Uncertainty of Air Pollution Cost Estimates: To What Extent Does It Matter?

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How large is the social cost penalty if one makes the wrong choice because of uncertainties in the estimates of the costs and benefits of environmental policy measures? For discrete choices there is no general rule other than the recommendation to always carefully compare costs and benefits when introducing policies for environmental protection. For continuous choices (e.g., the ceiling for the total emissions of a pollutant by an entire sector or region), it is instructive to look at the cost penalty as a function of the error in the incremental damage cost estimate. Using abatement cost curves for NO_x, SO_2, dioxins, and CO_2, this paper evaluates the cost penalty for errors in the following: national emission ceilings for NO_x and SO_2 in each of 12 countries of Europe, an emission ceiling for dioxins in the UK, and limits for the emission of CO_2 in Europe. The cost penalty turns out to be remarkably insensitive to errors. An error by a factor of 3 due to uncertainties in the damage estimates for NO_x and SO_2 increases the total social cost by at most 20% and in most cases much less. For dioxins, the total social cost is increased by at most 10%. For CO_2, several different possible cost curves are examined: for some the sensitivity to uncertainties is greater than for the other pollutants, but even here the penalty is less than 30% and in most cases much less if the true damage costs are twice as high as the ones estimated. The paper also quantifies the benefit of improving the accuracy of damage cost estimates by further research.

Introduction

A rational approach to the formulation of environmental policies requires a careful examination of their consequences. In particular, it is advisable to quantify the costs and benefits as much as possible, even if a comparison of costs and benefits may not be the only relevant criterion for a decision. However, many people question the usefulness of environmental cost−benefit analysis because the results have notoriously large uncertainties. This paper addresses that objection by asking "how large is the social cost penalty if one makes the wrong choice because of uncertainties in the cost or benefit estimates?".

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Among the many types of possible environmental regulations, some impose general limits on emissions for an entire country (e.g., the National Emissions Ceilings in Europe) or on atmospheric concentrations (e.g., air quality standards for ambient concentrations of SO_2), whereas others target specific sources of pollution (e.g., emission limits for SO_2 emitted by power plants). Even the general limits require, for their implementation, regulations for specific sources. Therefore, one needs to know the benefits of reducing the emissions of individual sources, that is, the damages avoided through the cutback of emissions from these origins.

The damage costs (also called external costs) can be calculated by an impact pathway analysis (i.e., an analysis of the chain emission → dispersion → dose−response function → monetary valuation). Much progress with the methodology for that has been made in recent years thanks to the ExternE (External Costs of Energy) project series of the European Commission (*1*−*3*) and analogous work in the United States (*4*−*7*). We also refer to a special issue of this journal for a discussion of monetary valuation of environmental impacts, especially the papers by Matthews and Lave (*8*), Pearce and Seccombe-Hett (*9*), Hammitt (*10*), and Mourato et al. (*11*). For specific results, we use the damage cost estimates of ExternE. The methodology and key assumptions of ExternE are very similar to the American studies.

A rigorous uncertainty analysis of damage costs would require a rather complicated Monte Carlo calculation, as described for example by Morgan and Henrion (*12*). That has not yet been done for the damage costs under consideration in this paper. One of the obstacles is the pervasive lack of information on the probability distributions of the numerous input parameters. Instead various shortcuts have been taken. The U.S. EPA (*5*) and Abt Associates (*7*) considered high and low estimates of the most uncertain input data and the corresponding high and low estimates of the damage costs. Levy et al. (*6*) carried out a large number of sensitivity studies, including different epidemiological assumptions and a comparison of two atmospheric models. The software of Rowe et al. (*4*) contains detailed probability distributions with a specified form (β distribution) and combines them according to the rules of statistics, but here too the main limitation is the lack of information on the uncertainties of all the input parameters.

Rabl and Spadaro (*13*) have shown that a simple analytic approximation of the uncertainty can be obtained if the largest sources of uncertainty (atmospheric modeling and monetary valuation of mortality) have distributions that are approximately log-normal, an assumption justified by the available data. Their analysis indicates that the damage costs of PM (particulate matter), NO_x, and SO_2 have an uncertainty that can be characterized to good approximation by a log-normal distribution with geometric standard deviation of about three; see also chapter 11 of ExternE 2000 (*2*) for an update. A geometric standard deviation (σ_G) corresponds to a multiplicative 68% probability confidence interval [μ_G/σ_G, $\mu_G\sigma_G$] around the median estimate μ_G; the 95% confidence interval is [μ_G/σ_G^2, $\mu_G\sigma_G^2$]. For dioxins or toxic metals that pass through the food chain and for global warming the uncertainty is even larger, with a geometric standard deviation of about 5−10; see Rabl and Spadaro (*14*) for dioxins and Spadaro and Rabl (*15*) for toxic metals. Uncertainties in findings from damage cost calculations affect many kinds of environmental scientific analyses in which

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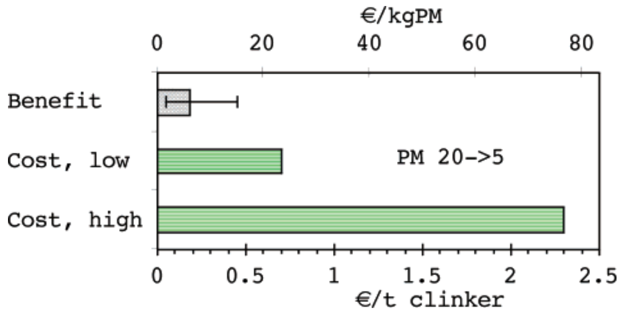

FIGURE 1. Comparison benefits for a reduction of average emission from 20 to 5 mg/m^3 (of emission limit from 50 to 15 mg/m^3). Costs and benefits are shown on two scales: Euro per $t_{clinker}$ (product of cement kiln, bottom scale) and Euro per kg_{PM} (top). Error bar indicates uncertainty of benefit. The uncertainty of the abatement cost is indicated by a high and a low estimate.

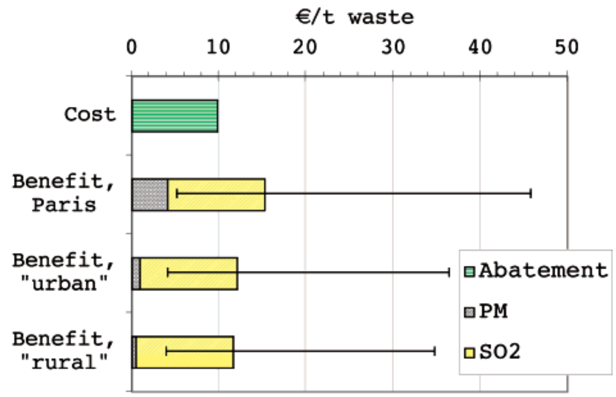

FIGURE 2. Cost and benefit for a reduction of emission limits for PM and SO_2 from municipal solid waste incinerators. Error bar indicates uncertainty of benefit.

these results play a role; see, for example, van der Zwaan and Rabl (*16*).

