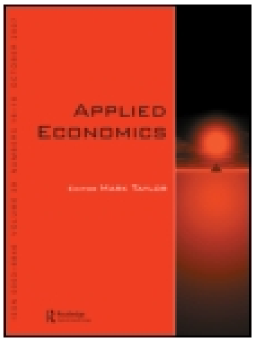

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Optimal pollution level: a theoretical identification

George E. Halkos[a,*] and Christos P. Kitsos[b]

[a]*Department of Economics, University of Thessaly, Argonavton and Filellinon, 38221 Volos, Greece*
[b]*Department of Mathematics, Technological University of Athens (TEI-A), Ag. Spyridonos and Pallikaridi, 12210 Athens, Greece*

In this paper, the optimal pollution level is identified under the assumptions of linear, quadratic and exponential cost functions. The corresponding optimal level of environmental policy is evaluated, with analytical forms in the linear and quadratic case, while in the exponential case, these values are obtained approximately. It is shown that, in principle, its existence obeys certain restrictions, which are investigated here. The evaluation of the benefit area is discussed and analytical forms for this particular area are calculated. The positive point, at least from a theoretical point of view, is that both the quadratic and the exponential case obey the same form when evaluating the benefit area. These benefit area evaluations can be used as indexes between different rival policies, and certainly the policy that produces the maximum area is the most beneficial policy.

I. Introduction

Much has been written recently about the use of negotiation and bargaining to resolve environmental conflicts. Negotiation and bargaining occur between governments to attempt to settle conflicts concerning land use, energy and air quality (Bingham, 1986). Recently attention has been given to four major environmental problems: the 'greenhouse effect' and the resulting threat of global climate change; the damage caused from acid rain and its transboundary nature; the problem of a hole in the ozone layer over the Antarctic; and deforestation (Nordhaus, 1990). Negotiations have taken place on these problems and a number of protocols have been signed. Barrett and OECD (1990) list 140 international environmental agreements on the control of acid rain and the protection of the ozone layer, while Grubb (1989) discusses the emerging negotiations on greenhouse gases.

The recognition of air pollution (say in the form of acid rain), as an externality, is vital in economic policy. The presence of transnational externalities implies that gains can be realized by cooperative behaviour. As there is no international or multinational 'government' that can enforce international environmental policy, these problems must be solved by voluntary agreements among the countries concerned. The problem is that of finding some institutional structure that will facilitate the appropriate agreements. Such a structure must be one that makes all parties (countries) better off. Otherwise, any agreement is unlikely. We thus seek structures that promise a Pareto-efficient outcome.

The main problem in promoting international cooperation is the unconvincing scientific evidence.

*Corresponding author. E-mail: halkos@uth.gr.

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Environmental economists recognize that uncertainty concerning the nature of the marginal abatement cost function and the marginal damage function is an important determinant of adopting Pareto-efficient policies. Uncertainty pervades the decision-maker in terms of calculating marginal abatement and marginal damage costs. Uncertainty at the firm level exists through the firm's marginal abatement cost function and through uncertainty induced by the control agency. Uncertainty about the firm's marginal abatement cost function is mainly technology-induced, because the abatement technology may be relatively new and not well-established and future cost savings due to learning-curve effects and/or potential scale economies are uncertain.

Additionally, uncertainty concerning future input prices implies an extra uncertainty on the firm's marginal abatement cost function. On the other hand, changes in pollution standards or tax rates or variations in the price of emission permits may create an additional source of disturbance.

Uncertainty at the level of the environmental control agency creates similar phenomena to those facing a firm, such as the uncertainty about the firm's marginal control cost curve, which in turn raises uncertainty about the aggregate marginal abatement cost curve facing society. Although the pollution control agency is presumably free from uncertainty about the firm as a result of policy changes, it has to cope with two more sources of uncertainty. The first refers to the fact that the pollution control agencies may have only a vague idea about the social marginal damage function, as the standard errors of estimates of health costs of air pollution are large. On the other hand, even if a firm's marginal abatement cost function is known, the marginal control cost curve facing the agency may be unknown.

In this paper, we try to identify the optimal pollution level under the assumptions of linear, quadratic and exponential abatement cost functions. In Section II, relevant existing literature is reviewed. In Section III we identify analytically the intersection of the marginal abatement cost curve with the marginal benefit curve in order to examine when and if an optimal level of pollution exists. In Section IV an empirical application comprising a sample of nine European countries with different industrial structures is presented. For these countries, the 'benefit area' is evaluated explicitly, provided the marginal benefit and abatement cost functions intersect. This is not always true and the conditions, under these so important economic functions, have a common point and they are analytically examined in this paper. The last section concludes the paper and comments on the policy implications related to this analysis providing evidence useful to the researcher.

