Modelling optimal nitrogen oxides abatement in Europe

Halkos, George

University of Thessaly, Department of Economics

1997

Modelling optimal nitrogen oxides abatement in Europe[1]

By

George E. Halkos

ABSTRACT

This study uses new abatement cost curves for nitrogen oxides relying on disaggregated source data to optimise NO_X abatement in a European framework. Linear and non-linear damage cost functions are assumed for NO_X emissions and their impacts on the empirical results are explored for first time. The paper also provides numerical estimates of the potential benefits from co-operation.

JEL Classification: ***Q2***

Keywords*:* Social welfare; Nash abatement costs; NO_X emission targets.

---

[1] An earlier version of this paper has been presented as:

Halkos, G., 1997. 'Modelling Optimal Nitrogen Oxides Abatement in Europe', Department of Economics, Discussion Paper Series, Number **97-03**, University of Wales Swansea, UK.

Introduction

Acidification and other environmental problems are associated with the long-range transport of sulphur and nitrogen oxides which require a co-ordinated strategy to control emissions. Although the detrimental effects of acidification were initially centred on sulphur, nitrogen depositions (in the form of nitrogen oxides and ammonia) are also an important factor contributing to various environmental problems. Some nitrogen in the atmosphere originates from natural sources such as oceans, lighting, volcanoes, etc., but the main source of nitrogen oxides emissions is energy combustion in power stations, industrial boilers and vehicles.

Throughout Europe the contribution of sulphur, nitrogen oxides and ammonia to total acidification is 60%, 20% and 20% respectively. Erisman (1991) claims that the contribution of nitrogen to total acidification is approximately 50% but it is higher in some European countries like the Netherlands (almost 70%). NO_X is a short-hand for nitric oxide (NO) and nitrogen dioxide (NO_2). Almost 50% of European NO_X emissions are due to traffic and most of the rest comes from power stations and industrial boilers. This varies from country to country. For instance, in the UK less than 30% of NO_X emissions is produced by traffic and most of the rest comes from stationary sources.

Nitrogen oxides and ammonia have impacts on vegetation and human health. They contribute to nitrogen saturation of soils and lakes and the resulting nitrogen leaching leads to nitrate pollution of groundwater. If they are converted into nitric acid they contribute to acidification of soils and lakes. Nitrogen oxides may be transferred over long distances. NO_X reacts with hydrocarbons in the presence of sunlight and contributes to the formation of photochemical oxidants known as smog. Breathing smog irritates the lungs and can lead to asthma. Usual symptoms are throat pain, eye irritation and coughing. Nitrogen dioxide contributes to kidney and heart damage. At high concentrations this pollution can be fatal.

Acidification provides a classic instance of economic inefficiency, as countries do not bear the full costs of the damage they cause. The recognition of the problems of pollution has led to political action within many countries on emission standards and regulations. However, the transboundary nature of the problem requires an international co-ordinated policy. This was first recognised by the 1979 Convention on Long-Range Transboundary Air Pollution, signed by 35 European countries (among them the EU and the UK), 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').

Negotiations in NO_X are however more complicated than those on SO_2, since there are no broadly accepted international air quality and emission standards on NO_X. This is due to the fact that there are differences in the domestic structure of industry and road transport between ECE members states. Most countries seem able to meet their specified sulphur emissions reductions but have difficulties in reducing NO_X emission levels as in NO_X abatement there is a large number of small polluters which act in an uncoordinated way. In addition, sulphur emissions seem easier to control than NO_X as a higher fraction of sulphur is deposited within 100 km of the source and can be attributed to individually large stationary sources like power stations and industrial boilers. In contrast NO_X are produced by both stationary and mobile (vehicles) sources. We must therefore avoid simply treating collective action problems identically even if they involve the same participants, as key components (group size, cost differences, etc.) may differ (Sandler, 1992).

After the importance of nitrogen deposition was recognised, the first international agreements were made in order to reduce emissions in Europe. On 31 October 1988, a number of countries signed the Sofia Protocol on the control of NO_X emissions which committed the signatories to stabilise their emissions up to 1994 at the level of any year between 1980 and 1987. Twelve European countries declared the intention to reduce their NO_x emissions by 30%, and six countries promised no further increase[2] .