In this paper, we compare benefits and abatement costs for several air pollutants and technologies. To begin with, one needs to distinguish between continuous and discrete policy choices. Setting the limit for SO_2 emissions from power plants is an example of a continuous choice; deciding whether to require a specific technology with a fixed emission rate is an example of a discrete choice (e.g., a particulate filter for diesel engines, in contrast to selective noncatalytic reduction of NO_x from stationary sources where the emission level can be gradually lowered by paying more). Some choices have been formulated in discrete terms, even though they should really be treated as continuous processes. For example, limits on SO_2 emissions from power plants have been proposed in terms of a choice between simple round numbers (such as 200 or 300 mg/m^3 of flue gas), even though it would be more rational to set them equal to the social optimum.

For discrete choices the situation is sometimes quite simple because the uncertainty, even if it is very large, has no effect if it does not change the ranking. We illustrate this point with two examples in the next section, one where the use of a cleaner technology is justified and one where it is not: requiring stricter regulations is not always the best use of scarce resources.

For continuous choices, the effect of uncertainty can be surprisingly small because near an optimum the total social cost varies only slowly as individual cost components are varied, as pointed out by Rabl (*17*) in the context of energy conservation. This is shown in a separate section of this paper, with an example of abatement cost curves for NO_x, SO_2, dioxins, and CO_2. The social optimum (i.e., the lowest total cost) corresponds to the emission level at which the marginal cost of abatement equals the marginal benefit. If the wrong level is chosen, the social cost will be larger. We evaluate this cost penalty as a function of the error in the damage cost estimate. By integrating the cost penalty over the probability distribution of damage cost errors, we also calculate the expectation value of the cost penalty. Plotting this expectation value versus the geometric standard deviation provides information on the value of reducing damage cost uncertainties by further research.

Discrete Choices

It is interesting to show two examples from Friedrich et al. (*18*). Figure 1 shows a comparison of social costs and benefits for a proposed reduction of the emission limit for particulate matter (PM) emitted by cement kilns that use waste as fuel, one of the issues under discussion in formulating the new EC Directive on the incineration of waste. Even the upper bound of the benefit is lower than the lower estimate of the abatement cost. For this case the cost−benefit criterion is unambiguous even in view of the uncertainties.

By contrast, Figure 2 shows an example where the proposed reduction of emission limits appears justified. This figure compares cost and benefit for a reduction of emission limits for PM and SO_2 from municipal solid waste incinerators: the limit for PM being reduced from 30 to 10 mg/m^3 and the one for SO_2 being reduced from 300 to 50 mg/m^3. This is the reduction brought about by the passage of the new EC Directive on the incineration of waste (*19*). Whereas in Figure 1 the benefit is shown for a single typical site, with most cement kilns being located in rural areas, in Figure 2 it is appropriate to show at least three sites for incinerators: a metropolis, a typical urban site, and a rural site. For all of these sites the benefit outweighs the cost: the new Directive appears justified, although the conclusion is not very firm because of the uncertainties.

The difference between Figures 1 and 2 arises from the differences in the technologies affected by the regulation. For waste incinerators the regulation under consideration reduces both PM and SO_2. The regulation for cement kilns reduces only PM (cement kilns emit no SO_2, with rare exceptions). The lesson to be drawn from these examples is that in some cases stricter limits for the emission of pollutants are clearly justified, and in other cases they are not.

For discrete binary choices, there is a critical value of the incremental damage cost:

$$D_{crit} = \Delta C_{ab}/\Delta E \quad (1)$$

where the optimal choice changes from one option to the other, ΔC_{ab} being the difference in abatement costs and ΔE being the difference in emissions between the two options. A cost penalty:

$$\Delta C = \Delta C_{ab} + D_{true}\Delta E \quad (2)$$

is incurred only if the choice was wrong, for example, if the true incremental damage cost D_{true} is larger than D_{crit} (when the option with higher E was chosen) or smaller than D_{crit} (when the option with lower E was chosen). Plotting a cost penalty ratio, as we do in the following section for continuous choices, makes no sense because the denominator would change with the transition at D_{crit}.

The cost penalty for discrete choices is very different from the one for continuous choices. For the latter there is a smoothly varying function with a minimum because the number of options to be implemented varies smoothly with the damage cost (in the approximation of smooth abatement cost curves).

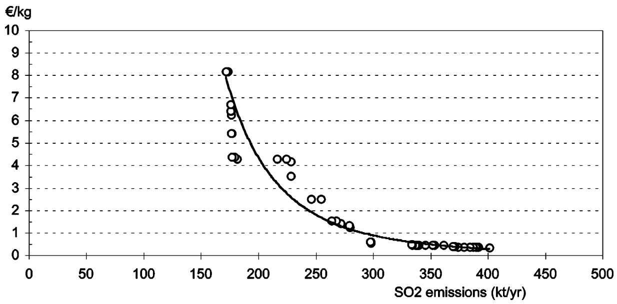

FIGURE 3. Marginal abatement cost data of IIASA (*20*) and curve fit for SO_2 in France vs the remaining total emission level. Initial emission "current legislation", 489 kt/yr.

Continuous Choices

NO_x and SO_2. Abatement costs for NO_x and SO_2 reductions in Europe have been published by IIASA (*20*) as part of a large international research program based on detailed analyses of the available technologies and their costs in each country. They have been obtained by a "bottom-up" analysis, based on detailed examination of all available technologies. To quote from the IIASA report: "In this paper we consider the cost curves for the year 2010. They are constructed with the 'Current legislation' situation as a starting point. This means that each curve ranks all emission control options that are still available on top of measures required by the current legislation, according to their cost-effectiveness. The initial emissions and control costs include measures, which are already adopted by the current legislation. The cost curve considers only the remaining potential for emission controls." Curves are presented separately for each country to account for the very different technological choices that are appropriate in different countries. Separate curves are shown for East and West Germany because the two parts of Germany are still very different in this regard, even a decade after their unification.

As a typical example, Figure 3 shows the marginal abatement cost for SO_2 in France (in Euro/kg) versus the remaining total emission level of the country (the data start from the current level of 489 kt/yr). The figure also shows the curve fit to the data points.

The data do not lie on a smooth curve because the various reductions involve transitions to different technologies. An analysis such as that of IIASA has limited resolution because it assumes essentially the same cost for a transition regardless of specific circumstances such as the detailed design of a particular power plant where a new abatement technology would be applied. In reality the costs usually vary because of different local conditions. Instead of a single large step at the transition, an analysis with finer resolution would find a sequence of smaller steps; of course, it is not practical and often not even possible to obtain data with such a level of detail. In any case, such cost variations tend to render the curve more smooth, without changing the general trend.

