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Original Article

Economic valuation of the mortality benefits of a regulation on SO_2 in 20 European cities

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Background: Since the 1970s, legislation has led to progress in tackling several air pollutants. We quantify the annual monetary benefits resulting from reductions in mortality from the year 2000 onwards following the implementation of three European Commission regulations to reduce the sulphur content in liquid fuels for vehicles. **Methods**: We first compute premature deaths attributable to these implementations for 20 European cities in the Aphekom project by using a two-stage health impact assessment method. We then justify our choice to only consider mortality effects as short-term effects. We rely on European studies when selecting the central value of a life-year estimate (€$_{2005}$ 86 600) used to compute the monetary benefits for each of the cities. We also conduct an independent sensitivity analysis as well as an integrated uncertainty analysis that simultaneously accounts for uncertainties concerning epidemiology and economic valuation. **Results**: The implementation of these regulations is estimated to have postponed 2212 (95% confidence interval: 772–3663) deaths per year attributable to reductions in sulphur dioxide for the 20 European cities, from the year 2000 onwards. We obtained annual mortality benefits related to the implementation of the European regulation on sulphur dioxide of €$_{2005}$ 191.6 million (95% confidence interval: €$_{2005}$ 66.9–€$_{2005}$ 317.2). **Conclusion**: Our approach is conservative in restricting to mortality effects and to short-term benefits only, thus only providing the lower-bound estimate. Our findings underline the health and monetary benefits to be obtained from implementing effective European policies on air pollution and ensuring compliance with them over time.

Introduction

Since the 1970s, air quality has been one of the European Union's major areas of activity. Legislation has led to progress in tackling several air pollutants, including sulphur dioxide (SO_2), lead, nitrogen oxide, carbon monoxide and benzene.[1] However, other pollutants such as ozone and particulate matter (PM) still require attention.

Reductions in air pollutant levels have long been acknowledged to lead to health benefits including reductions in the number of medical consultations and hospital admissions for respiratory and cardiovascular diseases, and of premature deaths.[2,3] Therefore, assessing the effectiveness of past regulations in terms of both health impacts and avoided health care costs should provide useful input to future regulations. Intervention studies constitute a relevant way to check and help validate results obtained in non-intervention studies, by focusing on the cause–effect relationship involved. In addition, they limit the confounding of issues with respect to other study designs by providing an exogenous change in exposure.[4,5]

A recent review of air pollution interventions reported consistent evidence that improved air quality following an intervention resulted in public health improvements.[6] Almost all intervention studies assessing changes in SO_2 and changes in health outcomes (such as a US nationwide copper smelter strike in the 1960s,[7] the 1990 Irish coal ban,[8] a 1990 regulation restricting the sulphur content of fuel in Hong Kong[9] or control regulations during the 2008 Beijing Summer Olympic Games[10]) demonstrate beneficial health effects from reducing SO_2 emissions in terms of mortality, asthma visits and cardio-respiratory hospital admissions.

Once the health benefits of an intervention study are estimated, the economic benefits can be assessed and used in cost–benefit analyses. Li *et al.*,[11] for instance, quantified the health benefits of curbing air pollution in Shanghai for two strategies aiming at lowering PM_{10} and compared them with the investment costs. They showed that the benefit-to-cost ratios exceed one in both cases (1–5 for the power-sector strategy and 2–15 for the industrial-sector strategy). Chestnut and Mills[12] reconsidered the US Acid Rain Program (Title IV of the 1990 Clean Air Act Amendments) costs and benefits, providing updated estimates of the health benefits. Controlling SO_2 and nitrogen oxide emissions led to total health and environmental benefits of more than US$100 billion annually in 2010, whereas costs were estimated at US$3 billion annually.