II. Background to the Problem

Excessive levels of environmental damage take place when social costs are not taken into consideration. This omission implies a market failure, which requires policy intervention for its correction. Before the decision makers intervene to correct the externality, they need a well-defined environmental policy target, which, in the case of pollution, should be the optimal level of pollution.

This in turn requires comparison of the damage cost (or benefit from damage reduction) with the cost of preventing damage. Economic theory suggests that the optimal pollution level occurs when the marginal damage cost equals the marginal abatement cost. The marginal damage shows pollution as a function of emissions of a specific pollutant. Damages are measured as the impact on human health, materials, recreational activities, buildings, lakes, rivers, etc. Attempts are made to measure existence values or other indirect use values using contingent valuation and other methods (Freeman, 1993; Bjornstad and Kahn, 1996). Obviously, the measurement of damage is important and difficult due to a number of practical problems as presented in Georgiou *et al.* (1997), Barbier (1998) and Farmer *et al.* (2001).

Costs and benefits from the air pollution abatement are not fully reflected in potential or actual exchanges. They represent incomplete or missing markets. Mäler (1989, 1990) and Newbery (1990, 1993) assume that the marginal damage cost is constant and independent of the amount of depositions, i.e. a linear damage cost function. Furthermore, assuming that countries are rational and act noncooperatively (taking the emissions of all other countries as given) and that damage caused by 1 tonne of sulphur is the same in all countries, they derive the condition that the marginal abatement cost (MAC), which they assume to be a quadratic function of abatement, equals the marginal damage cost (MD), which they assume to be linear, times the proportion of depositions that will be deposited in the home country (d_{ii}).

Halkos (1996) using a game theoretic approach consistent with mainstream economic theory, derives the general form of cooperative and noncooperative equilibria in an explicit and implicit set-up of a proposed model, under the assumptions of deterministic and stochastic deposits. He shows that under uncertainty the gains from cooperation are much less than under certainty. The Nash (noncooperative) abatement costs are similar under certainty and uncertainty, while the Nash damage costs are quite different, due to the assumptions of stochastic deposits. It is also shown that main polluters abate more under uncertainty, while pollutes abate more under certainty.

Halkos (1997) in a game theoretical framework and assuming that damage function is convex, that is, increasing at an increasing rate in deposits (AD_i), proves that, under such an assumption, the Nash and the Von Stackelberg equilibria just coincide. On the other hand, Kitsos (1999) discussed the problem of low dose effect of carcinogenesis and proposed a sequential method to evaluate the low dose percentile points. But the experiment design approach, to choose that situation which produces the lowest pollution level, is not applied in large-scale problems (to a municipality region, for example, or to a country) as it is performed for pharmaceutical designs following the Michelis–Menten model (Kitsos, 2001, 2002). That is, roughly speaking, we cannot create a polluted area in order to investigate the low dose effect of the pollution/chemicals to human health.

Kaitala *et al*. (1992) and Tahvonen *et al*. (1993) define the cost function $C_i(e_i)$, where e_i denotes the unconstrained emissions, as the minimal cost envelop encompassing the entire range of sulphur abatement options for country i in a given time period. The control costs are calculated for various sulphur reductions requirements ranging up to the maximal technologically feasible removal. The calculations are based on expected energy demands for the year 2000. The costs are measured in millions of Finnish marks per year and include both capital and operating costs. Kaitala *et al*. (1992) use quadratic approximations to the original piecewise linear cost functions and solve the problem of estimating the total damages from acidification by applying the indirect revealed preference method suggested by Mäler (1990).

III. Determining the Optimal Level of Pollution

Consider the typical situation of the optimal pollution level as in Fig. 1. The curves $g(z)$ and $\varphi(z)$ denote a country or a province or a municipality area's abatement cost and benefit functions respectively. The point of their intersection $I = I(z_0, k_0)$ represents the optimal level of pollution. In Fig. 1 it is assumed that the curves have an intersection, and therefore the area of the region AIB, created by these curves, is what is known as the 'benefit area' (Kneese, 1972, among others). This is typically the case, although as we shall prove, it is not always true.

This analysis considers three cases for the abatement cost function $g(z)$:

Case 1: The curve $g(z)$ is linear of the form $g(z) = \beta_0 + \beta_1 z$, $\beta_1 \neq 0$.

