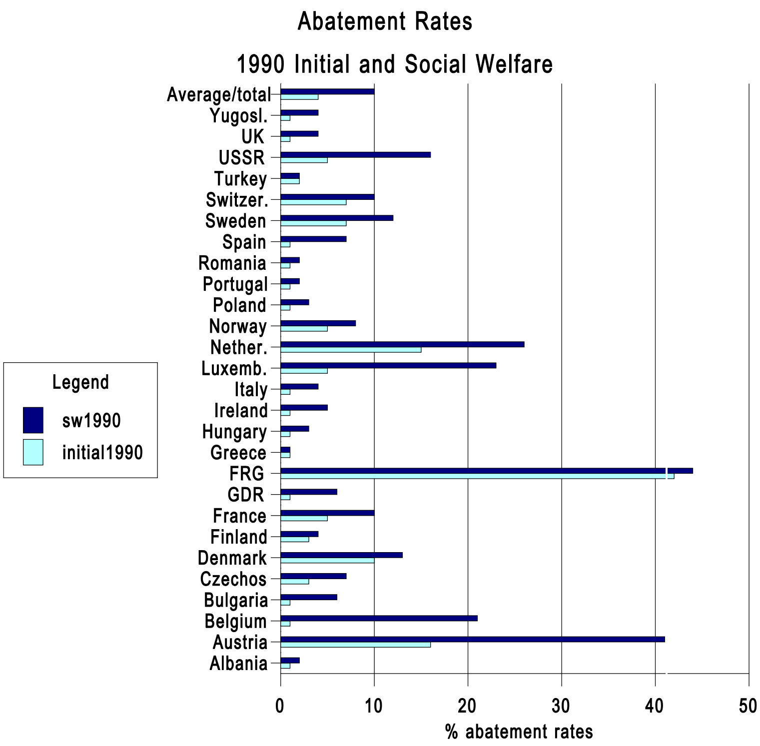

Figure 4: Abatement rates

ii. Nash, SW and Pareto Dominant Solutions for 2000

The results for the 2000 projections are summarized in Figure 5. The Nash abatement rates are calculated as a base case, using the damage function parameterization obtained for 1990 in conjunction with emissions for 2000. These Nash rates correspond to the initial rates in the 1990: they differ from the 1990 figures because different emission patterns for 2000 result in changed marginal damage costs which induce changed abatement rates. The SW rates should be compared with the Nash rates to indicate uncompensated gains and losses from cooperation. Finally, the Pareto rates are those which maximize SW with zero uncompensated losses.

Table 1 summarizes the aggregate consequences of each regime in the year 2000. About one-third of the monetary measure of gains from SW maximization is lost in the Pareto dominant case, but in terms of tones of sulphur, the difference is proportionately much greater. The aggregate gain from full cooperation is, however, only about 2% of total costs, although average abatement rises from 5% to 11%. The balance of total costs shifts from the damage to the abatement component.