This paper focuses on the quantification of the monetary benefits resulting from reductions in mortality following the implementation of the European regulation to reduce the sulphur content in liquid fuels. Indeed, European Council (EC) Directive 75/116/EEC limited the sulphur compound content in gas oil to 0.3% by weight (and 0.5% in zones where SO_2 was sufficiently low or insignificantly coming from gas oil) as of 1 October 1980.[13] Then, EC Directive 93/12/EEC introduced a regulation for the SO_2 content permitted in certain gas oils and diesel fuels, excluding member states seeking derogation[14]: 0.2% by weight as of 1 October 1994 and 0.05% by weight as of 1 October 1996. The maximum sulphur content of certain gas oil fuels for vehicles was further reduced by EC Directive 98/70/EC to 0.035% for diesel fuels and 0.015% for petrol as of 1 January 2000.[15] Council Directive 99/32/EC extended the 93/12/EEC Directive to cover certain liquid fuels derived from petroleum and used by seagoing ships[16] and specifies the following as the permitted maximum SO_2 content: 0.2% by mass as of 1 July 2000 and 0.1% by mass as of 1 January 2008.

Our study used data from 20 cities included in the Aphekom (Improving Knowledge and Communication for Decision Making on Air Pollution and Health in Europe) project, a research programme involving 60 scientists from 12 countries across Europe. Aphekom's objective was to provide new information and tools to enable decision-makers to set more effective European, national and local policies. To this end, it used traditional health impact assessment (HIA) techniques as well as innovative methods to explore the impact of air pollution on health in 25 European cities totalling nearly 39 million inhabitants.

Methods

Background

Because the implementation dates for the EC directives on SO_2 were 1994 (first stage), 1996 (second stage) and 2000 (third stage), city-specific daily data on urban background (UB) SO_2 concentrations, temperature and humidity measures and numbers of deaths [all-cause excluding external causes (ICD9: <800)] from 1990 to 2008 were collected using common guidelines based on the Apheis project.[17] Five cities were excluded due to missing data, leaving 20 cities from 11 countries in the analysis (see list in table 1).

However, not all countries complied with the implementation dates as specified in the council directives, because of local derogations for instance. Hence, the number of stages implemented and their corresponding implementation dates were not the same for every city. The following 14 cities implemented all three stages of the council directives: Athens, Bordeaux, Brussels, Dublin, Le Havre, Lille, London, Lyon, Marseille, Paris, Rome, Rouen, Stockholm and Strasbourg. The other six cities (Barcelona, Bilbao, Budapest, Ljubljana, Toulouse and Vienna) only applied the last implementation stage, namely, Council Directive 99/32/EC. Our analysis assesses the number of deaths from year 2000 onwards (after third implementation stage) compared with the pre-1993 period in all 20 cities. The impacts of each of the three implementation stages on respiratory (ICD9: 460–519), cardiovascular (ICD9: 390–459) and total (ICD9: [lt]800) mortality across the 20 cities have been reported in another study.[4]

Table 1 UB SO_2 mean and standard deviation (SD) concentration and number of attributable premature deaths for the 20 EU cities (upper and lower 95% CI bounds)

City	UB SO_2 [μgm^{-3}]		Attributable premature deaths		
	Mean SO_2	SD of SO_2	Number of cases	95 CI−	95 CI+
Athens (Greece)	38.97	26.96	507	177	842
Barcelona (Spain)	5.23	5.94	35	12	58
Bilbao (Spain)	17.46	7.19	14	5	24
Bordeaux (France)	7.22	5.06	18	6	29
Brussels (Belgium)	10.04	8.73	54	19	90
Budapest (Hungary)	29.07	19.56	390	136	647
Dublin (Ireland)	19.56	11.07	37	13	61
Le Havre (France)	23.38	28.26	23	8	38
Lille (France)	13.86	14.78	96	34	159
Ljubljana (Slovenia)	8.19	6.32	31	11	52
London (UK)	18.72	23.71	240	84	396
Lyon (France)	11.63	14.75	62	22	103
Marseille (France)	13.48	9.08	66	23	108
Paris (France)	12.16	10.88	314	110	519
Rome (Italy)	9.76	7.81	115	40	191
Rouen (France)	17.21	15.76	46	16	76
Stockholm (Sweden)	4.31	3.28	20	7	33
Strasbourg (France)	11.48	9.56	19	7	31
Toulouse (France)	21.67	15.85	35	12	58
Vienna (Austria)	8.92	11.70	90	31	148
Total	–	–	2212	772	3663