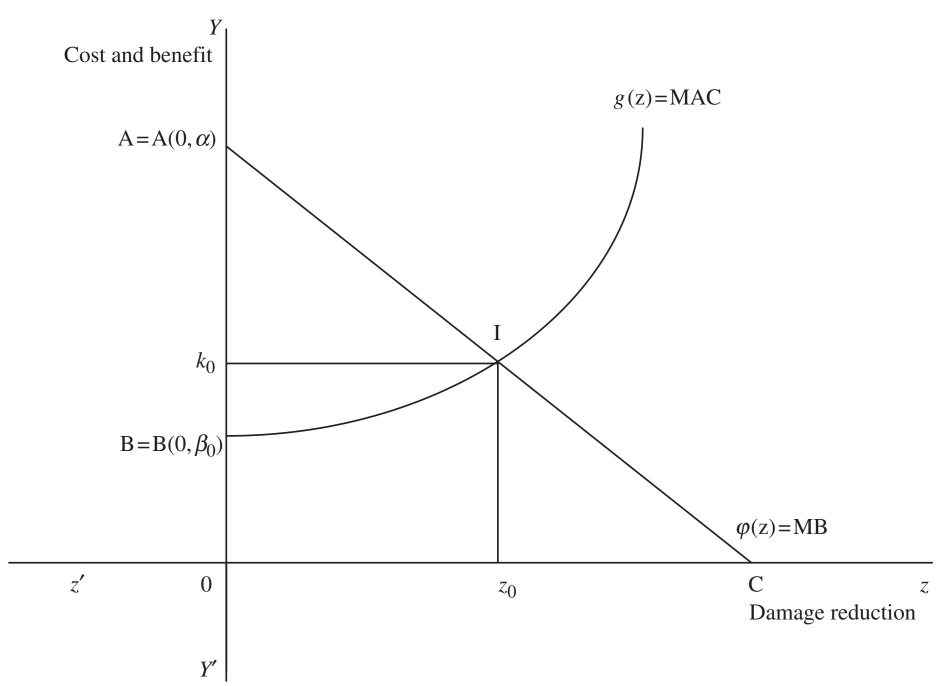

Fig. 1. Graphical presentation of the optimal level of pollution

Case 2: The curve $g(z)$ is quadratic of the form $g(z)=\beta_0+\beta_1 z+\beta_2 z^2$, $\beta_2>0$.

Case 3: The curve $g(z)$ is exponential of the form $g(z)=\beta_0 e^{\beta_1 z}$, $\beta_1\neq 0$.

All through this analysis the benefit (or damage) function $\varphi(z)$ is linear[1] of the form $\varphi(z)=\alpha+\beta z$. Moreover it is assumed that $\varphi(z)$ is a decreasing function and $\varphi(0)=\alpha>0$. For the three cases of $g(z)$ considered it is also assumed that $g(0)=\beta_0\geq 0$, and $g(z)$ is an increasing function i.e. the first derivative for each case is assumed to be positive.

For points $\mathrm{A}=\mathrm{A}(0,\alpha)$ and $\mathrm{B}=\mathrm{B}(0,\beta_0)$ in Fig. 1, it is assumed that $\alpha>\beta_0$. This is clear as if it is assumed that $\alpha<\beta_0$ there is no intersection, no benefit area and if we let $\alpha=\beta_0$ the benefit area coincides with the point, namely $\mathrm{A}=\mathrm{B}=\mathrm{I}$, that is a one-point area is created. We shall examine in the remainder of this paper how this crucial benefit area can be evaluated, providing an index when different areas are investigated (like countries or provinces), adopting different rival models and policies as are expressed by the two curves under investigation. We emphasize that these curves, $g(z)$ and $\varphi(z)$, can be approximated, as estimates of their coefficients can be obtained, through various methods. The most usual method is 'ordinary least squares' (OLS), see Halkos and Hutton (1994) for details and Section IV below.

We are considering three cases to examine under what restrictions the two curves have an intersection, represented as $\mathrm{I}=\mathrm{I}(z_0,k_0)$. That is, what are the values of the points z_0 and k_0, which give the optimal restriction on damages and the optimal cost (benefit), respectively. It is clear that, in principle, the intersection satisfies $g(z_0)=\varphi(z_0)$, with z_0 being the optimal restriction in damages. Let us examine each assumption and case in turn.