A month later (24 November 1988) the European Community drafted a Directive (88/609/EEC) to limit sulphur and NO_X emissions from large combustion plants known as the Large Combustion Plant Directive (LCPD). When the LCPD was drafted in 1988, ten out of twelve EEC countries had already met the stricter reductions mandated for 1997. Luxembourg (near the target) and Greece (far away from its target) were the two exceptions (Council of the European Communities, 1988). But for Europe, and at the end of 1992, reductions from 1987 levels were almost 3% on average. This implies that agreements to follow on NO_X will need to allow a longer time for achievement of targets.

Obviously the assumption of uniform percentage reductions in emissions by each country is inefficient, as the costs and opportunities for emission control vary between countries. Environmental objectives may vary because ecosystems are not uniformly assimilative of SO_2 and NO_x. In addition, the evaluation of damage caused by depositions varies across countries; SO_2 and NO_x are non-uniformly mixing pollutants and the pattern of depositions varies with the locational pattern of

---

[2] It is important to mention that as the base year selected by countries is not known these commitments were included here in the current reduction plans and using 1980 as the base year. If countries are not committed to the Protocol then we assume that there is no abatement in these countries. The analysis here will be limited to nitrogen oxides as the polluting substance to control. Ammonia was not part of the Convention but some countries like Sweden have specified national objectives for reducing ammonia emissions.

sources. Maler (1990) and Halkos (1994) have demonstrated the inefficiency of the 30% Club agreement by showing that a 40% reduction in total emissions is possible for the same total abatement cost by allocating abatement expenditure to equalise marginal costs across European countries. This ‘cost-effective’ allocation, however, would run into the same problems as the uniform emission reductions in securing agreement and implementation, since the net benefits would be unequally distributed, and could be negative for some countries. The problem of free-riding is serious in such circumstances. Barrett (1994) therefore claims that treaties containing more than a few participants are unlikely to achieve big co-operative gains.

Economic theory can predict the rational level of abatement under a variety of assumptions, ranging from completely non-cooperative to the fully co-operative cases. The benchmark against which to judge the benefits of co-operation is the non-cooperative Nash equilibrium, in which each country takes the policies of its neighbours as given, optimising within that context. The general principles of game theory in the pollution context are set out in Hoel (1991), but there have been few empirical applications so far reported. This paper uses new abatement data and model specifications to provide alternative numerical estimates of the potential benefits from co-operation. The results reported here differ from any previously reported, as in that abatement costs are derived from detailed plant-level research for each country. In our analysis we use the current reduction plans as the current level of abatement and try to optimise abatement efforts by allocating responsibility to European countries according to their contribution to damage as well as their cost-effectiveness in abating NO_X emissions. Linear and non-linear damage cost functions are assumed for NO_X emissions and their impacts on the empirical results are explored for first time.

Modelling optimal abatement

Measurement and approximation of abatement cost functions

In discussing emissions reduction, it is necessary to distinguish between primary abatement (by such means as switching to low -or nitrogen-free fuels, improved energy efficiency, conservation or any other measure reducing the output of electricity, heating, transportation etc.) and secondary. Secondary abatement involves the removal of nitrogen oxides from emissions before burning (e.g. by fuel switching), during burning (e.g. by combustion modifications, low NO_X burners, fluidized bed combustion) or after burning (e.g. by Flue Gas Denitrification). In this paper we are primarily concerned with the optimal pattern of secondary abatement.

The cost of an emission abatement method is given by the total annualised cost (TAC) of an abatement option, including capital and operating cost components:

$$TAC = [(TCC) * (r / (1-(1+r)^{-n})] + VOMC + FOMC$$

where TCC is the total capital cost ($), VOMC and FOMC are the variable and fixed operating and maintenance costs ($) respectively and $(r/(1-(1+r)^{-n})$ is the capital recovery factor at real discount rate r, which 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). The estimation of the annual operating and maintenance costs requires a great deal of information (for example, the nitrogen content of fuel used, the annual operating hours, removal efficiencies of the control methods, etc.) and consists of a fixed portion dependent on the use of the plant (e.g. maintenance and labour costs) and a variable portion dependent on the prices for electricity, labour, construction, sorbents and waste disposal and the specific demand for energy due to the abatement process. Table 1 presents the applicability requirements, the abatement efficiencies and the capital and operating costs of the main abatement options, as well as an estimate of the cost-effectiveness for each abatement technology (Halkos, 1996).

