MIT Joint Program on the Science and Policy of Global Change

Measuring Welfare Loss Caused by Air Pollution in Europe: A CGE Analysis

Kyung-Min Nam, Noelle E. Selin, John M. Reilly, and Sergey Paltsev

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Abstract

To evaluate the socio-economic impacts of air pollution, we develop an integrated approach based on computable general equilibrium (CGE). Applying our approach to Europe shows that even there, where air quality is relatively high compared with other parts of the world, health-related damages caused by air pollution are substantial. We estimate that in 2005, air pollution in Europe caused a consumption loss of around 220 billion Euro (year 2000 prices, around 3 percent of consumption level) and a social welfare loss of around 370 billion Euro, measured as the sum of lost consumption and leisure (around 2 percent of welfare level). In addition, we estimated that a set of 2020-targeting air quality improvement policy scenarios, which are proposed in the 2005 CAFE program, would bring 18 European countries as a whole a welfare gain of 37 to 49 billion Euro (year 2000 prices) in year 2020 alone.

Contents

1. INTRODUCTION

Outcomes related to human health account for the majority of the socio-economic costs induced by air pollution (EPA, 1997; Holland *et al*., 1999). This paper evaluates the impacts of air pollution on human health in Europe and on the European economy using an integrated model of pollution-health dynamics. Compared with standard methods, our approach addresses more comprehensively the cumulative health and economic burden of exposure to air pollution and the benefits of reducing pollution.

Conventional methods employed in other studies to quantify the health impacts of air pollutants are static, and provide estimates of damages at a single point in time (e.g., Aunan *et al*., 2004; Burtraw *et al*., 2003; Davis *et al*., 1997; EPA, 1999; Ostro and Chestnut, 1998; Vennemo *et al*., 2006; West *et al*., 2006; World Bank and SEPA, 2007). Point estimates may substantially underestimate health impacts of air pollution, because air pollution can affect health outcomes that only appear years later, and the effects of pollution can be cumulative. An

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example of this is premature death caused by chronic exposure to particulates.

A few studies have attempted to measure the health impacts of air pollution in the European region. Early studies defined exposure-response functions on the basis of existing epidemiological studies, and computed the number of diseases and premature deaths caused by air pollution at a single time (Krupnick *et al*., 1996; Olsthoorn *et al*., 1999; Künzli *et al*., 2000). They then valued these health endpoints by using survey data such as average costs that people are willing to pay in order to avoid specific health-related outcomes. More recent studies use a computable general equilibrium (CGE) modeling approach in order to assess economic impacts over time (Holland *et al*., 2005; Mayeres and Van Regemorter, 2008). In their approach, labor and leisure loss caused by air pollution can affect market equilibrium in the future. In their CGE models, however, chronic mortality is dealt with in the same manner as acute mortality, which inaccurately captures the flow of lost labor over time.

We go beyond these previous studies by analyzing the economic impacts on health that result from cumulative and acute exposure as it occurs over time. We apply to Europe a method that was developed and applied to the United States and China (Matus, 2005; Matus *et al*., 2008). We consider 14 separate health endpoints (e.g., hospital admissions, restricted activity days, premature death, etc.) in combination with observed and modeled air pollution data from 1970-2005 to estimate the lost time and additional expenditures on health care. We then apply a CGE model of the economy to estimate the total economic impact, valuing both work and non-work (i.e., leisure) time as well as the economic cost of reallocating economic resources to the health care sector. An important implication of this approach demonstrated by previous applications is that economic damages accumulate—lost income in earlier years means lower GDP and savings, and therefore less investment and growth over time.

The paper is organized as follows. In Section 2 we describe the CGE model and modifications made to analyze health effects. Section 3 discusses the economic and epidemiological inputs used in our study. Air quality data for Europe are outlined in Section 4, and the results of our simulations and a sensitivity analysis with respect to exposure-response relationships are provided in Section 5. We provide our benchmark analysis to Clean Air for Europe (CAFE)-proposed emission scenarios in Section 6, and conclusions from our study in Section 7.

2. THEORETICAL FRAMEWORK AND METHOD: EPPA-HE

For our analysis, we use the MIT Emissions Prediction Policy Analysis (EPPA) model, modified as reported in Matus *et al*. (2008) to address health effects and with updates and applications to Europe described below. EPPA is a multi-region, multi-sector, recursive dynamic CGE model of the world economy (Paltsev *et al*., 2005), which uses economic data from the GTAP dataset (Dimaranan and McDougall, 2002).