First, let us consider the case of linearity, that is both $\varphi(z)$ and $g(z)$ are linear. The intersection $\mathrm{I}=\mathrm{I}(z_0,k_0)$ satisfies the following relationship:

$$\beta_0+\beta_1 z_0=\alpha+\beta z_0 \Leftrightarrow \beta_0-\alpha =(\beta-\beta_1)z_0 \Leftrightarrow z_0 =\frac{\beta_0-\alpha}{\beta-\beta_1}=-\frac{\beta_0-\alpha}{\beta_1-\beta}. \quad (1)$$

Now we are asking for z_0 to be positive, i.e. to lie on the right half of the $z'z$ axis as in Fig. 1. This is true when $\beta_1>\beta$, as we have already imposed the assumption $\beta_0<\alpha$. So if both $g(z)$ and $\varphi(z)$ are linear the intersection exists at z_0 as in Equation 1 if $\beta_1>\beta$ and $\beta_0<\alpha$. The corresponding optimal cost or benefit values should be equal for both the curves. This is true as their difference is zero, indeed:

$$k_0=\varphi\left(\frac{\beta_0-\alpha}{\beta-\beta_1}\right)=\alpha+\beta\frac{\beta_0-\alpha}{\beta-\beta_1},$$
$$g\left(\frac{\beta_0-\alpha}{\beta-\beta_1}\right)=\beta_0+\beta_1\frac{\beta_0-\alpha}{\beta-\beta_1}.$$

Thus for $\varphi(z_0)-g(z_0)=0$:

$$(\beta_0-\alpha)\left[1+\frac{\beta_1-\beta}{\beta-\beta_1}\right]=0$$

i.e. $\varphi(z_0)=g(z_0)$.

The benefit area (hereafter BA), is evaluated, in principle, through the following relation:

$$\mathrm{BA}=(\mathrm{ABI})=(\mathrm{AI}z_0 0)-(\mathrm{BI}z_0 0) \quad (2)$$

where the functions in parenthesis are the evaluated areas of the corresponding geometrical figure (see Fig. 1).

Using Equation 2, the 'linear benefit area', say $\mathrm{BA_L}$ can be evaluated in the linear case. This can be evaluated as either the area of the triangle ABI, or using Equation 2, as the region ABI by subtraction, namely:

$$\mathrm{BA_L}=(\mathrm{ABI})=\frac{(\mathrm{AB})(\mathrm{I}k_0)}{2} =\frac{(\alpha-\beta_0)(0z_0)}{2}=\frac{(\alpha-\beta_0)^2}{2(\beta_1-\beta)}. \quad (2a)$$

Otherwise, using Equation 2 the area can be evaluated by subtraction of the areas of the two trapezoids, namely:

$$\mathrm{BA_L}=(\mathrm{ABI})=\frac{(\mathrm{I}z_0)+(\mathrm{A}0)}{2}(k_0\mathrm{I})-\frac{(0\mathrm{B})+(\mathrm{I}z_0)}{2}(0z_0) =(0z_0)\{[(\mathrm{I}z_0)+(\mathrm{A}0)-(0\mathrm{B})-(\mathrm{I}z_0)]/2\} =\frac{(\alpha-\beta_0)^2}{2(\beta_1-\beta)}$$

i.e. the expression (2a).

Let us consider now the case of a quadratic abatement cost function, which is the most likely case, i.e. $g(z)=\beta_0+\beta_1 z+\beta_2 z^2$.

It is assumed that $\mathrm{g}(0)=\beta_0>0$ and $\mathrm{d}g(z)/\mathrm{d}z=\beta_1+2\beta_2 z>0$, i.e. positive marginal abatement cost, that is $z>-(\beta_1/2\beta_2)$ which means that g is increasing.

[1] If instead it is considered as a quadratic, this could be of the form $\varphi(z)=\alpha+\beta z+\gamma z^2$, with $\alpha>0$ and $\alpha>\beta_0$. So the AC curve in Fig. 1, is a branch of a quadratic and the intersection C exists when $\beta^2-4\alpha\gamma\geq 0$. This quadratic branch is assumed to be approximated by a linear benefit function. Note that even in a quadratic benefit function the benefit area is evaluated through general expression (2), as defined in Section III.

The intersection can be evaluated using the same line of thought, as it obeys:

$$\varphi(z_0) = g(z_0) \Rightarrow \beta_0 + \beta_1 z_0 + \beta_2 z_0^2 = \alpha + \beta z_0. \quad (3)$$

We emphasize that the coefficients α, β, β_0, β_1, β_2 can be estimated applying the OLS method to the appropriate data set (Halkos and Hutton, 1994).