Table 1: Nitrogen oxides emission abatement options and costs (costs in $ million 1985). Costs for stationary sources are based on a new 500 MW power plant, using hard coal of 1% nitrogen content, 70% load factor. For mobile sources costs are for average European automobile of 1200 kg.

Abatement Method	Applicability	NO_X removal efficiency (%)	Capital Cost	Operating and Maintenance cost	Cost-effectiveness \$/ t NO_X removed
Fuel switching (e.g. oil to gas)	All users	Up to 70	-	-	Depends on relative price and nitrogen content
Low NO_X Burners	Power plants and industrial boilers	30	\$3.9 m	Negligible(1)	7-26
Combustion modifications	Power plants and industrial boilers	35	\$6.5 m-\$18.9 m	Negligible(1)	6-70
Flue Gas Denitrification	Power plants and industrial boilers				
SCR		80	\$26.5m(2)	\$0.2 /kWh	820-1850
SNCR		50-70	\$10.1 m	Negligible	680-1420
Fluidized Bed Combustion (FBC)	Power plants and industrial boilers	80	-	-	Undefined
Exhaust Gas Recirculation	Automobiles	Up to 30	\$45-\$84	Fuel efficiency change -5% to +0%	0-4500
Lean Burn Engines	Automobiles	80	\$210	Fuel efficiency change -5% to +15%	Savings of 5-85 per vehicle
Exhaust catalysts	Automobiles	90	\$170-520	Fuel efficiency change -4% to +5%	1300-1700

(1) We have assumed there are no incremental operating costs associated with these modifications.
(2) Excluding catalyst's costs

The abatement costs (per tonne NO_X removed) will vary among countries as a result of country -specific factors such as nitrogen content of fuels used, capacity utilisation, size of installations and labour, 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 optimal technology must be determined on a country-by-country basis. Full details of the abatement costs functions used here are reported in Halkos (1996). These control functions are based on research conducted using information at the level of the individual power station. The International Institute for Applied System Analysis (IIASA, Austria) cost estimates are based on more aggregate data. 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 nitrogen oxides abatement. The national cost curve therefore consists of a large number of very small steps, each step representing an abatement measure for an individual source that achieves an emission reduction of an extra unit at the least cost across all other units in the country. As an example, Figure 1 presents the total abatement cost curve for Sweden.

For analytical purposes, it is necessary to approximate the national cost curves by a functional form, at least over a relevant range such as that between current abatement levels and the values implied by International Agreements. Least squares equations of the form:

$$CA_i = a_{0i} + a_{1i} \; NOR_i + a_{2i} \; NOR_i^2$$

where CA_i is abatement cost and NOR_i are tonnes of NO_X removed, yield satisfactory approximations for all the countries analysed in this paper. It is assumed that CA_i functions are strictly convex with $CA_i' > 0$ and $CA_i'' > 0$, $\forall$ i.

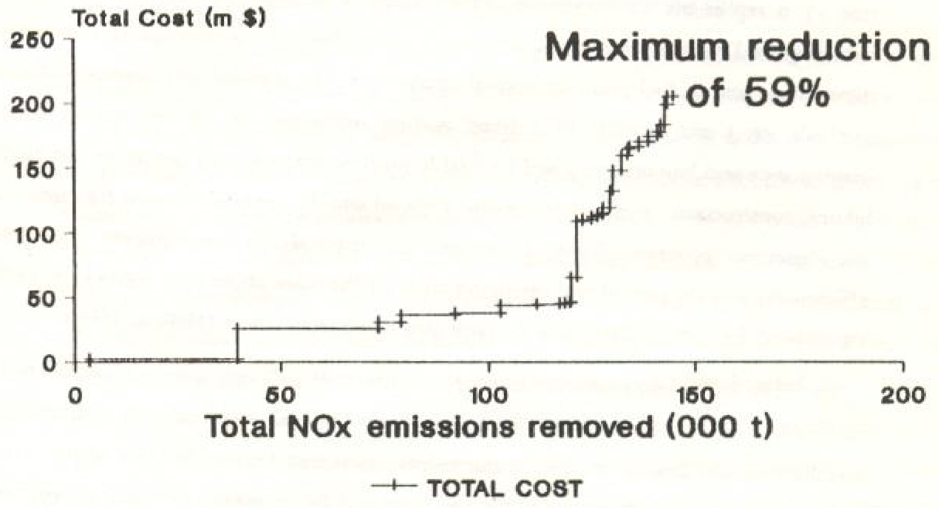

Figure 1
Sweden (Year 2000)