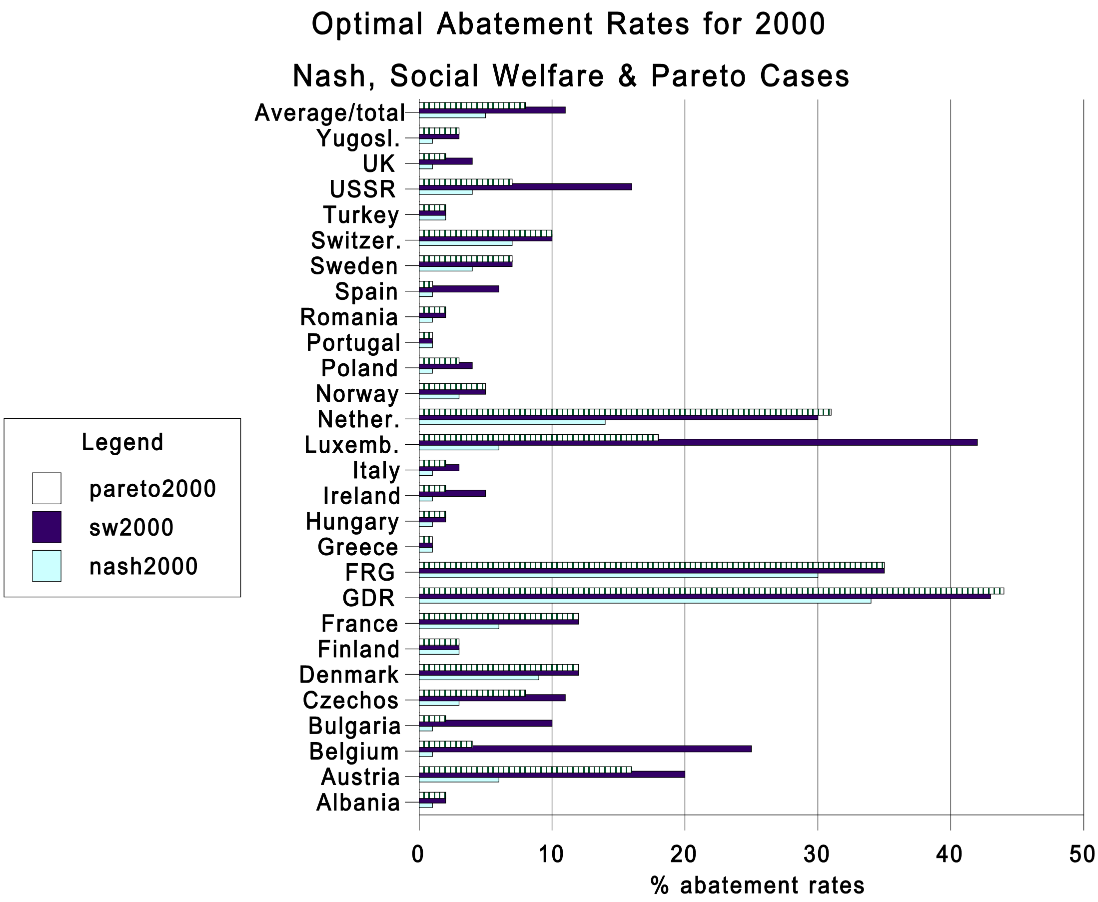

Figure 5: Optimal abatement rates

Table 1: Alternative solutions for the year 2000: Main Aggregates

Regime	Costs and Gains from Cooperation (US$m)	Sulphur Removed (thousand tones)
Nash	2113.2	1438.4
SW		
(i) Total	2068.7	3146.1
(ii) Difference from Nash	44.5	1707.7
Pareto Dominant		
(i) Total	2082.6	2153.6
(ii) Difference from Nash	30.6	715.2

Figure 6 shows the distribution of gains and losses under SW and PD. Under SW, 17 out of 27 countries gain without the need for side-payments, but in the PD solution their gains are reduced substantially. Belgium, USSR, Czechoslovakia and UK are the biggest losers, while Denmark, Finland, France, GDR, FRG, Netherlands and Switzerland are the biggest gainers from SW. As already noted, in this scenario, we treat today's Germany as GDR and FRG separately for abatement cost purposes but with the same damage function coefficient. Even with the major redistribution of benefits under PD, FRG and GDR are still the main beneficiaries. The figures for FRG dominate the results. The reason for this is that in 1990 FRG was by a large margin the biggest abater, and this fact is reflected in Germany's damage function coefficient and thus in the optimal abatement pattern for all Europe: any country whose emissions form any significant component of Germany's deposits is induced in both the SW and PD case to increase its abatement rates, reducing both damage cost and abatement cost for Germany.