Using a CGE model to estimate pollution costs has two major advantages. One is that a CGE model can describe economic dynamics (savings and investment) and resource reallocation implications of lost labor, leisure, and additional demands on the health services sector. The second is that a CGE model allows analysis of multiple scenarios. Our approach is to first develop a historical benchmark simulation that replicates actual economic performance where the health impacts associated with observed levels of pollution are included. We then analyze what would have happened if air pollution were at background levels, in order to estimate what economic performance would have been without pollution stemming from human activity. The difference between economic performance from this counterfactual scenario and our replication of actual performance gives us an estimate of the economic burden of air pollution. The estimate of burden changes over time as pollution levels change and as past exposure continues to affect economic performance. These dynamic effects of past exposure stem from lost lives due to chronic exposure and the impacts of lower economic activity on savings and investment, which then carry through to lower economic activity in future years. Our primary measure of economic performance is a change in welfare, which includes consumption and leisure and is measured as equivalent variation. Consumption is measured as total macroeconomic consumption. Leisure time is valued at the marginal wage rate. An average wage profile over the lifetime of an individual is applied to each age cohort to estimate the impact of air-pollution related deaths. Our counterfactual scenarios include simulation of the potential benefits of certain pollution goals.

As mentioned above, the EPPA-Health Effects (EPPA-HE) model is described in Matus *et al*. (2008). Briefly, it accommodates pollution-generated health costs in a feedback loop, which in turn affects the economy and the emissions of pollutants in later periods. The extended social accounting matrix (SAM), on which EPPA-HE is based, includes a household production sector that uses medical services and household labor to provide pollution health service. An increase in pollution health related household labor reduces the pool of labor and leisure available for other economic activities. The EPPA-HE model captures the magnitude of pollution health impacts on the basis of the size of additional medical services and their factor inputs, produced by air pollution and the amount of labor and leisure lost due to acute and chronic exposure to pollutants. As we are limited to the European aggregation in the EPPA model, which aggregates 18 European countries[1] into one region (EUR), we do not consider the EU-27, but only a subset of the EU countries (plus Norway, Iceland, and Switzerland) as a single region.[2]

EPPA-HE computes 29 different health outcomes (the health impacts of ozone or PM exposure on e.g., the number of asthma attacks, hospitalizations, restricted activity days, or premature deaths) on the basis of historical pollution levels, exposure-response (E-R) relationships, and demographic information. The health outcomes are then converted into health service requirements (i.e., cost of medical care) and lost labor and leisure. These changed levels of health service demands and labor availability are then used to force the economic module of EPPA-HE. The model is thus able to capture pollution-generated health outcomes and their subsequent ripple effects on the economy.

[1] The region EUR in EPPA version 4 includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, and the United Kingdom.

[2] EU-15 countries, represented in EUR region, account for 95 percent of the EU-27 GDP and 78 percent of the EU-27 population.

Following the air pollution health effects literature, we treat deaths due to chronic and acute pollution exposure differently. For acute exposure, we follow the literature and assume that deaths in such cases occur to individuals whose health condition was already poor, with pollution exposure leading to half a year of life lost on average. For chronic exposure, we assume that death is related to cardio-pulmonary or lung disease, and so we use age-specific death rates from these diseases to estimate a distribution for the age of death. To do this, we include a demographic module in the model that tracks five-year age cohorts, their exposure level throughout their lifetime and the death rate for each from cardio-pulmonary and lung diseases for each cohort. We assume that an increase in the death rate due to chronic exposure proportionally increases the cardio-pulmonary and lung death rate in each cohort. Because deaths from these diseases are much less prevalent among younger people who have had less time for these diseases to develop, this weights the deaths to be among the older population thereby reducing the average number of years of lost life. We assume that (i) death from chronic exposure occurs only in age groups of 30 and older, and (ii) the life expectancy of the whole population in the absence of excess air pollution is 75.