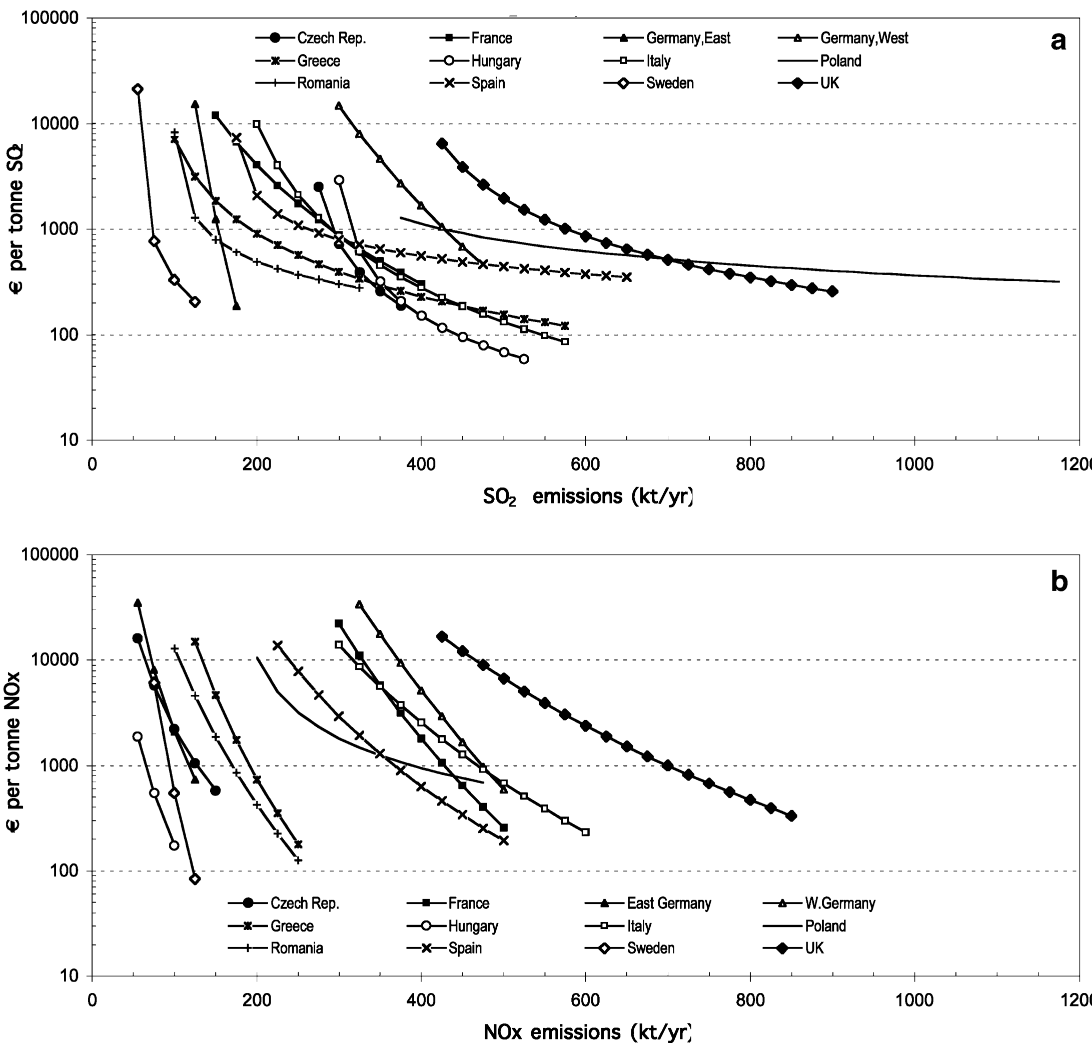

FIGURE 4. Our fits to the IIASA marginal abatement costs in 12 countries of Europe (the original data are not shown): (a) for SO_2 and (b) for NO_x.

TABLE 1. Coefficients α, β, and γ of the Curve Fits in Figure 4, Current Emission Level (E_s), Lowest Emission Level (E_{min}) for Which There Are Data, Estimated Marginal Damage Cost (D_{est}), Ratios $E_{0,est}/E_s$, $E_{0,est}/E_{min}$, x_{min}, and x_{max} ($E_{0,est}$ = Optimal Emission for D_{est})[a]

	α	β	γ	E_s (t/yr)	E_{min} (t/yr)	D_{est} (Euro/kg)	$E_{o,est}/E_s$	$E_{o,est}/E_{min}$	x_{min}	x_{max}	$C_{ab}(E_{o,est})$ (MEuro/yr)	$C_{tot}(E_{o,est})$ (MEuro/yr)
Section A: SO_2												
Czech Rep.	5.36E+08	2.60E+5	−1.275	3.68E+5	2.67E+5	12.2	0.72	0.99	0.02	0.60	114	3339
France	2.99E+23	0.00E+0	−3.748	4.89E+5	1.72E+5	10	0.32	0.92	0.01	0.72	547	2118
Germany, East	2.75E+41	6.00E+4	−7.740	1.65E+5	1.25E+5	10	0.78	1.03	0.04	1.48	96	1383
Germany, West	3.23E+45	0.00E+0	−7.548	4.73E+5	2.96E+5	10	0.67	1.07	0.05	1.62	448	3606
Greece	5.84E+10	6.50E+4	−1.522	5.62E+5	9.27E+4	7	0.18	1.08	0.02	1.45	355	1058
Hungary	2.54E+08	2.90E+5	−1.235	5.46E+5	2.96E+5	11.3	0.54	0.99	0.00	0.53	103	3417
Italy	2.67E+14	1.50E+5	−2.220	5.93E+5	2.09E+5	10	0.34	0.96	0.01	0.69	380	2378
Poland	3.58E+06	2.60E+5	−0.680	1.51E+6	3.90E+5	9.9	0.18	0.68	0.03	0.12	818	3449
Romania	1.95E+06	9.80E+4	−0.718	5.94E+5	1.00E+5	10	0.17	0.99	0.02	0.75	223	1219
Spain	1.44E+06	1.71E+5	−0.637	7.93E+5	1.73E+5	10	0.22	1.01	0.03	1.37	437	2171
Sweden	3.89E+07	5.40E+4	−1.088	6.86E+4	5.44E+4	10	0.82	1.03	0.11	5.75	36	596
UK	7.45E+10	3.65E+5	−1.478	1.10E+6	4.30E+5	10	0.37	0.95	0.02	0.58	691	4789
Section B: NO_x												
Czech Rep.	8.16E+19	0.00E+0	−3.313	1.33E+5	5.57E+4	12.4	0.45	1.07	0.07	1.24	269	1007
France	1.61E+52	0.00E+0	−8.738	5.05E+5	2.90E+5	16	0.62	1.08	0.01	1.89	629	5612
Germany, East	6.80E+26	0.00E+0	−4.702	1.30E+5	6.14E+4	16	0.50	1.06	0.04	1.30	259	1298
Germany, West	1.54E+85	−2.00E+5	−14.10	5.05E+5	3.18E+5	16	0.70	1.11	0.03	2.57	648	6310
Greece	5.43E+36	0.00E+0	−6.388	2.71E+5	1.25E+5	7	0.52	1.13	0.02	2.19	178	1163
Hungary	1.30E+22	0.00E+0	−3.974	9.10E+4	3.08E+4	11.7	0.38	1.13	0.02	1.61	129	535
Italy	3.53E+36	0.00E+0	−5.916	6.28E+5	2.64E+5	10	0.51	1.20	0.02	2.96	623	3798
Poland	7.31E+08	1.75E+5	−1.100	4.84E+5	1.92E+5	9.6	0.42	1.05	0.07	1.65	566	2510
Romania	6.21E+38	−5.00E+4	−6.700	2.62E+5	9.19E+4	9.6	0.41	1.16	0.01	1.96	259	1285
Spain	5.43E+32	0.00E+0	−5.343	5.35E+5	2.25E+5	10	0.45	1.06	0.01	1.36	533	2921
Sweden	5.86E+44	0.00E+0	−8.406	1.13E+5	6.64E+4	10	0.63	1.07	0.02	1.71	93	800
UK	1.24E+36	0.00E+0	−5.662	9.02E+5	4.08E+5	10	0.52	1.14	0.02	2.11	953	5611