Computation of attributable premature deaths

We used a two-stage hierarchical modelling approach to assess the mortality impact of the regulation up to implementation of the third stage. In the first stage, data of each city were analysed separately, whereas in the second stage, evidence across cities was combined using meta-regression techniques. Briefly, for the first stage, city-specific estimates were estimated from a Poisson regression model linking mortality to UB SO_2, adjusting for temperature, day of the week, seasonality and time trend. Generalized additive models[18] were used to control potential non-linearity between confounders and mortality. The exposure variable used for UB SO_2 was the average of lags 1 and 2 (i.e. 1 and 2 days prior to the mortality event).[4] Additionally, dummy variables and their interaction with UB SO_2 were included in the model, depending on when council directives were successfully implemented in each city. The second stage of the modelling approach was designed to pool the city-specific estimates of air pollution effects on health, using meta-regression techniques.

SO_2 effects on mortality in each city were combined in a meta-analysis based on generalized least squares to provide overall estimates. Variables representing potential effect modifiers (yearly means of SO_2, PM_{10} and temperature) were included in the second-step regression models to account for city heterogeneity. Details on the whole methodology have been previously published,[19] and models were run using R statistical software.[20]

The combined estimate of SO_2 effect on mortality was then used in the HIA to estimate the attributable number of premature deaths (table 1).

Monetary assessment

Special features of the monetary assessment

By reducing UB SO_2 levels in the 20 cities, the regulation has two potential effects on mortality: short-term and long-term.

For acute (or short-term, ST) mortality effects, the number of premature deaths avoided is generally computed through time-series analyses and proportional hazard models. The gains in life expectancy corresponding to each of these premature deaths can be considered to be in the range of a few months, certainly lower than 1 year.[21]

For chronic (or long-term, LT) mortality effects, the number of premature deaths avoided is generally obtained via cohort studies that monitor populations exposed to different levels of pollution. One of the crucial issues is the magnitude of the gain in life expectancy related to these premature deaths. Although no definitive answer exists, a 10-year gain seems to be supported by three types of evidence: medical, epidemiological and empirical from past practice.[21–24]

Depending on whether the mortality effects are acute or chronic, there are two possible ways to deal with the time that elapses between a reduction in air pollution exposure due to the implementation of a regulation and the achievement of full health benefits.

In the 'steady-state' approach, the mortality effects corresponding to two different levels of air pollution are assessed and the number of premature deaths attributed to a change in air pollution exposure is computed as the difference between the numbers of premature deaths resulting from the respective steady states. This clear, simple and informative approach is accurate for acute (or ST) mortality effects, and provides an idea of the magnitude of the public health problem for chronic (or LT) health effects.

In the 'marginal (benefit)' approach, the impact of a reduction in today's air pollution exposure on the future flow of mortality effects is estimated. Reducing air pollution exposure via the implementation of a regulation in a given year does not produce all its chronic (or LT) effects in the same year because these effects are cumulative.[25–28] This approach is appropriate for cost–benefit analysis where chronic mortality effects are involved: the flow of discounted future benefits can be properly compared with the costs of the policy that generates these benefits.

Although the two approaches are similar for acute (ST) mortality effects, they differ for chronic (LT) mortality effects due to the latency period before the achievement of full mortality benefits and the additional impact of discounting future monetary benefits. In this paper, we consider mortality effects as ST effects only because the health data analysis relies on time-series studies and not on cohort studies. Because it takes a conservative standpoint, the economic evaluation thus constitutes a lower bound of the mortality effects of the regulation.

Economic values chosen

The valuation of mortality effects follows the standard valuation procedure adopted in ExternE,[29] New-Ext[30] or CAFE,[31] which consists in using monetary values derived from stated preferences' surveys, hence relying on preference-derived rather than market-derived values. However, the choice of a proper economic value is crucial because the gain in life expectancy related to a prevented premature death differs according to whether it concerns those affected by chronic or by acute effects (see previous text). Given that we consider ST effects only, the gain in life expectancy associated with each of the premature deaths is assumed to be 'around 1 year',[21] so a value of a life year (VOLY) was chosen here instead of a value of a statistical life.