Recall that for the points $A = A(0, \alpha)$, $B = B(0, \beta_0)$ we assume that $\alpha > \beta_0$. We rearrange Equation 3 as:

$$(\beta_0 - \alpha) + (\beta_1 - \beta)z_0 + \beta_2 z_0^2 = 0. \quad (4)$$

If we set $K = \beta_0 - \alpha$, $L = \beta_1 - \beta$ then Equation 4 becomes:

$$\beta_2 z_0^2 + L z_0 + K = 0. \quad (5)$$

The roots of Equation 5 are:

$$z_0 = \frac{-L \pm \sqrt{D}}{2\beta_2} \quad (6)$$

with:

$$D = L^2 - 4\beta_2 K = (\beta_1 - \beta)^2 - 4\beta_2(\beta_0 - \alpha) \quad (7)$$

Then, considering the cases of positive, zero and negative D, we can obtain results for the roots of Equation 4 using Equation 6. The negative D has no economic meaning, so a zero D, leads from (6) to an optimal restriction on damages of the form:

$$z_0 = -\frac{L}{2\beta_2} = -\frac{\beta_1 - \beta}{2\beta_2}. \quad (7a)$$

When assuming $\beta_1 < \beta$ the value of z_0 is positive, as β_2 has been assumed positive already. Thus the corresponding values, for the evaluated z_0 are:

$$\varphi(z_0) = \alpha - \beta\frac{\beta_1 - \beta}{2\beta_2}$$

and

$$g(z_0) = \beta_0 + \beta_1\left[-\frac{\beta_1 - \beta}{2\beta_2}\right] + \beta_2\left[-\frac{\beta_1 - \beta}{2\beta_2}\right]^2$$

Thus, with $\varphi(z_0) - g(z_0) = 0$, this is equivalent to:

$$(\alpha - \beta_0) + (\beta_1 - \beta)\left[\frac{\beta_1 - \beta}{2\beta_2}\right] = \beta_2\left[\frac{\beta_1 - \beta}{2\beta_2}\right]^2 \quad (8)$$

$$(\alpha - \beta_0) + \frac{(\beta_1 - \beta)^2}{2\beta_2} = \frac{(\beta_1 - \beta)^2}{4\beta_2}. \quad (8a)$$

From Equation 7, when $D = 0$, the relation (8a) holds with:

$$\beta_1 = \beta \quad \text{and} \quad \alpha = \beta_0 \quad (9)$$

Thus from relation 7a and Equation 9 the corresponding value of z_0 is $z_0 = 0$. So the only common point if $D = 0$ is $A \equiv B$. That is, Equation 5 has only one real root, which is of zero value and the intersection is A, which coincides with B. But in such a case, there is no area (AIB) to be evaluated and the situation is pathological.

The practical use of $g(z)$ is certainly when $D > 0$, with D as in Equation 7. Under the assumptions $\beta_0 - \alpha < 0$, $\beta_2 > 0$ the quantity $-4\beta_2(\beta_0 - \alpha) > 0$ and therefore $D > 0$. This is true because the sum of the roots (equal to $2z_0$) is positive, while the product of the roots (equals to $(\beta_0 - \alpha)/\beta_2$) is negative. We are interested in at least a positive root z_0 in Equation 5, which under the assumption $\alpha > \beta_0$ can be evaluated only when $\beta_1 < \beta$, from Equation 6.

The corresponding benefit area (ABI) for the quadratic case, BA_Q say, is evaluated through the general form Equation 2 subtracting from the trapezoidal $AIz_0 0$ the area $BIz_0 0$, namely:

$$BA_Q = \frac{(OA) + (Iz_0)}{2}(0z_0) - \int_0^{z_0} g(z)dz$$
$$= \frac{\alpha + g(z_0)}{2} z_0 - [G(z_0) - G(0)] \quad (10)$$

with $G(z) = \beta_0 z + \beta_1(z^2/2) + \beta_2(z^3/3)$, which implies that $G(0) = 0$. So Equation 10 is reduced to:

$$BA_Q = \frac{\alpha + g(z_0)}{2} z_0 - G(z_0) \quad (11)$$

with z_0 as in Equation 6 and the assumptions $\beta_1 < \beta$ and $\alpha > \beta_0$. As in (2a), a general form for the benefit area is produced when a linear marginal abatement cost $g(z)$ is examined, with Equation 11 being the general form for the benefit area evaluated when a quadratic marginal abatement cost $g(z)$ is examined. We shall now prove that Equation 10 is more general, and that it also satisfies the exponential case of marginal cost, discussed below.