3. ECONOMIC/DEMOGRAPHIC INPUTS AND EPIDEMIOLOGICAL PARAMETERS

3.1 Economic and Demographic Data

EPPA-HE requires historical information on market transactions, resource/income distribution, and demographic growth as key inputs. It solves for 5-year time intervals starting in 1970. We scale the GDP from the original GTAP data to 1970 levels and benchmark labor productivity growth to replicate actual GDP growth in Europe for the period 1970 to 2005 based on World Bank statistics (World Bank, 2009).

We construct the model's basic demographic inputs such as age cohort-specific population/mortality and urbanization rates at the EUR level (1970-2005) from time series estimates of national population, published by the United Nations Statistical Division (UN, 1999, 2008). Overall and cohort-specific cardio-pulmonary mortality rates are computed from the World Health Organization (WHO) database (WHO, 2009). Information on cardio-pulmonary mortality is used to modify the original E-R function for chronic mortality (0.25 % chronic mortality rate increase per unit PM_{10} concentration measured in $\mu g/m^3$) into age-conditioned forms. Matus *et al*. (2008) provide further details on this conversion process.

3.2 Health Endpoints and Exposure-Response Functions

Epidemiological literature has extensively documented the link between major air pollutants and associated health outcomes (e.g., Anderson *et al*., 2004; Aunan and Pan, 2004; Dockery *et al*., 1993; Hiltermann *et al*., 1998; Hurley *et al*., 2005; Kunzli *et al*., 2000; Ostro and Rothschild, 1989; Pope *et al*., 1995; Pope *et al*., 2002; Pope *et al*., 2004; Samet *et al*., 2000; Venners *et al*., 2003; Zhang *et al*., 2002). The ExternE project (Holland *et al*., 1999), initiated by the European Commission, synthesizes existing epidemiological studies, and provides a comprehensive list of

Table 1. Exposure-Response Functions[†].

Receptor	Impact Category	Pollutant	ExternE (1999)* E-R fct	ExternE (1999)* C. I. (95%) Low	ExternE (1999)* C. I. (95%) High	ExternE (2005)** E-R fct	ExternE (2005)** C. I. (95%) Low	ExternE (2005)** C. I. (95%) High	Notes
Entire Population	Respiratory hospital admissions	PM_{10}	2.07E-06	3.58E-07	3.78E-06	7.03E-06	3.83E-06	1.03E-05	
		O_3	3.54E-06	6.12E-07	6.47E-06	use ExternE (1999) numbers, except for elderly population.			
	Cerebrovascular hospital admissions	PM_{10}	5.04E-06	3.88E-07	9.69E-06	5.04E-06	3.88E-07	9.69E-06	
	Cardiovascular hospital admissions	PM_{10}	n/a			4.34E-06	2.17E-06	6.51E-06	
	Respiratory symptoms days	O_3	3.30E-02	5.71E-03	6.03E-02	use ExternE (1999) numbers.			
	Asthma attacks	O_3	4.29E-03	3.30E-04	8.25E-03	use ExternE (1999) numbers.			
	Acute Mortality	O_3	0.06%	0.00%	0.12%	0.03%	0.01%	0.04%	
		PM_{10}	0.04%	0.00%	0.08%	0.06%	0.04%	0.08%	
	Chronic Mortality***	PM_{10}	0.25%	0.02%	0.48%	use ExternE (1999) numbers.			
Children	Chronic Bronchitis	PM_{10}	1.61E-03	1.24E-04	3.10E-03	use ExternE (1999) numbers.			
	Chronic Cough	PM_{10}	2.07E-03	1.59E-04	3.98E-03	use ExternE (1999) numbers.			
	Respiratory symptoms days	PM_{10}	n/a			1.86E-01	9.20E-02	2.77E-01	
	Bronchodilator usage	PM_{10}	7.80E-02	6.00E-03	1.50E-01	1.80E-02	-6.90E-02	1.06E-01	Defined on children aged 5-14 years meeting the PEACE study criteria (around 15% of children in Northern and Eastern Europe and 25% in Western Europe.)
	Cough	PM_{10}	1.33E-01	2.30E-02	2.43E-01	n/a			
		O_3	n/a			9.30E-02	-1.90E-02	2.22E-01	ER functions on cough for ozone are defined on general population of ages 5-14.
	Lower respiratiry symptoms (wheeze)	PM_{10}	1.03E-01	1.78E-02	1.88E-01	1.86E-01	9.20E-02	2.77E-01	ExternE (2005) LRS values for PM include impacts on cough.
		O_3	n/a			1.60E-02	-4.30E-02	8.10E-02	LRS ER functions for ozone, which do not take into account cough, are defined on general population of ages 5-14.
Adults	Restricted activity day	PM_{10}	2.50E-02	1.92E-03	4.81E-02	5.41E-02	4.75E-02	6.08E-02	Restricted activity days include both minor restrcted days and work loss days.
	Minor restricted activity day	O_3	9.76E-03	7.51E-04	1.88E-02	1.15E-02	4.40E-03	1.86E-02	Part of restricted activity days
		PM_{10}	4.90E-05	3.77E-06	9.42E-05	3.46E-02	2.81E-02	4.12E-02	
	Work loss day	PM_{10}	n/a			1.24E-02	1.06E-02	1.42E-02	Part of restricted activity days
	Respiratory symptoms days	PM_{10}	n/a			1.30E-01	1.50E-02	2.43E-01	defined only on adults population with chronic respiritory symptoms (around 30% of adult population)
	Chronic bronchitis	PM_{10}	4.90E-05	8.48E-06	8.95E-05	2.65E-05	-1.90E-06	5.41E-05	
	Bronchodilator usage	PM_{10}	1.63E-01	1.25E-02	3.13E-01	9.12E-02	-9.12E-02	2.77E-01	Defined on population of 20+ with well-established asthma (around 4.5% of total adult population).
		O_3	n/a			7.30E-02	-2.55E-02	1.57E-01	
	Cough	PM_{10}	1.68E-01	2.91E-02	3.07E-01	n/a			
	Lower respiratory symptoms (wheeze)	PM_{10}	6.10E-02	1.06E-02	1.11E-01	1.30E-01	1.50E-02	2.43E-01	LRS ER functions for PM are defined on adult population with chronic respiratory symptoms (around 30% of total adult population); ExternE (2005) LRS values for PM include impacts on cough.
Elderly 65+	Respiratory hospital admissions	O_3	n/a			1.25E-05	-5.00E-06	3.00E-05	
	Congestive heart failure	PM_{10}	1.85E-05	1.42E-06	3.56E-05	use ExternE (1999) numbers.			
	Ischaemic heart disease	PM_{10}	1.75E-05	1.35E-06	3.37E-05	use ExternE (1999) numbers.			