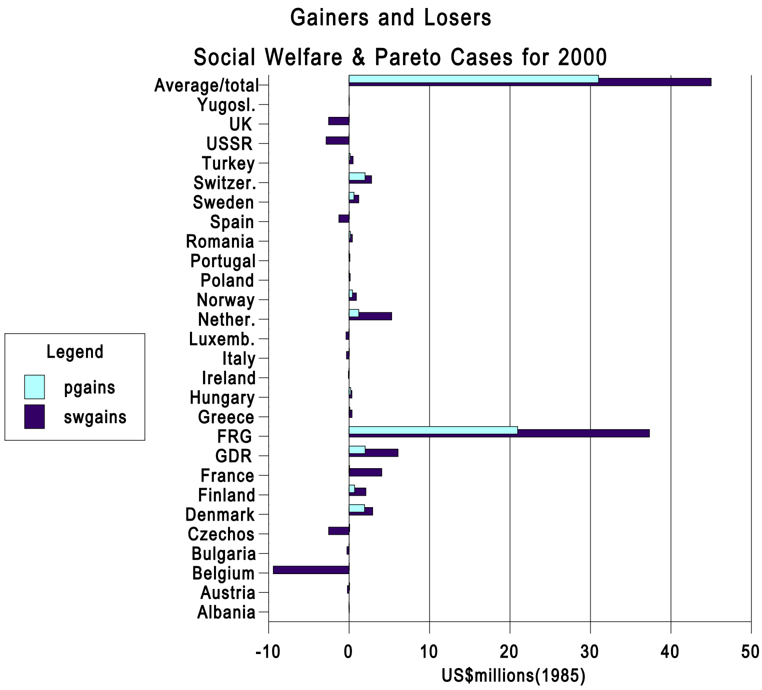

Figure 6: Gains and losses

iii. Bilateral examples

The table below illustrates the difference between full multilateral and bilateral cooperation. The case of FRG and GDR is interesting because of their political union: the results show that GDR loses in each case, but the multilateral loss (relative to Nash) is much greater; by contrast, FRG's multilateral gains are much greater than bilateral gains. Thus both gain from the extra abatement of their neighbors, while GDR also incurs significantly greater abatement costs in the multilateral case. Bilateral negotiation between UK and FRG, however, yield trivial gains in total, FRG being the gainer; but even in the multilateral case, the UK is much less affected than FRG. The reason is that the UK gains little from others' abatement, while its relatively high marginal cost of abatement prevents a large absolute increase in abatement (although the abatement rate increases sharply proportionately). The third pair, Austria and Italy, shows a small gain from bilateral cooperation, but both lose from higher abatement costs under multilateral cooperation: the significance of this example is that such a pair might easily negotiate a bilateral agreement but would require generous side-payments from a multilateral agreement, intrinsically more difficult to negotiate. For these three pairs, the Stackelberg solutions are very close to the Nash solutions, and are therefore not reported separately: this demonstrates the small degree of policy interdependence in the bilateral case, since an individual neighbor has much less effect than the collection of all neighbors.

Table 2: Total cost ($m) and kilotons of sulphur removed (Kt) in Nash, bilateral social welfare (Bil SW) and multilateral social welfare (Mul SW)

Country	Nash $m	Nash Kt	Bil SW $m	Bil SW Kt	Mul SW $m	Mul SW Kt
GDR	103.92	24.24	107.0	124.52	109.42	163.46
FRG	419.88	340.34	413.7	339.92	392.06	372.69
TOTAL	523.80	364.58	520.7	464.44	501.48	536.15
FRG	419.88	340.34	418.9	340.31	392.06	372.69
UK	118.44	19.06	118.93	47.45	120.01	73.31
TOTAL	538.32	359.40	537.83	387.76	512.07	446.0
Austria	6.71	8.57	6.7	9.16	6.93	31.1
Italy	112.3	11.01	112.3	12.42	112.55	41.73
TOTAL	119.01	19.58	118.98	21.58	119.48	72.83

iv. Primary vs secondary abatement in 2000 and the New Protocol

To infer the contributions of primary and secondary abatement to the New Protocol targets, we compare the target abatement rates with SW optimal secondary rates. Target *less* SW optimal secondary provides an estimate of the required primary contribution, in the form of an abatement deficit. This estimate will be biased downward; however, since the SW rates are computed for IIASA gross emission projections for 2000: high levels of primary abatement, such as fuel-switching, would reduce gross emissions, resulting in lower secondary abatement rates in our model. The residual role for primary abatement is nevertheless very high. Figure 7 shows that primary abatement must contribute more than 80% of total abatement, and that for most countries major primary programs will be required. Turkey, Switzerland, Portugal, Luxembourg, Greece and Albania appear to be the only countries with relatively modest primary abatement requirements; the feasibility of the targets for the rest of Europe must be in question.