Let us consider an exponential function $g(z) = \beta_0 \exp(\beta_1 z)$. In this case the general line of thought for the intersection leads to:

$$\beta_0 e^{\beta_1 z_0} = \alpha + \beta z_0 \Leftrightarrow \exp(\beta_1 z_0) = \alpha^* + \beta^* z_0$$

with $\alpha^* = (\alpha/\beta_0)$, $\beta^* = (\beta/\beta_0)$ with $\beta_0 \neq 0$, resulting in

$$\beta_1 z_0 = \ln(\alpha^* + \beta^* z_0) \Leftrightarrow z_0$$
$$= \frac{1}{\beta_1}\ln(\alpha^* + \beta^* z_0) = F(z_0) \quad (12)$$

where, in Equation 12, the definition of the smooth function $F(z)$ is obvious. Now Equation 12, $z_0 = F(z_0)$, can only be solved adopting an iterative scheme, through the fixed-point theorem (Ortega and Rheinbolt, 1970). The iteration, formed as

$$z_{0,n+1} = \frac{1}{\beta_1}\ln(\alpha^* + \beta^* z_{0,n}) \quad n = 0, 1, 2, \ldots \quad (13)$$

converges to z_0, i.e. $\lim z_{0,n+1} \to z_0 = F(z_0)$. That is, the optimal damage restriction level z_0 in the exponential case only be evaluated approximately and therefore the corresponding optimal cost or benefit level is also only approximate. Practically, this results in the value of $g(z_0)$–$\varphi(z_0)$ not being zero, but close to zero.

The corresponding benefit area (AIB) for the exponential case, BA_E say, is then evaluated through Equation 2 as:

$$BA_E = (AIz_00) - \int_0^{z_0} g(z)dz = \frac{\alpha + g(z_0)}{2} z_0 - [G(z_0) - G(0)] \quad (14)$$

with

$$G(z_0) - G(0) = \int_0^{z_0} \beta_0 e^{\beta_1 z} dz = \frac{\beta_0}{\beta_1} \int_0^{z_0} e^{\beta_1 z} d(\beta_1 z) = \frac{\beta_0}{\beta_1}(e^{\beta_1 z_0} - 1) \quad (15)$$

i.e. $G(0) = 1$ in this case. Therefore, Equation 10 still holds, providing an index for the benefit area for both quadratic and exponential cases, but with $G(z_0)$ as in Equation 15 and z_0 approximated as in Equation 13.

IV. An Empirical Application

Let us now discuss how the two curves $g(z)$, the abatement cost and $\varphi(z)$, the benefit, can be approximated. We shall use estimates for data, from nine different European countries chosen randomly and for reasons of experimentation.

Consider first the determination of the abatement cost function. This measures the cost of eliminating tonnes of a pollutant, say sulphur (S) emissions, and varies between countries depending on the existing power generation technology, and on the local costs of implementing best practice abatement techniques. To control 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. The abatement costs (per tonne of S 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 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 optimization must be carried out on a country-by-country basis. Full details of the abatement cost functions used here are reported in Halkos (1995).

For analytical purposes, it is necessary to approximate the national cost curves by a functional form over the relevant range, which should span at least the range between current abatement levels and those implied by the '30% Club' targets (Halkos and Hutton, 1994). We found that least squares equations of the form

$$g(z) = TAC = \beta_0 + \beta_1 \cdot TSR + \beta_2 \cdot TSR^2 \quad (16)$$

where TSR represents total sulphur removed and TAC total abatement cost, yield satisfactory approximations for the countries analysed in this paper. Such a quadratic fit provided adjusted R^2 greater than 98%, for all cases investigated.

Next, the damage function $\varphi(z)$ is investigated. The problem of estimating the benefit functions (or equivalently the damage cost functions) of countries is more difficult than the estimation of abatement costs, since the consequences of damage (say in the form of acidification) cannot be identified with the same accuracy. Due to the transboundary pollution nature of the acidification problem we must ensure that the model takes account of the distribution of the externality among the various victims (countries in our case). Each victim (country) receives a certain number of units of pollutant whose deposition is due to the other countries' emissions as well as its own emissions. This assignment is summarized in the European Monitoring and Evaluation Programme (EMEP) transfer coefficient matrix (EMEP, 1989).[2]

[2] Dividing the contribution to depositions in country i from any European country j by the total depositions in this country i we find the transfer coefficient of emissions in country j deposited in country i. Assuming linearity, and if E_i is the total annual sulphur emission in country j, AD_i is the total annual sulphur deposition in country i, α_i is the abatement efficiency coefficient in country i and d_{ij} is the transfer coefficient from country j to i, indicating what proportions of emissions from any source country is ultimately deposited in any receiving country, then the deposition of sulphur in country i is given by:

$$AD_i = \sum_j d_{ij}(1 - \alpha_j)E_j + B_i \quad \forall i,j \quad i,j = 1, \ldots, N$$

where B_i is the level of the so-called background deposition attributable to natural sources (such as volcanoes, forest fires, biological decay, etc.) in receptor country i, or to pollution remaining too long in the atmosphere to be tracked by the model, i.e. probably attributable not only to natural sources but also to emissions whose origin cannot be determined.