Because the regulation effects are assessed in European cities, we relied on European studies when selecting the VOLY. To allow for the uncertainty pertaining in the economic valuation, we use a low, a central and a high estimate of a VOLY. First, for the low estimate, we take the recent results from the New Energy Externalities Developments for Sustainability (NEEDS) program[31] (based on a 3-month life expectancy gain with protesters and outliers deleted) conducted in 10 European countries: $€_{2005}$ 40 000. Then, for the high estimate, we choose $€_{2005}$ 133 200, the mean VOLY (annual change 5:10 000 scenario) obtained in a study representative of the European population, undertaken for the EC DG Research-funded New-Ext[30] project and used in CAFE cost–benefit analysis.[21] Finally, the arithmetic mean of high and low values provides the central VOLY estimate: $€_{2005}$ 86 600.

Note that in the absence of reliable country-specific VOLY, the valuation of mortality uses one common VOLY for all cities, because we consider it to be ethically unacceptable to account for differences across countries by ex-post wealth adjustments. Adjusting by gross domestic product per capita, for instance, would lead to a fourfold lower VOLY in Budapest than in Dublin.[32]

Results

Results on SO_2 trends

Figure 1 shows a plot of yearly UB SO_2 averages for 12 Aphekom cities from 1990 to 2004 (see Henschel *et al.*[33] for a detailed analysis of the hourly SO_2 pollution patterns for six of the cities). There is no clear step change in UB SO_2 concentrations after implementation of the directives; rather, a gradual decline in SO_2 levels is observed. The decreasing levels over time are probably driven by the successful implementation of various national and international regulations, including the protocols under the Convention on Long-range Transboundary Air Pollution,[34] the installation of flue gas desulphurization units at power plants and political and economic reforms in Eastern European countries, as well as reductions in the sulphur content in fuel oil.[35] The increase in SO_2 levels in Athens in 2002 and 2003 is mainly related to unfavourable winter conditions but not to structural changes in the sources of emissions. Moreover, rational behaviour in anticipation of an increase in the cost of a tonne of SO_2 (due to desulphurization) may have led some major users of sulphurized fuel before 1994 to switch to natural gas prior to the implementation of the regulation.

Results on HIA

Inference by eye[36] did not provide evidence of changes in the slope of the SO_2–mortality dose–response curve after implementation of the different legislations: 0.62 (95% CI: 0.3–0.95) before 1994, 0.71 (95% CI: 0.01–1.4) between 1994 and 1996, 0.64 (95% CI: 0.09–1.19) between 1996 and 2000 and 1.16 (95% CI: −0.67 to 3.02) after 2000. This is not altogether unexpected because it is consistent with a linear dose–response curve down to very low concentrations. Over the study period, a decrease of $10\,\mu gm^{-3}$ in UB SO_2 levels was associated with a (pooled) decrease in daily all-cause mortality of 0.53% (95% CI: 0.18–0.83). These findings were broadly comparable with results from the APHEA multi-city study in Europe: Katsouyanni *et al.*[37] found that an increase of $50\,\mu gm^{-3}$ in SO_2 was associated with an approximate increase of 3% for all-cause mortality.

Applying the two-stage approach to city-specific mortality incidence and SO_2 level increases from pre- to post-intervention period, the HIA analysis of the mortality data suggests an overall 2212 (95% CI: 772–3663) premature deaths avoided per year associated with decreases in SO_2 for 20 cities from year 2000 onwards (after third implementation stage) compared with the pre-1993 period (see column labelled 'Attributable premature deaths' in table 1 for results by city with the corresponding 95% CI). The lowest number of postponed deaths attributable to the regulation is obtained in Bilbao (14) and the highest in Athens (507).