[a] For $x < x_{min}$, the true optimum $E_{o,true} > E_s$ (no abatement cost) and for $x > x_{max}$ the cost curve is extrapolated below E_{min}. The last two columns show abatement cost and total cost for $E_{o,est}$. $x = D_{true}/D_{est}$.

For the remainder of this paper, we represent the abatement cost curves by smooth interpolating functions. Our fits to the IIASA costs for NO_x and SO_2 reductions in 12 countries of Europe are shown in Figure 4. The functional form of the marginal abatement cost (in Euro/t) is

$$\frac{dC_{ab}}{d(-E)} = \alpha(E-\beta)^{\gamma} \quad (3)$$

in which C_{ab} is the abatement cost (in Euro/yr); E is the remaining emission level (in t/yr); and α, β, and γ are coefficients determined by least-squares regression (we choose the signs so that dC_{ab} is positive for a reduction of E, and α is positive). The coefficients are listed in Table 1, together with other information to be explained later in the paper. It is crucial to use consistent units for the calculations. Even though we have used Euro/yr for C, t/yr for E, and Euro/t for D for the calculations, in the figures and tables we show different units to avoid large numbers.

The cost of reducing the emission level from a starting point E_s to E is of course the integral of the marginal cost:

$$C_{ab} = \frac{\alpha}{\gamma+1}[(E_s-\beta)^{\gamma+1} - (E-\beta)^{\gamma+1}] \quad (4)$$

We approximate the damage cost C_{dam} by a linear function of the emission level E:

$$C_{dam} = DE \quad (5)$$

in which D is the marginal damage cost (in Euro/kg). Linearity has been found to be a good approximation for PM, SO_2, and NO_x (*1*). Otherwise the damage can be approximated by a straight line in the vicinity of the optimum; the only change required for our formulation is the addition of a constant to the total cost. Such a constant has no effect on the choice of the optimum, although it would have to be added to numerator and denominator of the cost penalty ratio in eq 10. For CO_2, linearity is probably an acceptable approximation for the range of interest, namely, the changes in emissions that are likely to be made during the foreseeable future.

For NO_x and SO_2 the ExternE damage costs assume that the damage comes mostly or entirely from the secondary pollutants that they create. Since the creation of secondary pollutants takes place over distances of tens to hundreds of kilometers, the variation of their damage cost with emission site is so small that a single value can be taken for an entire country.

The optimal emission level E_o is found by minimizing the total cost $C_{tot} = C_{ab} + C_{dam}$ with respect to E:

$$E_o = \beta + \left(\frac{D}{\alpha}\right)^{1/\gamma} \quad (6)$$

As an example, C_{ab}, C_{dam}, and C_{tot} for SO_2 in France are shown in Figure 5. Let D_{true} be the true value of D, which is unknown, and let D_{est} be the estimate. The damage cost estimate D_{est} and the corresponding optimum $E_{o,est}$ are indicated in Table 1, which also uses $E_{o,est}/E_s$ as a ratio to show how much reduction is needed from the current level. We have interpolated atmospheric dispersion results of ExternE (*1*) in order to estimate typical values of D_{est} for power plants in the respective countries (*21*). Note that the damage cost estimates of ExternE have been evolving over the years to take into account new scientific evidence, and the costs to be published soon will be somewhat lower, although the general conclusions of this paper will continue to hold.

The optimization is based on D_{est} but the true cost borne by society corresponds to the true damage $D_{true}E_{o,est}$:

$$C_{tot}(E_{o,est}) = C_{ab}(E_{o,est}) + D_{true}E_{o,est} \quad (7)$$

$C_{tot}(E_{o,est})$ increases on either side of the truly optimal emission level $E_{o,true}$.

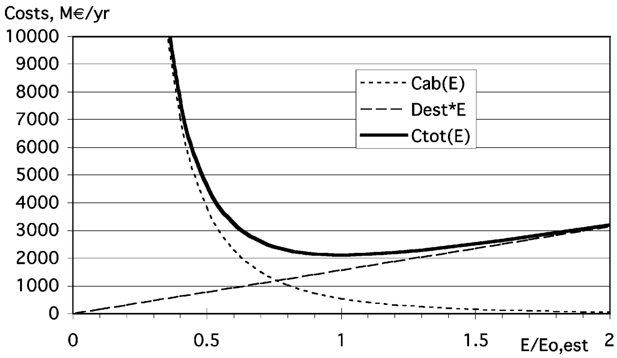

FIGURE 5. Abatement cost, damage cost, and total cost as function of the emission *E* (expressed as ratio $E/E_{o,est}$) for the example of SO_2 in France.

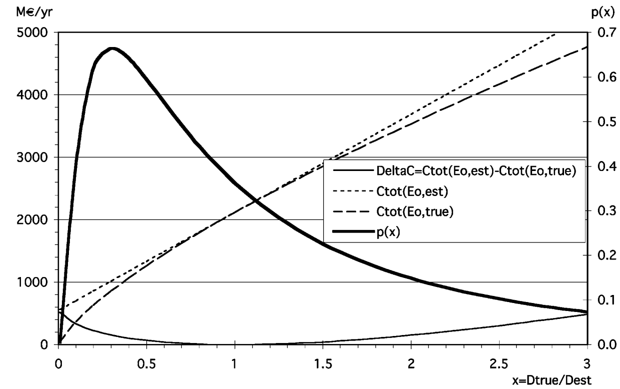

FIGURE 6. $C_{tot}(E_{o,est})$, $C_{tot}(E_{o,true})$ and $C_{tot}(E_{o,est}) - C_{tot}(E_{o,true})$ (all evaluated with the true damage cost D_{true}) as function of the ratio $x = D_{true}/D_{est}$ for SO_2 in France. Thick curve with right-hand axis shows log-normal probability distribution $p(x)$ with geometric mean $\mu_G = 1$ and geometric standard deviation $\sigma_G = 3$.