There are technical, political and economic obstacles to high levels of primary abatement. Among the technical issues are the low calorific value and the ash characteristics of low sulphur coal affecting the operation of electrostatic precipitators. Politically, there are many problems such as resistance to the substitution of imports for domestic fuel, environmental concerns surrounding nuclear power and employment effects in coal-mining communities. Finally, in Eastern Europe, where many of the greatest changes are required and serious economic problems have arisen, retrofitting of secondary abatement equipment to old generators may be impracticable, and the costs would amount to 1-2% of GDP compared with no more than 0.4 % for all Europe. It may be necessary that Western Europe provides some form of aid to ensure achievement of agreed targets.

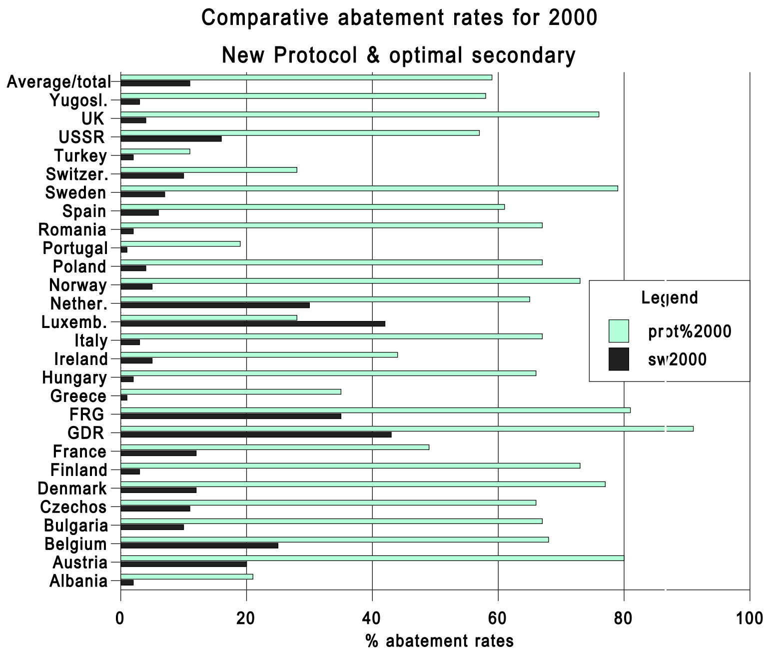

Figure 7: Comparative abatement rates for 2000

5. Summary and Conclusions

i. The "30% Club" sulphur abatement targets for 2000 have recently been substantially revised, mainly upward, and will require major programs of fuel switching or other methods to reduce consumption of sulphur fuels.

ii. Fully cooperative secondary abatement policy would reduce total abatement plus damage costs for 2000 by about 2%, and would result in a 6% reduction in sulphur deposits. In the absence of any mechanism to assess and ensure side-payments, maximum cost savings are reduced to about 1.5% and deposits reductions are reduced to about 3% in the Pareto-dominant solution. These figures are considerably smaller than those reported by Mäler [15], but caution is needed in comparing solutions. Mäler's study was based on much lower IIASA projected gross emissions for 2000 than ours' (11,522 vs 27,745 kilotons); the

EMEP data have been revised to attribute greater tonnage to sea and unidentified destinations - our calibrations are based on 1990 data, while Mäler's are based on 1984; for 11 out of Mäler's 26 countries, "full cooperative" abatement (corresponding to our SW) is constrained at the maximum feasible, while we find internal solutions for all cases; and Mäler's use of linear damage functions will tend to produce both greater levels of abatement and greater damage cost estimates. Mäler shows tonnage of sulphur abated at 4500 kilotons (i.e. 9011 kt. Of SO_2), compared to our 3146 kilotons, representing 39% and 11% average abatement rates respectively. The greatest difference, however, is in the monetary benefits estimates: we estimate maximum benefits at $45m, whereas Mäler's figure is DM6248m ($2000m approximately). Mäler's estimates of marginal damage must be larger than ours. Newbery [17] also reports figures similar to Mäler's using a different methodology for damage estimation, with 30% average abatement or about 3400 kilotons of sulphur. In interpreting these figures, it is essential to recognize that Mäler's and Newbery's results are independent of the total level of projected emissions, so that their tonnage figures may be compared with ours' while the abatement rates are not comparable: this is because of their use of linear damage functions. Results for abatement tonnage under full cooperation are therefore broadly similar, whereas benefit estimates are very different

iii. Germany dominates the picture in Europe: as its initial abatement level is high its calibrated damage function ensures continuing high levels of abatement and measured costs. The union of FRG and GDR is shown to redistribute the costs of this policy in favor of FRG.