Mortality benefits

Results and sensitivity analysis

Based on the number of premature deaths computed in table 1 and the central estimate associated with a premature death avoided (€86 600), the annual economic benefit related to the implementation of the EC regulations on SO_2 amounts to €191.6 million (95% CI: €66.9 million–€317.2 million). The detailed results as well as the upper and lower 95% CI bounds for each city are given in table 2. Bilbao obtains the lowest annual economic benefits, with €1.2 million (95% CI: €0.4 million–€2.1 million), and Athens obtains the highest, with €43.9 million (95% CI: €15.3 million–€72.9 million).

We perform a sensitivity analysis specific to the economic valuation by applying the low (€40 000) and high (€133 200) estimates of the VOLY to the number of premature deaths provided by the epidemiological computations. Results are presented in table 2 and represent a range of monetary benefits (low and high) for the number of premature deaths as well as for the related upper and lower 95% CI bounds.

Uncertainty analysis

Uncertainty analysis simultaneously accounts for uncertainties concerning epidemiology and economic valuation through an integrated approach. The results of the HIA and the economic values are treated as random variables with specified distributions of probability. Monte Carlo simulations are used to propagate the

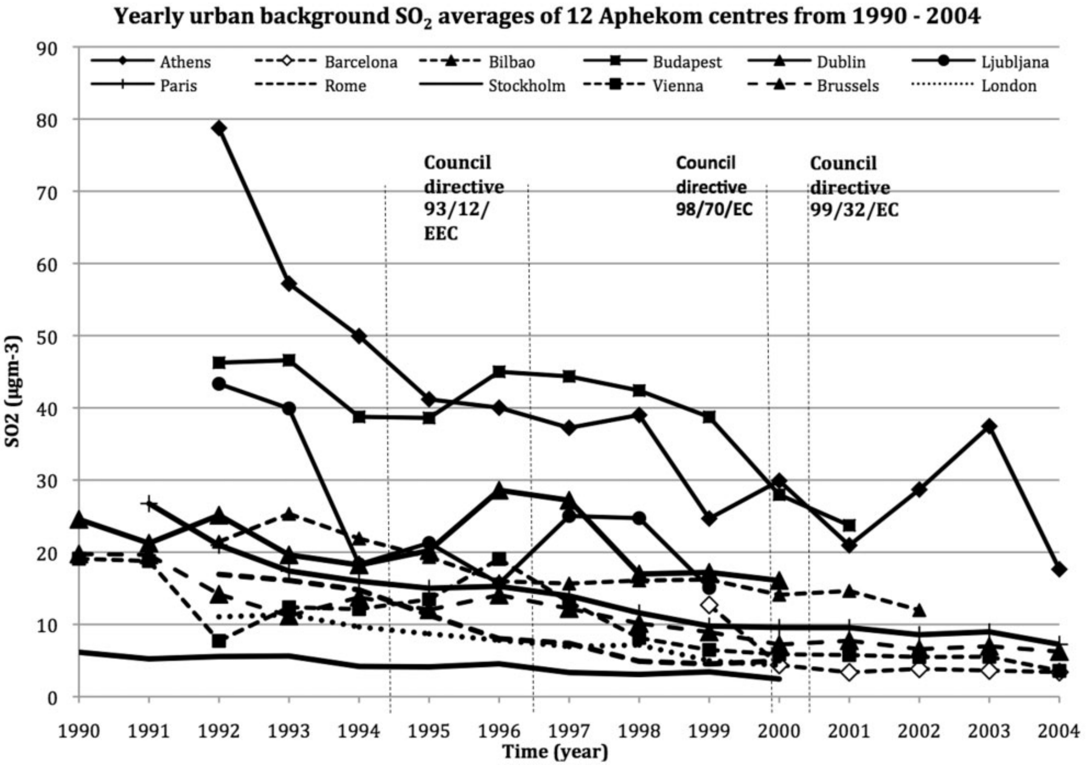

Figure 1 Plot of yearly UB SO_2 averages of 12 Aphekom cities* from 1990 to 2004 (*of the nine French cities involved in the project, only Paris is included here)

Table 2 Annual monetary benefits for the 20 EU from 2000 onwards compared with the pre-1993 period (central, low and high estimates of the number of premature deaths and of the upper and lower 95% CI bounds)