To evaluate the effect of errors in the optimization, Figure 6 shows $C_{tot}(E_{o,est})$, $C_{tot}(E_{o,true})$, and the cost penalty:

$$\Delta C = C_{tot}(E_{o,est}) - C_{tot}(E_{o,true}) \tag{8}$$

as function of the ratio

$$x = D_{true}/D_{est} \tag{9}$$

It is also instructive to plot the cost penalty ratio:

$$R = C_{tot}(E_{o,est})/C_{tot}(E_{o,true}) \tag{10}$$

as a function of x, both numerator and denominator being evaluated with the true damage cost D_{true}. If the true damage cost is very low, the optimal emission level of eq 6 would be higher than the current emission E_s. But since an increase of emissions above E_s is not an option, we consider that the abatement cost is 0 for $E_o > E_s$. After some algebra one finds

$$R = \frac{[(E_s - \beta)^{\gamma+1} - (D_{est}/\alpha)^{(\gamma+1)/\gamma}] + x(\gamma+1)(D_{est}/\alpha)[\beta + (D_{est}/\alpha)^{1/\gamma}]}{[(E_s - \beta)^{\gamma+1} - (xD_{est}/\alpha)^{(\gamma+1)/\gamma}] + x(\gamma+1)(D_{est}/\alpha)[\beta + (xD_{est}/\alpha)^{1/\gamma}]}$$
$$\text{if } D_{true} > x_{min}D_{est} = \alpha(E_s - \beta)^{\gamma} \tag{11}$$

and

$$R = \frac{[(E_s - \beta)^{\gamma+1} - (D_{est}/\alpha)^{(\gamma+1)/\gamma}] + x(\gamma+1)(D_{est}/\alpha)[\beta + (D_{est}/\alpha)^{1/\gamma}]}{x(\gamma+1)(D_{est}/\alpha)E_s}$$
$$\text{if } D_{true} < x_{min}D_{est} = \alpha(E_s - \beta)^{\gamma} \tag{12}$$

At $\gamma = -1$ the right-hand side is equal to unity regardless of x; however, a closer look at eq 4 shows that the total abatement cost C_{ab} is singular at $\gamma = -1$ and that eq 10 is not valid at this point. The correct form at $\gamma = -1$ is easy to determine and R is continuous, but we do not show that here. Figure 7 shows the cost penalty ratio R versus the error $x = D_{true}/D_{est}$ in the damage cost estimate.

The optimum is very broad: even if the damage cost is 3 times too large or too small, the cost penalty is less than about 20%. The reason the optimum of R is so broad can be understood by looking at Figure 6: both $C_{tot}(E_{o,est})$ and $C_{tot}(E_{o,true})$ increase strongly with x, but their difference is relatively small, implying that their ratio is relatively close to unity. Note that the cost curves have been obtained only for the emission range $[E_{min}, E_s]$ in Figure 4, and it is risky to extrapolate R beyond this range (i.e., to $x > x_{max} = D_{true,max}/D_{est}$ with $D_{true,max} = \alpha(E_{min} - \beta)^{\gamma}$. Therefore, we show the extrapolated portion of R as dashed lines in Figure 7. Finally Figure 8 shows how the optimal emission level varies with the error in the damage cost estimate for SO_2. For the other pollutants the shapes are similar.

We do not show analogous results for PM because it is a primary pollutant (harmful in the form in which it is emitted) and the incremental damage cost can vary by 1 or even 2 orders of magnitude depending on the site of the source and its height above the ground (*2, 3*). One would need abatement cost curves for each site and height, something that is not available.

Even though we have considered only the uncertainty of the damage cost, our results are equally applicable to uncertainties in abatement cost because the optimal emission level E_o of eq 6 depends on the ratio (D/α) of the damage cost and abatement cost parameters.

Dioxins. We show results for dioxins even though it is a primary pollutant. Since the ingestion dose is about 2 orders of magnitude larger than the inhalation dose and typical food intake comes from sites distributed over tens to thousands of kilometers. As a result the variation of the damage with emission site or stack height is negligible, as shown by Spadaro and Rabl (*15*). The damage cost for dioxin emissions to air in Europe has been estimated by Rabl and Spadaro (*14*). For abatement costs we use the data of ENTEC (*22*); they are shown in Figure 9 together with our curve fit. The ENTEC report also contains data for abatement "beyond business as usual measures", which we do not show because they turn out to lie entirely beyond the optimum according to our damage cost estimate, by contrast to the measures in Figure 9 for which further reduction is justified. The corresponding cost penalty ratio is shown in Figure 10. The optimum is remarkably broad: even for the very large uncertainties of the damage cost estimate (an order of magnitude in either direction), the cost penalty is less than 20% on the side of small x (true damage smaller than estimate) and less than 10% on the side of large x (true damage larger than estimate).

CO_2. Since so far relatively little effort has been put in actually reducing greenhouse gas emissions, in particular for CO_2, to obtain carbon dioxide marginal cost curves we must largely rely on calculations and modeling results as presented over recent years in the literature (see, for example, Weyant and Hill (*23*) and Reilly et al. (*24, 25*)). Marginal cost curve findings from modeling studies on global warming, to which anthropogenically produced CO_2 is the largest contributor, have been reported abundantly. Like the curves for NO_x and SO_2, they are based on major international assess-

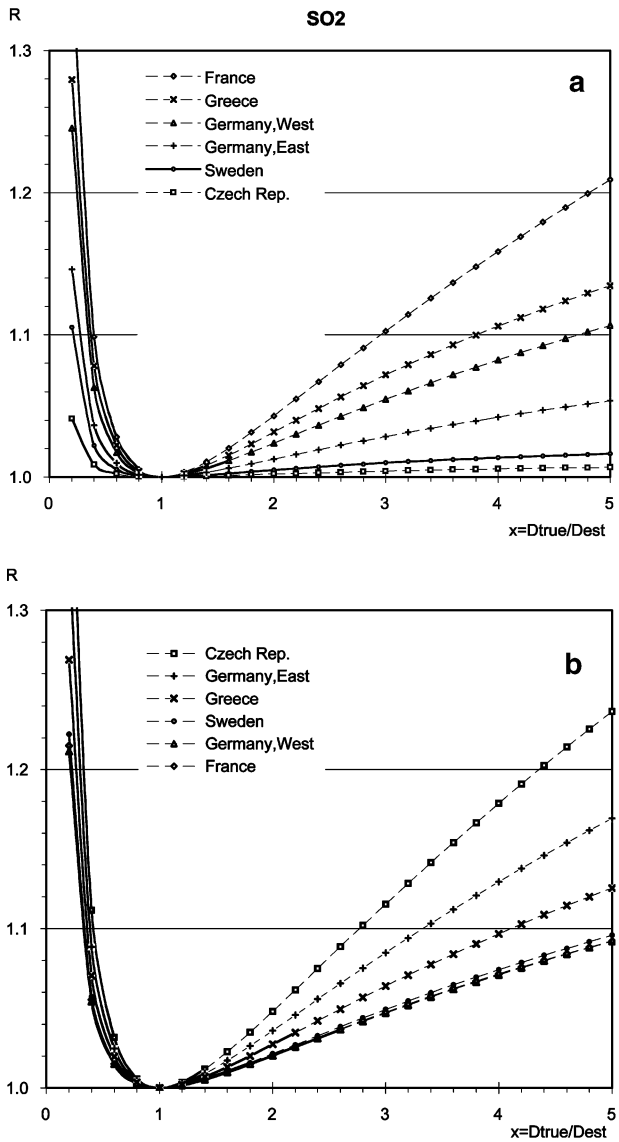

FIGURE 7. Cost penalty ratio R vs the error $x = D_{true}/D_{est}$ in the damage cost estimate for several countries, selected to show extremes as well as intermediate curves. The labels are placed in the same order as the curves. Dashed lines correspond to the extrapolated regions of the cost curves. (a) SO_2; (b) NO_x.