iv. Bilateral cooperation is studied for a few countries: since some pairs (e.g. Austria and Italy) can conclude advantageous bilateral agreements but have uncompensated losses from multilateral agreements, it is clear that the level of side-payments needed to sustain the latter must yield positive net gains. The Pareto-dominant solution would require a similar condition. Although of theoretical interest, the Stackelberg solutions where one country assumes the role of leader in a bilateral game were of no practical interest in the cases studied. The formation of coalitions intermediate between non-cooperation and full multilateral cooperation is a possible response to the pervasive free-rider problems attending any attempt at full cooperation; and Heal [10] shows that in the presence of fixed costs of membership, the optimum size of coalition may be less than the total number of possible participants.

v. In the absence of cooperation, the abatement rates predicted for 2000 are similar to those for 1990, with the exceptions of the two Germanys and Austria. The revised parameterization for 2000 induces an equalization of the burden of abatement between East and West Germany; this benefits Austria by reducing its deposits from the old GDR, so that Austria reduces its own abatement rate. The overall effect is to increase average abatement from 4% in 1990 to 5% in 2000. The Austria effect noted here illustrates the interdependence resulting from the assumption of a non-linear damage function.

Acknowledgements:

We are indebted to Charles Perrings, Michael Chadwick and Markus Amann for advice or discussion on an earlier version of this paper. Any remaining errors are the authors' responsibility.

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Appendices

I **Table A1** Summary of results: abatement rates, costs and gains.