[†] E-R functions for acute and chronic mortality have the unit of [%Δannual mortality rate/μg/m^3]. The rest E-R functions are measured in [cases/(yr-person-μg/m^3)].

Source: [*] Computed from Holland *et al*. (1999); [**] Computed from Bickel and Friedrich (2005); [***] Adapted from Pope *et al*. (2002).

Table 2. Valuation of Health-end Outcomes.

Outcome	Unit	Cost (year 2000 Euro)
Hospital Admission	per admission	2,000
Emergency Room Visits for respiratory illness	per visit	670
General Practitioner visits:		
Asthma	per consultation	53
Lower Respiratory Symptoms	per consultation	75
Respiratory Symptoms in Asthmatics:		
Adults	per event	130
Children	per event	280
Respiratory medication use - adults and children	per day	1
Restricted Activity Day	per day	130
Cough day	per day	38
Symptom day	per day	38
Work loss day	per day	82
Minor Restricted Activity day	per day	38
Chronic Bronchitis	per case	190,000

Source: Adapted from Bickel and Friedrich (2005), p. 156.

E-R functions. We use these E-R functions from the ExternE study and as updated for ozone and particulate matter as reported in Bickel and Friedrich (2005). We also use the valuation table of health endpoints developed in the ExternE studies. **Tables 1** and **2** summarize E-R functions and health endpoint valuation outcomes used in the EPPA-HE model.

4. AIR QUALITY DATA

In this section we focus on impacts from exposure to ozone (O_3) and particulate matter (PM_{10}). Ozone and particulate matter are considered the pollutants with the most potential to affect human health (EEA, 2009a). Confirming this conclusion, the U.S. study of Matus *et al*. (2008) found that among the five criteria air pollutants defined by the United States Environmental Protection Agency (ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, and particulate matter), over 95 percent of the health costs were attributable to exposure to ozone and particulate matter.