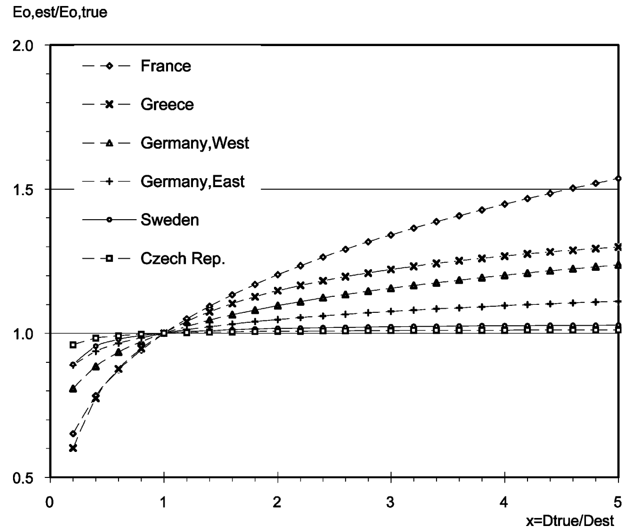

FIGURE 8. Error $E_{o,est}/E_{o,true}$ of the optimal emission level versus the error $x = D_{true}/D_{est}$ in the damage cost estimate for SO_2.

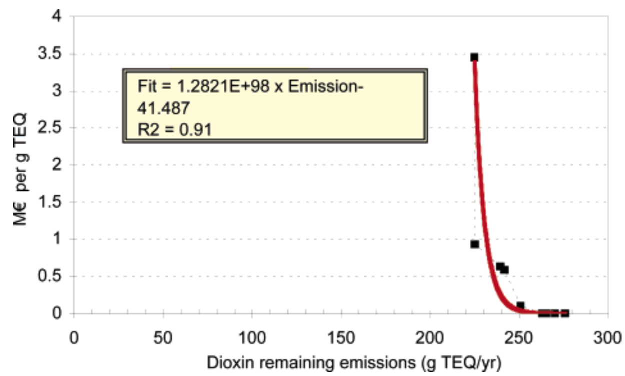

FIGURE 9. U.K. marginal abatement cost data of ENTEC (*22*) for dioxins together with curve fit. Business as usual measures (reference year 2000). TEQ = toxic equivalent 2,3,7,8-TCDD.

ments of cost data. The derived marginal cost curves involve large variations depending on the technique through which they have been obtained. While energy system 'bottom-up' models usually include a simulation of marginal abatement cost curves explicitly, economic 'top-down' models often involve such curves indirectly, for example through the modeling of a shadow price for carbon emissions that can be interpreted as the tax required to meet a certain temperature constraint. Especially in the latter case the cost curves are to a large extent determined by the specific features of the model under consideration, for example, by the way through which it simulates technological change, see van der Zwaan et al. (*26*).

Figure 11 depicts 8 cases of marginal cost dependencies covering the wide range of cost curve results as obtained through different methods employed in the literature (the curves displayed do not include phenomena such as "co-benefits"). The curves have been obtained through a variation of the parameters as in eq 3 in such a way as to obtain realistic cost evolutions (but different for the 8 chosen cases to reflect varying findings from different authors). Instead of looking at individual EU countries—which is possible when empirical and more detailed data are available, as shown for the other pollutants in this paper—we consider Europe as a whole, and inspect different possible future marginal cost patterns. The region includes the current EU plus a number of neighboring countries (some of which are currently candidate members for near-future accession to the EU). [In addition to the 25 current EU member states, countries such as Bulgaria, Croatia, Iceland, Norway, Romania, Switzerland, and Ukraine (but not Russia) are included in this area.] This region represents today some 5000 Mt of CO_2/yr of carbon dioxide emissions. [Note that this number is approximate only, presently increasing over time, and depends on the inventory framework used to account for CO_2 emissions from different sources.]

We assume that at 5000 Mt of CO_2/yr the marginal abatement cost is close to zero since at current emission levels various options abound through which carbon reductions can be achieved at relatively low costs. Only when emissions are reduced to a level of 4000 Mt of CO_2/yr do we assume that significant costs are incurred (for which reason it matters only moderately what the precise level of carbon emissions actually is today). Different estimates are made for marginal abatement costs for the point at which a level of 4000 Mt of CO_2/yr is reached and onward, down to 1000

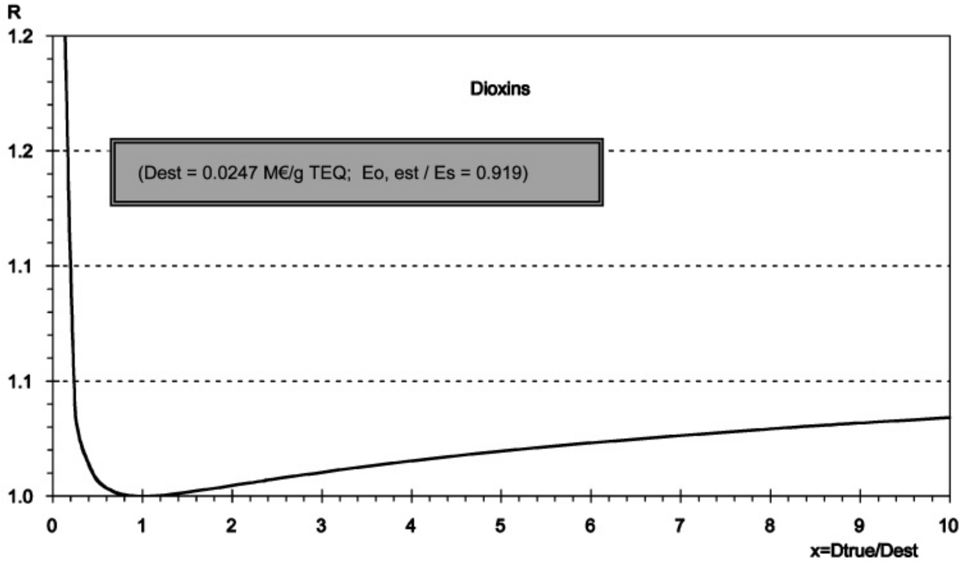

FIGURE 10. Cost penalty ratio R vs error $x = D_{true}/D_{est}$ in the damage cost estimate for dioxins.