City	Monetary valuation (million € 2005)								
	Central estimate (VOLY = €86 600)			Low estimate (VOLY = €40 000)			High estimate (VOLY = €133 200)		
	Benefits	95 CI−	95 CI+	Benefits	95 CI−	95 CI+	Benefits	95 CI−	95 CI+
Athens	43.9	15.3	72.9	20.3	7.1	33.7	67.5	23.6	112.2
Barcelona	3.0	1.0	5.0	1.4	0.5	2.3	4.7	1.6	7.7
Bilbao	1.2	0.4	2.1	0.6	0.2	1.0	1.9	0.7	3.2
Bordeaux	1.6	0.5	2.5	0.7	0.2	1.2	2.4	0.8	3.9
Brussels	4.7	1.6	7.8	2.2	0.8	3.6	7.2	2.5	12.0
Budapest	33.8	11.8	56.0	15.6	5.4	25.9	51.9	18.1	86.2
Dublin	3.2	1.1	5.3	1.5	0.5	2.4	4.9	1.7	8.1
Le Havre	2.0	0.7	3.3	0.9	0.3	1.5	3.1	1.1	5.1
Lille	8.3	2.9	13.8	3.8	1.4	6.4	12.8	4.5	21.2
Ljubljana	2.7	1.0	4.5	1.2	0.4	2.1	4.1	1.5	6.9
London	20.8	7.3	34.3	9.6	3.4	15.8	32.0	11.2	52.7
Lyon	5.4	1.9	8.9	2.5	0.9	4.1	8.3	2.9	13.7
Marseille	5.7	2.0	9.4	2.6	0.9	4.3	8.8	3.1	14.4
Paris	27.2	9.5	44.9	12.6	4.4	20.8	41.8	14.7	69.1
Rome	10.0	3.5	16.5	4.6	1.6	7.6	15.3	5.3	25.4
Rouen	4.0	1.4	6.6	1.8	0.6	3.0	6.1	2.1	10.1
Stockholm	1.7	0.6	2.9	0.8	0.3	1.3	2.7	0.9	4.4
Strasbourg	1.6	0.6	2.7	0.8	0.3	1.2	2.5	0.9	4.1
Toulouse	3.0	1.0	5.0	1.4	0.5	2.3	4.7	1.6	7.7
Vienna	7.8	2.7	12.8	3.6	1.2	5.9	12.0	4.1	19.7
Total	191.6	66.9	317.2	88.5	30.9	146.5	294.6	102.8	487.9

uncertainty in the numbers of premature deaths and the VOLY, by drawing random samples from the distributions. Each draw generates an estimate of the annual monetary benefits, and a sufficient number of draws makes it possible to characterize the distribution of these monetary benefits.[38]

A normal distribution is used to characterize the spread of the mortality data, defined in terms of its mean and standard deviation. This choice relies on the assumptions and data obtained by the HIA. A triangular distribution is used for the VOLY, defined in terms of a modal central value, a maximum and a minimum. The triangular distribution is typically used when knowledge of the variable is more subjective than objective.

Once these probability distributions are defined, the model is run using 10 000 Monte Carlo samples and provides probabilized