Damage cost function and its approximation

Similarly, the damage cost function depends on NO_X deposits, and is also country-specific. It is expressed as:

$$DC_i = DC_i (D_i) \qquad \text{(and with } DC_i' > 0\text{)}$$

where DC_i is the damage cost and D_i is deposits of NO_X in each country. This function is assumed to be strictly increasing. Deposits are presented in the international transfer matrix, provided by the European Monitoring and Evaluation Program (Norwegian Meteorological Institute; EMEP 1993) and which can be expressed as follows:

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

where the parenthesis estimates the net emissions from country i which are given by the difference between uncontrolled emissions (E_j) and tonnes of NO_X removed (NOR_j). These emissions are the output of power stations, petroleum refineries, industries and vehicles, which we take here as exogenous. d_{ij} is the proportion of net emissions from country j which are deposited in country i: these proportions are assumed fixed. Country i also receives D_{iB}, other backgrounds deposits (from the rest of the world, volcanoes, etc.).

It is often assumed for empirical purposes that the damage function is a linear function of deposits (see e.g. Maler (1989,1990) and Newbery (1990)), while theoretical work assumes convexity i.e. $DC_i'' > 0$ (see e.g. Welsch, 1993; Halkos and Hutton, 1993; Hutton and Halkos, 1995). Relative to the damage functions, it is more likely that doubling the rate of deposition will more than double the damage caused. But as the consequences of acidification cannot be identified with any certainty, we infer parameters by assuming that countries act non-cooperatively (like Nash agents) equating national marginal damage cost with national marginal abatement cost, the latter being obtained from the cost functions described above. Here we will compare both assumptions of linearity and convexity.

Modelling abatement and damage costs

For each country i the total cost arising from a given level of nitrogen oxides emissions is assumed to be given as:

$$TC_i = PC_i + CA_i\,(NOR_i) + DC_i\,(D_i)$$

where PC_i is production costs (omitted here for simplicity), CA_i is abatement cost and DC_i is damage cost. As mentioned, cost of abatement is modelled by quadratic functions of nitrogen oxides removed, and we assume damage costs are also quadratic in deposits, so we have:

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

The non-cooperative case is modelled as the multilateral Nash equilibrium, with NOR as the choice variable and with the first-order conditions yielding the reaction functions. In the social welfare (SW) maximisation case, each country chooses abatement (NOR_i) to set aggregate marginal cost to zero. The optimum is achieved by equating the individual marginal abatement cost to the negative of marginal damage cost. As marginal damage costs (with respect to abatement) are negative and marginal abatement costs are increasing, it is clear that abatement is higher under SW maximisation. But social welfare equilibrium requires side-payments to ensure that no country is a net loser relative to the Nash non-cooperative solution and that agreement on monitoring and on the measurement of abatement and damage costs can be reached.

It follows from the first order condition that when total cost is minimised with respect to NOR_i:

$$c_{2i}=[(a_{li}+2\ a_{2i}\ NOR_i)/2\ d_{ii}\ D_i]-(c_{li}\ /2D_i).$$

If, like Maler (1989,1990) and Newbery (1990), we set $c_{2i}=0$, then $c_{li}=(a_{li}+2a_{2i}\ NOR_i)/d_{ii}$, and total cost becomes:

$$TC_i=[a_{0i}+a_{li}\ NOR_i+a_{2i}\ NOR_i^2]+[c_{0i}\ +\ \{(a_{li}+2\ a_{2i}\ NOR_i)/d_{ii}\ \}D_i\ ] \qquad (i)$$

Instead, if we want to retain nonlinearity, we restrict c_{li} and c_{2i} becomes

$$c_{2i}=(a_{li}+2a_{2i}NOR_i)/2d_{ii}D_i$$

yielding total costs of

$$TC_i=[a_{0i}+a_{li}\ NOR_i+a_{2i}\ NOR_i^2]+[c_{0i}\ +\ \{(a_{li}+2a_{2i}NOR_i)/2d_{ii}\ \}D_i\ ] \qquad (ii)$$

Comparing (i) and (ii), this choice obviously halves the implied total damage costs at the optimum; and the positive second derivative means that the benefits from reductions in deposits will also be less than those implied by a linear damage function.