TABLE 2. Coefficients α, β, and γ of Eq 3 for the Curves in Figure 11, Current Emission Level E_s, Estimated Marginal Damage Cost (D_{est}), and Optimal Emission $E_{o,est}$ for D_{est} (as Fraction of E_s)[a]

CO_2	MAC_{4000}	MAC_{1000}	α	β	γ	E_s	D_{est}	$E_{o,est}/E_s$
case 1	17	310	1.6E+11	8E+8	−1.05	5E+9	19	0.73
case 2	11	240	3.2E+11	8E+8	−1.1	5E+9	19	0.55
case 3	5	140	1.3E+12	8E+8	−1.2	5E+9	19	0.37
case 4	2	80	5.1E+12	8E+8	−1.3	5E+9	19	0.28
case 5	16	200	1.6E+11	7E+8	−1.05	5E+9	19	0.71
case 6	17	640	1.6E+11	9E+8	−1.05	5E+9	19	0.75
case 7	8	150	8.0E+10	8E+8	−1.05	5E+9	19	0.45
case 8	33	610	3.2E+11	8E+8	−1.05	5E+9	19	1.26

[a] The units are t_{CO_2}/yr for E and Euro/t_{CO_2} for D. MAC = marginal abatement cost.

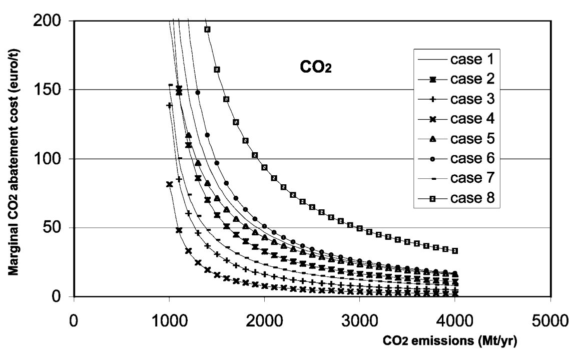

FIGURE 11. Future marginal abatement cost curves for CO_2 reduction efforts for Europe.

Mt of CO_2/yr. The 8 different cases depicted include start-off abatement costs of only a couple Euro/t_{CO2} to over 30 Euro/t_{CO_2} (values that are typically encountered in the literature for the current costs of abatement or for the value of avoiding emissions, were a carbon emission policy introduced today) (irrespective of whether, for example, through a carbon tax or a trade of permits). These values increase (at different rates for different cases) when lower carbon emission values are reached, supposedly to values varying from at least 80 Euro/t_{CO_2} to numbers of a few (or even several) hundreds of Euro/t_{CO_2}. The 8 cases are chosen such as to cover a large variety of possibilities of how marginal carbon dioxide abatement costs could eventually materialize.

The parameters α, β, and γ to obtain these curves, for all 8 cases, are given in Table 2. This table also depicts the marginal abatement cost at a carbon emission level of 4000 Mt/yr (MAC_{4000}) and at a level of 1000 Mt/yr (MAC_{1000}), as well as the estimated marginal damage cost D_{est} and the optimal emission $E_{o,est}$ for D_{est} (as a fraction of E_s). For D_{est} we take 19 Euro/t_{CO_2} in all 8 cases, based on the latest recommendations of ExternE (*3*); it is equal to the cost of implementing the Kyoto protocol in the EU. The variability of the $E_{o,est}/E_s$ ratio proves to be as high as in the cases of SO_2 and NO_x (see Table 1).

Two additional tests are investigated (cases 9 and 10) in which the damage cost is assumed to be a factor of 10 higher or lower, respectively, than the value of 19 Euro/t_{CO_2} as stated in Table 2. These tests are performed around the parameter values of case 3, since we consider this a "central" scenario, with relatively low start-off values for the marginal abatement costs and with high but not excessive abatement costs when low carbon emission values are reached, given that technological change may well allow for savings precluding costs as high as several hundreds of Euro/t_{CO_2}. For all 10 cases, Figure 12 shows our findings on the cost penalty ratio R versus the error $x = D_{true}/D_{est}$ in the damage cost estimate. Note that the curves for case 8 and for case 3, 1.9 Euro/t_{CO_2} are not very meaningful because the optimal emission level is above the current 5000 Mt/yr.

As for the variation of the optimal emission level with the error in the damage cost estimate, it is similar to our findings for SO_2 and NO_x and is therefore not shown here.

TABLE 3. Expectation Value $R_{exp} - 1$ of Cost Penalty for Several Cases[a]

SO_2		NO_x		CO_2[b]		
	$\sigma_G = 3$		$\sigma_G = 3$		$\sigma_G = 5$	$\sigma_G = 10$
Czech Rep.	0.011 (*b*)	France	0.077 (0.057)	case 3, 190 Euro/t	0.19	0.94
W. Germany	0.090 (0.066)	Greece	0.099 (0.072)	case 3, 19 Euro/t	0.74	3.48
France	0.140 (0.09)	Czech Rep.	0.167 (0.112)	case 4, 19 Euro/t	0.48	2.39

[a] For SO_2 and NO_x, the numbers in parentheses indicate the contribution to R_{exp} between $x = 0$ and $x = x_{max}$. [b] Since the curve fit is meaningless for $E < \beta$, we have truncated the x integration for all cases with $\beta > 0$ by setting integrand = 0 for all x above the value corresponding to $E_{min} = \beta$.

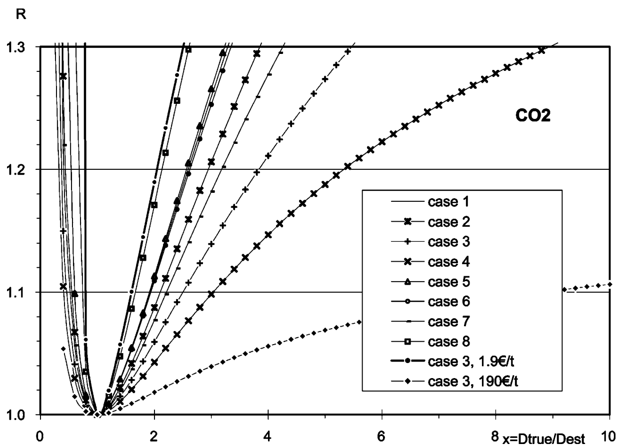

FIGURE 12. Cost penalty ratio R vs the error $x = D_{true}/D_{est}$ in the damage cost estimate for CO_2. D_{est} = 19 Euro/t for cases 1−8.