Table 1. Some empirical estimates of the benefit area

Country	α	β	β_0	β_1	β_2	Eff	z_0	BA
Spain	71.69	0.0072	69.06	0.0039	0.00014	10.6	149.35	273.74
France	33.15	0.2773	21.45	0.1644	0.00134	43.3	144.62	1115.91
Greece	3.73	0.0341	2.29	0.0265	0.00099	1.6	42.12	42.60
Italy	11.01	0.0300	7.78	0.0226	0.00021	12.9	142.88	332.83
Poland	16.21	0.0231	2.49	0.01778	0.00019	100.0	277.08	2574.46
Portugal	1.03	0.0317	0.76	0.06673	0.00689			
Romania	9.09	0.0113	5.78	0.00998	0.000153	13.1	151.46	339.05
Sweden	6.398	0.0642	9.61	0.7617	0.01620			
UK	19.06	0.0687	9.59	0.04423	0.000212	80.0	276.80	2060.39

In common with other studies, we do not directly estimate the damage function, but we infer its 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 (for details see Hutton and Halkos, 1995).

Table 1 presents model fits for different countries. Specifically, it presents first estimates of $\varphi(z)$ and $g(z)$ for different countries and then the efficiency index and the optimal point corresponding to the intersection. The last column presents the corresponding BA index as evaluated from the available parameter estimates. The sample of countries chosen was randomly selected, having in mind to examine representative parts of the European territory as well as some industrial countries (as heavy polluters).

From Table 1 it is clear that evaluation of the benefit area, as was developed in Section III, provides an index to compare the different policies adopted by different countries, on the basis of how large a benefit area is eventually provided; i.e. a qualitative approach has been developed to compare different policies. Certainly the policy with the maximum benefit area is the best, and those with minimum benefit area are worst. Notice as the restriction $\beta > \beta_1$ is not satisfied for Portugal and Sweden, there is no benefit area to be evaluated. Clearly the index BA provides a new measure for comparing the policies adopted. However, the evaluation of optimal damage reduction z_0, as has been noted in this paper, provides evidence that the larger it is the better the environmental policy. The efficiency Eff of the benefit area, in comparison with the maximum evaluated from the sample of countries under investigation, can be estimated. We propose as a measure of efficiency the ratio

$$\text{Eff} = \left[\frac{\text{BA}}{\max \text{BA}}\right] * 100. \qquad (17)$$

This value has been evaluated in Table 1 for seven of the nine European countries considered here. So there is a measure of what percentage of the adopted policy matches that policy which provides the maximum benefit area. As can be seen, large industrial upwind counties (like France and the UK) seem to have a very large benefit area. Looking at the EMEP transfer coefficients matrix it can be seen that the countries with large benefit areas are those with large numbers on the diagonal. This shows the importance of domestic sources of pollution. Poland in Central Europe shows the largest benefit area. The large off-diagonal transfer coefficients indicate in general the major effects of one country on another, and especially the externalities imposed by the Eastern European countries on the others.

On the other hand, downwind or near to the sea countries seem to have small benefit areas. Additionally, the damage caused by acidification depends on where the deposition occurs. In the case of deposition over the sea it is less likely to have much harmful effect, as the sea is naturally alkaline. Similarly, if it occurs over sparsely populated areas with acid-tolerant soils then the damage is low (Newbery, 1990). Deposits on rivers and lakes or on densely populated areas may be very damaging.

V. Conclusions and Policy Implications

The analysis of the effectiveness of environmental programmes and regulations requires the comparison of benefits (damage costs) and costs associated with the reduction of different pollutants. The typical approach to define the optimal pollution level has been to equate the marginal damage of an extra unit of pollution with the corresponding marginal abatement cost.

In this paper the optimal pollution level under different assumptions for the abatement cost function was examined and discussed. The corresponding optimal cost and benefit points were evaluated analytically. It is shown that this is feasible in the linear and quadratic cases, while in the exponential case, only approximate values can be obtained.

The explicit evaluation of the benefit area was also discussed and analytical forms for this particular area were calculated for different policies. In this way the optimal level was evaluated. We show that:

1. The optimal pollution level can be evaluated only under certain conditions as were derived is Section III. Specifically, it is required that
   i. In all cases $\alpha > \beta_0$. That is, the constant term in the benefit function (we may think of this as the background deposition) is bigger than the abatement cost at level $z = 0$ (we may think of the fixed costs of operating an abatement method at level $z = 0$).
   ii. For the linear and quadratic cases $\beta > \beta_1$. That is, the slope of the benefit function must be greater than the marginal abatement cost at level $z = 0$.
   iii. For the quadratic case it is required that $\beta_2 > 0$ while for the exponential case β_0, $\beta_1 > 0$.
2. Both the quadratic and the exponential cases are of the same form in terms of evaluating the benefit area. These calculations can be used as indexes between different rival policies, and certainly the policy that produces the maximum area is this policy which is most beneficial.
3. An important finding is that large industrial upwind counties seem to have a very large benefit area, while downwind near-to-the-sea countries or sparsely populated areas with acid tolerant soils seem to have small benefit areas.