Numerical Results

The empirical estimates derived here show that fully co-operative secondary abatement policy would raise the average abatement rate from 6% in total (or 20% for countries committed to the protocol) to 33.5% (in the case of a linear damage function) and to 27% (for a quadratic damage function). Table 2 compares the current reduction plans (actual or planned) and the derived SW abatement rates for all countries and the average for Europe, based on IIASA's data on NO_X emissions. Countries with positive signs may increase their emissions.

It can be seen that the SW rate considerably exceeds the current rates, and in the cases of Austria, Belgium, Bulgaria, former Czechoslovakia, Germany, Hungary, Italy, Poland, Romania, Spain, UK and the former Yugoslavia very large increases are indicated. Denmark, Finland, Ireland, Netherlands, Sweden and Switzerland will have to abate slightly more according to the model's prediction compared with the current reduction plans. Overall, the average SW abatement rate is about six times and more than four times higher when we assume linear and quadratic damage cost functions respectively compared to the current reduction plans.

Table 3 presents the costs of abatement according to the CRP and the SW optimising cases. It can be seen that the implication of the CRP costs $1.05 bn and achieves an emissions reduction of almost 6%. Here we rely on emissions levels projected for the year 2000. As it can seen from Table 2, almost half of the European countries have agreed to a 30% reduction in their emissions compared to a based year (which was taken to be 1980) whilst six countries promised no further increase. However, total European emissions are expected to decline by only 6% due to the economic development in Southern European countries which did not agree to any emissions reduction. So we try here to optimise the abatement scenario and to see what countries can achieve, taking into account not only the abatement cost, but also the damage cost imposed on themselves and their neighbours.

Table 2: Abatement rates in % assuming linear and non-linear damage cost functions

Countries	Emissions 1980	Nash Abatement	Linear Social Welfare	Quadratic Social Welfare
Albania	28	+64	9.5	6
Austria	239	30	45	39
Belgium	439	30	53	44
Bulgaria	357	0	43	31
Former Czech	796	0	48	36
Denmark	250	30	35	32
Finland	234	30	34	32
France	1944	30	30	30
Germany	3741	30	53	42
Greece	239	+82	7	3
Hungary	305	+18	38	28
Ireland	89	+31	18	15.5
Italy	1458	30	48	33
Luxembourg	31	30	40	33
Netherlands	577	30	37	32
Norway	169	30	33	28
Poland	1597	0	32	22
Portugal	149	+51	19	16
Romania	661	+29	39	26
Spain	950	0	40	27
Sweden	333	30	33	31
Switzerland	186	30	37	35
Turkey	356	+192	3.5	3.0
UK	2324	0	29	20
Former USSR	9454	0	19	15
Former Yugoslavia	394	+45	50	34
AVERAGE/TOTAL	27317	6	33.5	27

Emissions levels in 1980 are in thousand tonnes of NO_X (Source: Amann, 1989)

Table 3: Nash and social welfare abatement costs assuming linear and non-linear damage cost functions (in m $ 1985)

Countries	Nash abatement cost	Linear Social Welfare abatement cost	Quadratic Social Welfare abatement cost
Albania	0	1.4	1.2
Austria	17.3	41.7	36.23
Belgium	24.31	131.21	111.32
Bulgaria	38.76	148.9	63.3
Former Czech	11.6	92.95	49.6
Denmark	5.2	14.7	10.37
Finland	18.17	58.3	23.7
France	66.4	81.1	72.4
Germany	156.3	508.42	341.2
Greece	0	5.85	2.46
Hungary	0	23.24	15.11
Ireland	0	2.3	1.6
Italy	434.27	701.2	563.3
Luxembourg	6.43	11.29	7.4
Netherlands	7.94	30.52	13.8
Norway	43.63	59.86	46.4
Poland	18.2	83.4	52.7
Portugal	0	16.36	14.2
Romania	0	122.83	60.9
Spain	73.4	270.02	83.6
Sweden	10.68	15.94	11.43
Switzerland	4.73	8.3	5.81
Turkey	0	5.75	5.7
UK	47.41	367.9	196.33
Former USSR	68.3	425.27	230.4
Former Yugoslavia	0	254.3	98.8
TOTALS	1053	3483	2119

With the assumption of a linear damage cost function we can achieve an almost 6 times higher emissions reduction with an only 3.5 times higher cost, or more than 4 times higher emissions reduction with slightly less than double the cost when we assume a quadratic damage cost function. The implied abatement cost is high for Belgium, former Czechoslovakia, Germany, Italy, Romania, the former USSR, the UK and the former Yugoslavia and relatively low for Denmark, Finland, Greece, Hungary, Ireland, Switzerland, Luxembourg, Portugal and Turkey.