Expectation Value of Cost Penalty and Value of Information

The different points of the cost penalty curves have different probabilities. The expectation value of the cost penalty ratio is

$$R_{exp} = \int_0^{\infty} R(D_{true})p(D_{true})\mathrm{d}D_{true} \tag{13}$$

where $p(D_{true})$ is the probability distribution of the true marginal damage cost for which we assume a log-normal distribution with geometric standard deviation σ_G. Numerical results for several representative cases are shown as $R_{exp} - 1$ in Table 3. The selected cases are the low, intermediate and high curves of R versus x (except for case 3, 1.9 Euro/t_{CO_2} whose optimum would be above E_s). Since the extrapolation of the cost curves for NO_x and SO_2 below E_{min} (corresponding to $x > x_{max}$) is uncertain, we indicate in parentheses the contribution of the integral from $x = 0$ to $x = x_{max}$. For CO_2 the uncertainties are larger, and even the estimation of σ_G is problematic; therefore, we show $R_{exp} - 1$ for $\sigma_G = 5$ and $\sigma_G = 10$.

The expectation value of R does not directly indicate the cost because both numerator and denominator change with x. Therefore, we also evaluate the expectation value of the cost penalty difference $\Delta C = C_{tot}(E_{o,est}) - C_{tot}(E_{o,true})$:

$$\Delta C_{exp} = \int_0^{\infty} \Delta C(D_{true})p(D_{true})\,\mathrm{d}D_{true} \tag{14}$$

It is especially interesting to plot ΔC_{exp} as a function of σ_G because such a graph shows the value of further research to improve the available information on abatement and damage costs. Figure 13 shows some examples selected to correspond to intermediate curves of the cost penalty ratio R. Since these graphs show the cost penalty per year, one has to multiply by the discounted lifetime of the abatement technologies, on the order of 20 yr, to obtain the total value of information.

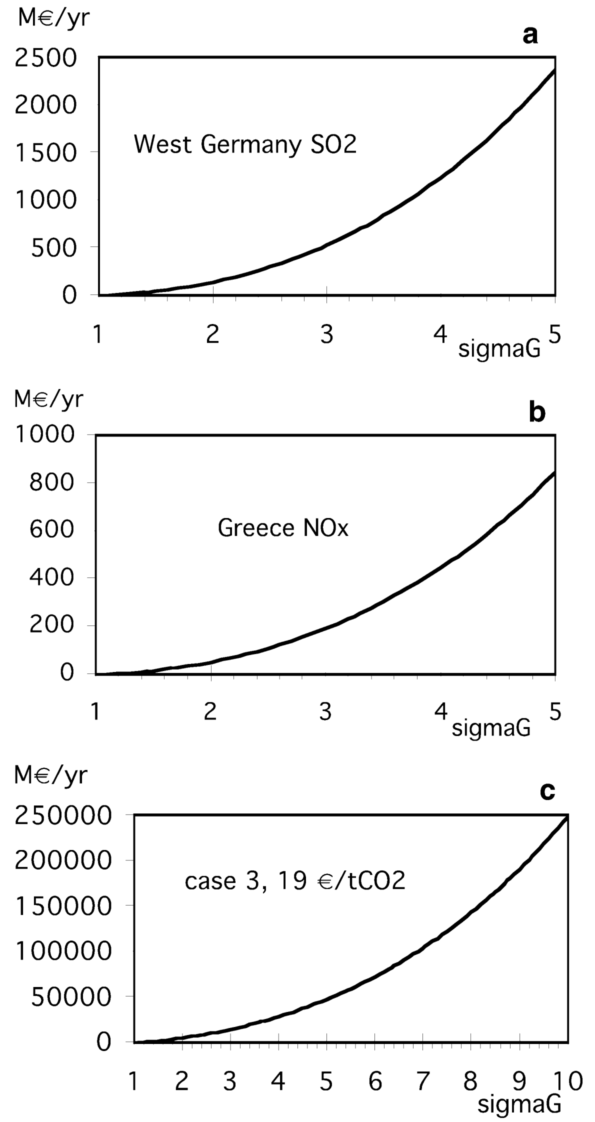

FIGURE 13. Expectation value ΔC_{exp} of the annual cost penalty difference vs σ_G for (a) SO_2 abatement in West Germany, (b) NO_x abatement in Greece, and (c) CO_2 abatement for case 3. Lifetime cost is annual cost times discounted lifetime, on the order of 20 yr.

Discussion

We have focused on uncertainties of damage costs, but one should not forget that abatement costs are also uncertain. To the extent that the uncertainties of the latter are represented by uncertainties in the coefficient α, the effect is the same as for uncertainties of the damage cost D, because the optimal emission level of eq 6 is a function of the ratio (D/α). For that reason we do not show separate results.

Having evaluated, for several examples of discrete and continuous choices, the cost penalty to society if one makes the wrong choice because of errors or uncertainties in the cost or benefit estimates, what general conclusions can be drawn?

For continuous choices, we have found a remarkable insensitivity to uncertainties. For NO_x and SO_2 an error by a factor of 3 increases the total social cost by at most 20% and in most cases much less. For dioxins and for CO_2 the uncertainties of the damage cost are even larger than in the case of NO_x and SO_2, easily an order of magnitude in either direction. However, the shape of the abatement cost curve for dioxins is such that the tolerance to errors is even greater than in the case of NO_x and SO_2. For CO_2 some of the curves imply somewhat greater sensitivity to uncertainties, but even here the penalty is less than 30%, and in most case much less if the true damage costs are twice as high as the ones estimated.

We do not know how general the large tolerance to uncertainties is; each case could be different and may have to be analyzed with specific data. Nonetheless, the examples we have found span a sufficiently wide range to suggest that a large tolerance to uncertainties may be the rule rather than the exception, also for other types of pollution. Unfortunately that is difficult to verify because the necessary abatement cost curves are generally not available. To see what characteristics of the cost curves determine the sensitivity to uncertainties, it is instructive to expand the cost penalty ratio R of eq 10 in powers of $(x - 1)$ around $x = 1$, where $x = D_{true}/D_{est}$. Keeping terms up to the second power one finds:

$$R = \frac{1}{1 - \dfrac{(1 - x)^2 {D_{est}}^2}{2[C_{ab}(E_{o,est}) + xD_{est}E_{o,est}]C_{ab}''(E_{o,est})}} \qquad (15)$$

The variation with x is small near $x = 1$ (i.e., low sensitivity to uncertainties) if $C_{ab}(E)$ and/or its second derivative, evaluated at the estimated optimal emission level $E_{o,est}$, are large as compared to the estimated marginal damage cost D_{est}.

For discrete choices there is a cost penalty only if the wrong choice is made. Sometimes the difference between cost and benefit is larger than the uncertainties, and a robust conclusion can be drawn. But there is no general conclusion for discrete choices. Nonetheless, this lack of a general conclusion for discrete choices is less limiting than it might appear. Most discrete choices are either intrinsically continuous and should be formulated as such (see the discussion of emission limits for power plants in the Introduction), or else they concern specific local situations, for example, the decision whether to install improved pollution control in a particular waste incinerator. The latter type of discrete choice is not made in isolation but in the context of regulations that affect all similar installation an entire country or region. Thus, it is really just a particular implementation of a continuous choice.

The analysis of this paper also provides information on the value of information in this domain. By plotting the expectation value of the cost penalty versus the geometric standard deviation, as we have done for several examples, one can quantify the benefit of improving the accuracy of cost estimates by further research.

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