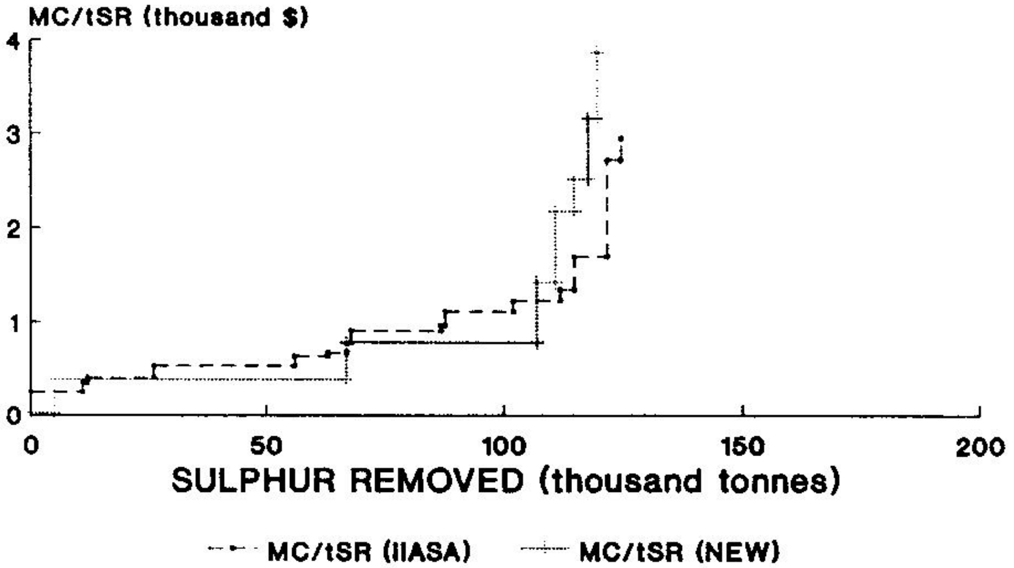
Countries	initabate	sw1990	nash2000	sw2000	pareto2000	swtc	swgains	paretotc	pgains	np2000	30%2000
Albania	1	2	1	2	2	0.90	0.029	0.90	0.010	21	57
Austria	16	41	6	20	16	12.16	-0.214	11.90	0.056	80	30
Belgium	1	21	1	25	4	12.65	-9.430	3.20	0.020	68	2
Bulgaria	1	6	1	10	2	1.96	-0.271	1.70	0.007	67	53
Czechos	3	7	3	11	8	92.42	-2.550	89.80	0.060	66	14
Denmark	10	13	9	12	12	36.08	2.930	37.10	1.910	77	-23
Finland	3	4	3	3	3	33.20	2.084	34.60	0.672	73	6
France	5	10	6	12	12	153.12	4.060	157.10	0.052	49	-77
GDR	1	6	34	43	44	331.72	6.080	335.80	1.996	91	20
FRG	42	44	30	35	35	568.34	37.330	584.70	20.940	81	19
Greece	1	1	1	1	1	25.35	0.354	25.60	0.084	35	70
Hungary	1	3	1	2	2	26.98	0.343	27.10	0.200	66	25
Ireland	1	5	1	5	2	1.40	-0.092	1.30	0.012	44	34
Italy	1	4	1	3	2	120.90	-0.325	120.50	0.033	67	14
Luxemb.	5	23	6	42	18	1.40	-0.381	0.97	0.015	28	-20
Nether.	15	26	14	30	31	64.72	5.289	68.80	1.200	65	-7
Norway	5	8	3	5	5	11.20	0.901	11.70	0.410	73	21
Poland	1	3	1	4	3	101.20	0.137	101.30	0.005	67	31
Portugal	1	2	1	1	1	11.80	0.091	11.90	0.006	19	49
Romania	1	2	1	2	2	49.50	0.401	49.80	0.160	67	61
Spain	1	7	1	6	1	97.13	-1.272	95.80	0.030	61	39
Sweden	7	12	4	7	7	15.43	1.200	16.10	0.602	79	13
Switzer.	7	10	7	10	10	37.48	2.791	38.30	1.980	28	-5
Turkey	2	2	2	2	2	58.51	0.489	58.90	0.135	11	81
USSR	5	16	4	16	7	17.13	-2.861	14.30	0.007	57	40
UK	1	4	1	4	2	125.94	-2.557	123.40	0.020	76	19
Yugosl.	1	4	1	3	3	60.11	0.028	60.10	0.001	58	62
Ave/total	4	10	5	11	8	2069.00	45.000	2083.00	31.000		

Note:
initabate=initial % abatement rate; sw1990, sw2000 = SW % rates for 1990, 2000; nash2000= nash % rate for 2000; pareto2000= PD % rate for 2000; swtc = SW total costs for 2000; swgains, pgains = Nash total cost less swtc and PD total costs; np2000 = New Protocol % rate for 2000; 30%2000 = 30% Cluc % rate for 2000.