Table 4 presents the damage cost estimates when we assume linear and non-linear damage cost functions and when countries co-operate or act independently. It is interesting to note that assuming linear damage costs implies a damage cost of $8 bn while if we assume a quadratic damage function the cost is halved. On the other hand, the SW solutions are nearer for both linear and quadratic cases compared with the non-cooperative solutions. The industrialised countries, and mainly Germany, the Scandinavian countries, the Netherlands, Switzerland and some Eastern European countries face very high damage costs.

Looking at the total numbers and at Table 5, we see that acting independently yields total costs of $9.1 bn when we assume a linear damage cost function and $5.1b when we assume a non-linear damage cost function. If countries co-operate, and if we assume a linear damage cost function, this leads to a 33.5% emissions reduction with a cost of $8.6 bn, which consists of a damage cost equal to $5.1 bn and an abatement cost of $3.5 bn. On the other hand, assuming a quadratic damage cost function leads to a 27% emissions reduction implying a total cost of $5 bn which is associated with an abatement cost of $2.1 bn and a damage cost of $2.9 bn. These results should be expected, since the scenario of the current reduction plan relies on the idea that countries act independently trying a certain emission target in the first stage and then attempt to see if they can achieve better emission and deposition levels if they co-operate.

Table 4: Nash and social welfare damage costs assuming linear and non-linear damage cost functions (in m $ 1985)

Countries	Linear Nash damage cost	Quadratic Nash damage cost	Linear Social Welfare damage cost	Quadratic Social Welfare damage cost
Albania	7.0	3.5	4.17	2.1
Austria	101.74	50.87	94.13	42.88
Belgium	34.3	17.15	23.84	11.86
Bulgaria	105.4	52.7	73.95	36.82
Former Czech	344.82	172.41	191.02	90.96
Denmark	277.22	138.61	181.46	103.1
Finland	106.16	53.08	73.82	52.78
France	399.7	199.85	304.34	180.72
Germany	1224.46	612.23	729.4	406.08
Greece	70.16	35.08	43.0	25.66
Hungary	264.22	132.11	178.44	92.94
Ireland	23.72	11.86	18.82	8.22
Italy	541.52	270.52	336.16	167.32
Luxembourg	11.2	5.6	9.06	5.16
Netherlands	189.24	94.62	115.52	42.74
Norway	687.32	343.66	506.22	324.24
Poland	844.1	422.05	583.92	357.96
Portugal	33.02	16.51	30.32	11.1
Romania	359.3	179.65	193.78	99.34
Spain	505.06	252.53	283.75	227.4
Sweden	149.6	74.8	120.44	73.22
Switzerland	228.26	114.13	156.9	88.64
Turkey	36.47	30.9	32.88	25.9
UK	580.68	290.34	342.9	168.9
Former USSR	585.88	292.94	318.48	161.82
Former Yugoslavia	296.02	148.01	151.94	92.48
TOTALS	8007	4016	5099	2900

Table 5: Nash and social welfare total costs (in m $ 1985)