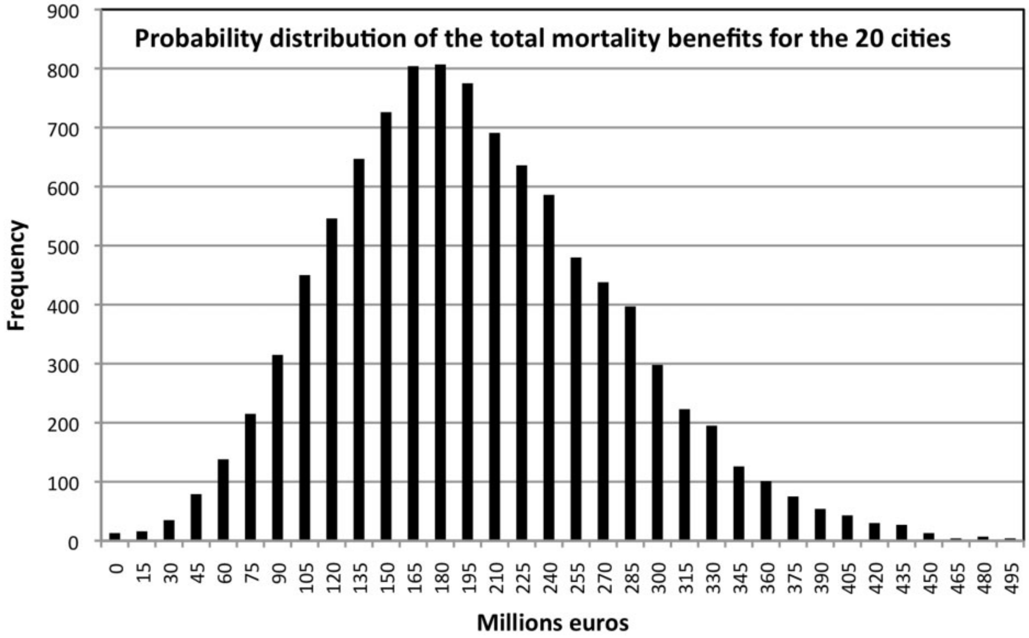

Figure 2 Probability distribution of the annual monetary benefits for the 20 EU cities (generated from Monte Carlo sampling over 10 000 iterations)

distributions of the product of the annual number of postponed deaths and the VOLY, representing the annual mortality benefits. Figure 2 shows the distribution of the annual mortality benefits for the 20 EU cities that implemented the third implementation stage. The mean is €191.44 million, and the empirical 95% CI is €57.5 million–€363.6 million. This range is slightly wider than the range obtained previously because it accounts jointly for epidemiological and economic uncertainties.

Discussion

Our findings underline the health and monetary benefits obtained from drafting and implementing effective EU policies on air pollution, and by ensuring compliance with them over time. They show a marked and sustained reduction in ambient SO_2 levels over time in the 20 cities. Some of this decrease is attributable to the implementation of Council Directive 93/12/EEC and its amended version, and we estimate that some 2200 premature deaths were prevented annually, valued at €192 million.

We should bear in mind that SO_2 emissions have long been acknowledged to also generate direct monetary effects on morbidity[39] and crops,[40,41] as well as more intangible effects on the environment[42,43] that were not assessed in our study. Chestnut and Mills,[12] when assessing the US Acid Rain Program benefits, account for effects on ST and LT human health benefits as well as visibility, natural resources and deposition on materials. This paper thus only partially evaluates the full economic benefits of the regulation, as it limits itself to ST mortality effects.

Moreover, although the regulation on SO_2 has two potential effects on mortality, ST and LT, we take a conservative standpoint, restricting mortality effects to ST effects and consequently valuing them with a VOLY instead of a value of a statistical life. The economic evaluation thus constitutes a lower bound of the mortality gains of the regulation.

Finally, we should acknowledge that the benefits of SO_2 reduction may also have arisen from reductions in other pollutants. SO_2 was not the only pollutant to decrease over the period studied, black smoke, for instance, also decreases, and we cannot distinguish the separate effects of the various pollutants. Thus, care should be taken in future work not to double count by repeating the analysis on other pollutants and totalling the results. Moreover, the concentration–response functions used to assess the mortality impact are derived from observational studies that only provide evidence for associations, and causality cannot be inferred because other (non-pollution) factors cannot be ruled out.

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Conflicts of interest: None declared.

Keypoints

- We quantify the monetary benefits resulting from reductions in mortality following the implementation of the European regulation to reduce the sulphur content in liquid fuels.
- We find a marked and sustained reduction in ambient SO_2 levels over time for 20 European cities, and we estimate that some 2200 premature deaths were prevented annually, valued at €192 million.
- We perform both sensitivity and uncertainty analyses and obtain a slightly wider range for the latter, as it jointly accounts for epidemiological and economic uncertainties.

- Our findings underline the health and monetary benefits obtained from drafting and implementing effective EU policies on air pollution, and by ensuring compliance with them over time.
- By assessing the effectiveness of past regulations in terms of both health impacts and avoided health costs, we provide useful input to future regulations.

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