Finally, it is worth mentioning that the pathological situations of one point benefit area were also examined so that the study to be complete in hands of the interested researcher.

References

Barbier, E. (1998) *The Economics of Environment and Development: Selected Essays*, Edward Elgar, London.

Barrett, G. W. and OECD (1990) Economic analysis of international environmental agreements, Environment Directorate, OECD Paris.

Bingham, G. (1986) *Resolving Environmental Disputes: A Decade of Experience*, Conservation Foundation, Washington, DC.

Bjornstad, D. and Kahn, J. (1996) *The Contingent Valuation of Environmental Resource: Methodological Issues and Research Needs*, Edward Elgar, London.

EMEP (1989) Airborne transboundary transport of sulphur and nitrogen over Europe: model description and calculations, EMEP/MSC-W Report 2/89.

Farmer, A., Kahn, J. R., McDonald, J. A. and O'Neill, R. (2001) Rethinking the optimal level of environmental quality: justifications for strict environmental policy, *Ecological Economics*, **36**, 461–73.

Freeman III, A. (1993) *The Measurement of Environmental and Resource Values: Theory and Methods*, Resources for the Future, Washington DC.

Georgiou, S., Pearce, D., Whittington, D. and Moran, D. (1997) *Economic Values and the Environment in the Developing World*, Edward Elgar, London.

Grubb, M. (1989) *The Greenhouse Effect: Negotiating Targets*, Royal Institution of International Affairs, Chatman House, London.

Halkos, G. (1995) An evaluation of the direct cost of abatement under the main desulfurization technologies, *Energy Sources*, **17**, 391–412.

Halkos, G. (1996) Incomplete information in the acid rain game, *Empirica Journal of Applied Economics and Economic Policy*, **23**, 129–48.

Halkos, G. (1997) Modelling optimal nitrogen oxides abatement in Europe, *International Journal of Energy, Environment, Economics*, **5**, 233–48.

Halkos, G. and Hutton, J. P. (1994) A game-theoretic approach to pollution control problems, Discussion Paper 9405, Department of Environmental Economics and Environmental Management, University of York.

Hutton, J. P. and Halkos, G. (1995) Optimal acid rain abatement policy in Europe: an analysis for the year 2000, *Energy Economics*, **17**, 259–75.

Kaitala, V., Pohjola, M. and Tahvonen, O. (1992) Transboundary air pollution and soil acidification: a dynamic analysis of an acid rain game between Finland and the USSR, *Environmental and Resource Economics*, **2**, 161–81.

Kitsos, C. P. (1999) Optimal designs for estimating the percentiles of the risk in multistage models in carcinogenesis, *Biometrical Journal*, **41**, 33–43.

Kitsos, C. P. (2001) Design aspects for the Michaelis–Menten model, *Biometrical Letters*, **38**, 53–66.

Kitsos, C. P. (2002) The simple linear calibration problem as an optimal experimental design, *Communications in Statistics Theory and Methods*, **31**, 1167–77.

Kneese, A. V. (1972) Rationalizing decisions in the quality management of water supply in urban-industrial areas, in *Readings in Urban Economics* (Eds) M. Edel and J. Rothenberg, MacMillan, New York.

Ortega, J. M. and Rheinboldt, W. C. (1970) *Iterative Solution of Non-Linear Equations in Several Variables*, Academic Press, New York.

Mäler, K. G. (1989) The acid rain game, in *Valuation, Methods and Policy Making in Environmental Economics* (Eds) H. Folmer and E. Ireland, Oxford University Press, Oxford, Chapter 12.

Mäler, K. G. (1990) International environmental problems, *Oxford Review of Economic Policy*, **6**, 80–108.

Newbery, D. (1990) Acid rain, *Economic Policy*, **11**, 288–346.

Newbery, D. (1993) The impact of EC environmental policy on British coal, *Oxford Review of Economic Policy*, **9**, 66–95.

Nordhaus, W. D. (1990) The cost of slowing climate change: a survey, Discussion Paper, Department of Economics, Yale University.

Tahvonen, O., Kaitala, V. and Pohjola, M. (1993) A Finnish-Soviet acid rain game: cooperative equilibria, cost efficiency and sulphur agreements, *Journal of Environmental Economics and Management*, **24**, 87–100.