Countries	Linear Nash and social welfare total cost		Quadratic Nash and social welfare total cost		GAIN (Linear)	GAIN (Quadratic)
Albania	7.0	5.75	3.5	3.3	+1.43	+0.2
Austria	119.04	135.83	68.17	79.11	-16.79	-10.94
Belgium	58.61	155.05	41.46	123.18	-96.44	-81.72
Bulgaria	144.16	222.85	91.46	100.12	-78.69	-8.66
Former Czech	356.42	283.97	184.01	140.56	+72.45	+43.45
Denmark	282.42	196.16	143.81	113.47	+86.25	+30.34
Finland	124.33	132.12	71.25	76.48	-7.79	-5.23
France	466.1	385.44	306.25	253.12	+80.66	+53.13
Germany	1380.76	1227.82	768.53	747.28	+142.94	+21.25
Greece	70.16	48.85	35.08	28.12	+21.31	+6.96
Hungary	264.22	201.68	132.11	108.05	+62.54	+24.06
Ireland	23.72	21.12	11.86	9.82	+2.6	+2.04
Italy	975.79	1037.36	704.79	760.62	-61.57	-55.83
Luxembourg	17.63	20.35	12.03	12.52	-2.72	-0.49
Netherlands	197.18	146.04	102.56	56.54	+51.14	+46.02
Norway	730.95	566.08	387.29	370.64	+164.87	+16.65
Poland	862.3	667.32	440.25	410.66	+194.98	+29.59
Portugal	33.02	46.68	16.51	25.3	-13.66	-8.79
Romania	359.3	316.61	179.65	160.24	+42.69	+19.41
Spain	578.46	553.77	325.93	311.0	+24.69	+14.93
Sweden	160.28	136.38	85.48	84.65	+23.9	+0.83
Switzerland	232.99	165.2	118.86	94.45	+67.79	+24.41
Turkey	36.47	35.63	30.9	31.6	-2.16	-0.7
UK	628.09	710.8	337.75	365.23	-82.71	-27.48
Former USSR	654.18	743.75	361.24	392.22	-89.57	-30.98
Former Yugoslavia	296.02	406.24	148.01	191.28	-110.22	-43.27
TOTALS	9060	8582	5109	5050	+478	+59

Finally, the social welfare maximization (SW) rates can be compared with the Nash rates to indicate the magnitudes of the uncompensated gains and losses from co-operation. As can be seen from Table 5, and the last two columns, the gains that can be achieved if countries cooperate instead of acting independently are negative for Austria, Belgium, Bulgaria, Finland, Italy, Luxembourg, Portugal, Turkey, the former USSR, the UK and the former Yugoslavia and these should be compensated.

The aggregate gain from full co-operation is about 8 times higher when we assume a linear damage cost function compared to a non-linear one. The former Czechoslovakia, Denmark, France, Germany, Hungary, Netherlands, Norway, Poland and Switzerland are the biggest gainers from SW. In previous work, Germany dominated the picture in Europe for the case of sulphur abatement (Halkos and Hutton, 1994). It seems that the transition period of the incorporation of the former GDR into the FRG may have implied an intense period of change and GDR (one of the biggest polluters) was no longer restricted (as in the case its Eastern neighbours) by lack of finance and other economic constraints. This rapid restructuring may therefore have increased the significance of the environmental gains for GDR but not necessarily for FRG.

It has to be mentioned that the results will change if we consider a simultaneous abatement of NO_X and ammonia (NH_3). Amann and Klaassen (1993) claim that simultaneous control of NO_X and NH_3 emissions can accomplish the same nitrogen deposits as the maximum feasible reductions of NO_X emissions only, and with 23% lower abatement costs. Depending on deposition targets, simultaneous reduction can reduce European abatement costs between 13 and 80%. Thus the consideration of the two pollutants at the same time may lead to substantial cost savings. These cost savings are attained by replacing expensive ways of abating NO_X

emissions (for instance, the three-way catalyst for gasoline cars) by inexpensive control of NH_3 emissions. According to Amann and Klaassen, the cost-effective options to reduce ammonia are the low-ammonia application of manure for all animal categories, stable adaptations (such as manure flushing) and abatement of industrial emissions. The cost estimates depend on animal type and technology. The main cost parameters are the stable size, the amount of manure used etc. Additional reductions may be achieved in the chemical industry by applying stripping and absorption techniques. Cost estimates for NH_3 emissions are more uncertain than those of NO_X due to lack of practical experience.

Conclusions and Policy Implications

Using recent data on nitrogen oxides emissions and depositions, together with new detailed estimates of abatement costs, estimates of the total costs of NO_X pollution for 26 European countries have been derived. These estimates allowed the calculations of the effects of non-cooperative policies to the case of full co-operation. Among the main conclusions to be drawn is that estimates of the economic benefits from co-operation are higher when we assume a linear damage cost function compared with the assumption of a quadratic damage cost function. In interpreting the derived figures, it is essential to recognise that the results derived using linear damage cost functions are completely insensitive to the total level of projected emissions. While tonnage figures may be compared with the case of assuming quadratic damage cost functions, abatement rates are not comparable. This is a consequence of using linear damage functions which makes the figures for abatement rates simply functions of emission rates. Results for abatement tonnage under full co-operation are therefore similar, whereas benefit estimates are different. Thus we tend to overestimate the benefits from co-operation.