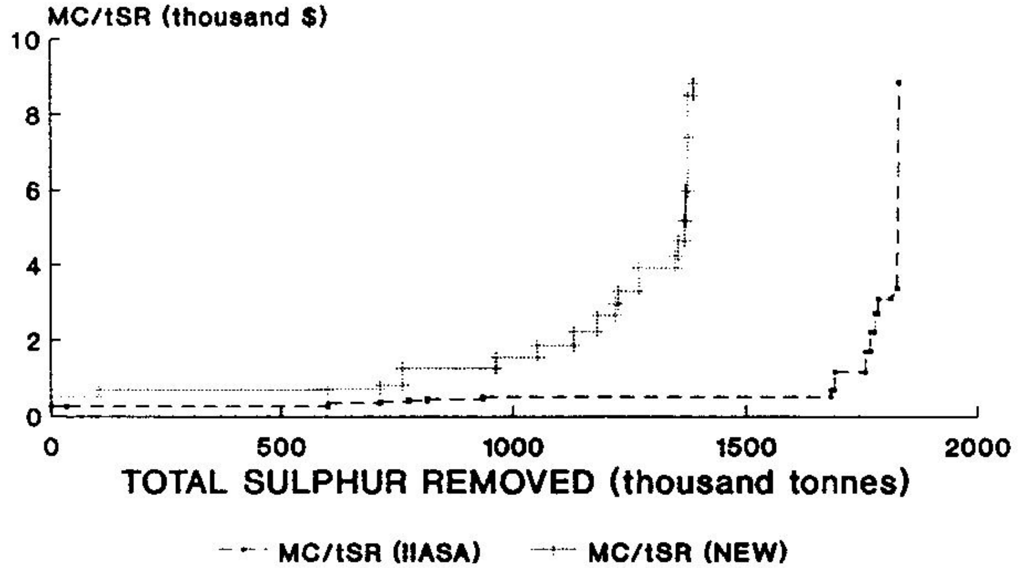
II **Abatement cost curve comparisons**

The marginal cost curves for the 27 European countries in the year 2000 presented in Halkos [7,9] can be divided into two main groups of countries: those for which new cost values are always higher than IIASA's (e.g. Greece, Denmark, Finland, Ireland, Italy, France, FRG, Portugal, U.K.) and those which present a "mixed" evidence, i.e. for some portions of the curves IIASA is more expensive, or vice-versa (e.g. Austria, Belgium, Spain, Sweden, the Netherlands, Norway, Turkey). As a representative example of each case the marginal abatement cost curves for the UK and Austria follow.

AUSTRIA YEAR 2000
NEW AND IIASA MARGINAL COST CURVE



UNITED KINGDOM YEAR 2000
NEW AND IIASA MARGINAL COST CURVE



III Current levels of abatement

The cost curves derived in our model represent a "hypothetical" situation, as far as they assume that countries apply a number of technologies for each fuel used and in the most cost-effective way. However, the reality is different. In this section, the current level of abatement (if any) in each European country is presented in Table A2. Table A3 presents the number of control units installed in each European country (if there are any) at the end of 1989. The first column represents the number of units that are retrofitted and their total capacity (in MWe), the second column gives the same information but for new installations and the third column gives the totals (i.e. number of retrofitted and new units and their total capacity).

Table A2: Levels of abatement reductions and proposals (in 1000 t)

Countries	1989 level	(%)	post 1990 Addition	(%)	post 1990 Total	(%)
Austria	29	15.51	5.31	2.84	34.31	18.35
Belgium	2.482	0.8	1.635	0.5	4.117	1.3
Denmark	14.18	9.92	18.565	12.98	32.745	22.9
Finland	8.139	3.0	10.601	4.0	18.74	7.0
France	1.945	0.25	1.418	0.2	3.363	0.45
FRG	651.7	41.9	49.82	3.2	701.5	45.1
Italy	3.422	0.2	139.56	8.2	142.98	8.4
Netherlands	34.989	14.46	15.215	6.3	50.204	20.76
Spain	0.06	.0023	7.013	0.27	7.073	0.272
Sweden	8.419	3.4	0.973	0.4	9.392	3.8
UK	7.236	0.4	198.975	10.8	206.211	11.2
Turkey	-	-	37.13	1.7	37.13	1.7
Czechoslovakia	26.422	2.2	16.985	1.4	43.407	3.6
GDR	15.083	0.72	-	-	15.083	0.72
Ireland	0.357	0.43	-	-	0.357	0.43

Table A3: Number of units and capacity of SO_2 control equipment currently in use (end 1989)

Countries	Retrofitted No	Units MWe	New No	Installations MWe	Totals No	MWe
Austria	5	600	14	1449	19	2049
Belgium	-	-	11	201	11	201
Denmark	1	350	6	630	7	980
Finland	3	540	31	430	34	970
France	-	-	19	1005	19	1005
FRG	158	36300	65	5255	223	41555
Italy	-	-	4	245	4	245
Netherlands	5	2732	2	31	7	2763
Spain	-	-	1	2	1	2
Sweden	12	683	61	752	73	1435
UK	-	-	131	389	131	389
Ireland	-	-	2	24	2	24
GDR	1	250	-	-	1	250
Czechoslovakia	4	400	-	-	4	400

Sources: IEA Coal Research [12]; Vernon [24]; IEA Coal Research: personal communication