In general, Europe as a whole, benefit from co-operation, and the gains from co-operation permit compensation of the losers. If countries cooperate they will achieve a more than four times higher emissions reduction for almost a double abatement cost. At the same time, all countries will participate in the agreement and will be obliged to undertake responsibilities according to the damage caused and their cost-effectiveness in abating NO_X emissions.

Finally, reducing NO_X in stationary sources may involve the slowing down of the mixing rate of the fuel and air and the lowering of the temperature at which fossil fuels (oil/coal) are burnt. Best available technologies for power plants, petroleum refineries and industrial boilers seem to be a combination of combustion modification and selective catalytic reduction achieving abatement efficiency of 90%. At the same time the most cost-effective way to reduce nitrogen oxides emissions from gasoline cars is by fitting a three-way catalytic converter to the car exhaust. It is worth mentioning that abating NO_X emissions may lead to additional impacts on the environment, which have been excluded in this paper. For instance, the use of catalytic converters for cars reduce NO_X but also volatile organic compounds (precursors both to tropospheric ozone in European cities) which were not taken under consideration in our analysis.

Acknowledgements: Thanks are due to Dr Paul Latreille at the University of Wales Swansea and to Professors Charles Perrings and John Hutton at the University York for helpful comments and discussions on an earlier draft. The use of data sources and their interpretation, as well as any remaining errors are solely the author's responsibility**.**

REFERENCES

Amann, M. (1989). *Potential and costs for control of NO_X emissions in Europe*. International Institute for Applied Systems Analysis, SR-89-1, Laxenburg, Austria.

Amann, M. and Klaassen, G. (1993). *Cost-effective strategies for reducing nitrogen deposition in Europe.* Status Report SR-93-002, International Institute for Applied Systems Analysis, SR-89-1, Laxenburg, Austria.

Barrett S. (1994). Self-enforcing international environmental agreements. *Oxford Economics Papers*, **46:** 878-94.

Council of the European Communities (1988). *Council directive of 24 November 1988 (88/609/EEC) on the limitation of emissions of certain pollutants in the air from large combustion plants.* Official Journal of the European Community, 50, 336/1-336/13.

EMEP (1993). *Airborne Transboundary Transport of sulphur and nitrogen over Europe: model description and calculations.* Meteorological Synthesizing Centre-West, The Norwegian Metorological Institute, EMEP/MSC-W Report 1/93.

Erisman, J.W., (1991). *Acid deposition in the Netherlands, RIVM report nr. 723001002.* National Institute for Public Health and Environment Protection, Bilthoven, The Netherlands.

Halkos, G.E. (1994); Optimal abatement of sulphur in Europe. *Environmental and Resource Economics*, **4(2)**: 127-150.

Halkos G. and Hutton, J., (1993). *Acid Rain Games in Europe.* Discussion Papers **93/12**, Department of Economics, University of York.

Hutton, J P. and Halkos, G E, (1995). Optimal acid rain abatement policy for Europe: An analysis for the year 2000, *Energy Economics*, **17(4):** 259-275.

Halkos, G.E. (1996). *Evaluating the direct costs of controlling NO_X emissions in Europe*. Discussion Paper **9612**, Department of Economics, University of Wales Swansea.

Hoel, M. (1991). Global Environmental Problems: the effects of unilateral actions taken by one country. *Journal of Environmental Economics and Management*, **20:** 55-70.

Maler, K.G. (1989). *The Acid Rain Game: valuation, methods and policy making in environmental economics*. In H. Folmer and E. Ierland (eds), Valuation Methods and Policy Making in Environmental Economics, Chapter 12, Blackwell.

Maler, K.G. (1990). International environmental problems; *Oxford Review of economic policy*, **6(1):** 80-107.

Newbery, D. (1990). Acid Rain. *Economic Policy*, **11:** 297-346.

Sandler, T. (1992). *Collective action: theory and applications.* Ann Arbor: University of Michigan Press.

Welsch H. (1993). An equilibrium framework for global pollution problems. *Journal of Environmental Economics and Management* **25:** 64-79.