Our estimates of ground-level ozone data are based on model results from the European Monitoring and Evaluation Programme (EMEP) database, co-maintained by the United Nations Economic Commission for Europe (UNECE) and the Co-operative programme for monitoring and evaluation of long range transmission of air pollutants in Europe (EMEP and UNECE, 2006). EMEP ozone data are available between 1980 and 2004. Because we are interested in the cumulative effects of air pollution, we assume that concentrations in for 1970 and 1975 were the same as those in 1980. We also use 2004 data for 2005. Among various ground level ozone measurements, provided by the EMEP database, we used annual means of 8-hour daily maximum, for which E-R functions are defined.

For input into EPPA-HE, we compute a representative air quality number for the European region for each year and each pollutant. As the goal of our research is to estimate the impact of air pollution on human health, we use population weights to construct average concentrations for Europe. For this purpose we use a 1°×1° world population share grid data for 1990 (SEDAC, 2009) as a weight for ozone and PM concentrations for all years' air quality data. Original EMEP grids, each of which is sized at 50 km × 50 km, are converted into 1°×1° to match those of the population data by using ArcGIS software and the inverted distance weighted (IDW) spatial interpolation technique (See **Figures 1** and **2**).

We do not use the same data sources for PM, however, because EMEP PM concentration estimates substantially underestimate actual PM levels for two reasons (EMEP, 2001). One reason is that the EMEP model is designed to estimate PM concentration solely from secondary inorganic aerosol (SIA) concentrations and primary emissions of particles, while ignoring other key components such as resuspended anthropogenic and natural mineral dust, sea salt, and biogenic aerosols, which also substantially contribute to PM concentration. Second, the EMEP model was built on underestimated SIA concentration inputs. Thus, we use two alternative data sources for PM: the AirBase database, maintained by the European Environment Agency (2009b), and the World Development Indicators (WDI) database, published by the World Bank (2009). The AirBase database provides historical concentration levels both of PM and of Total Suspended Particulate (TSP). When PM_{10} data were not available, we convert TSP data into PM_{10} concentrations by applying a factor of 0.55, following Dockery and Pope (1994). While for at least some major monitoring stations the data extends back to 1976, data for some stations for some years are missing and the station coverage prior to the late 1990s is very sparse. To fill missing data, we first compute the average ratio of PM data from a set of monitoring stations

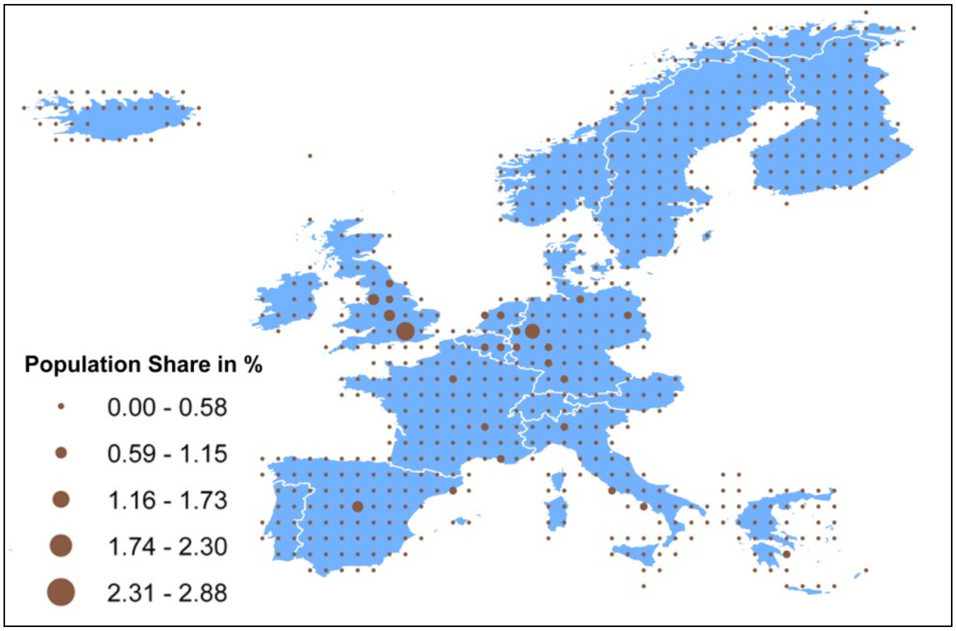

Figure 1. Population Share Grid, EUR, 1990.

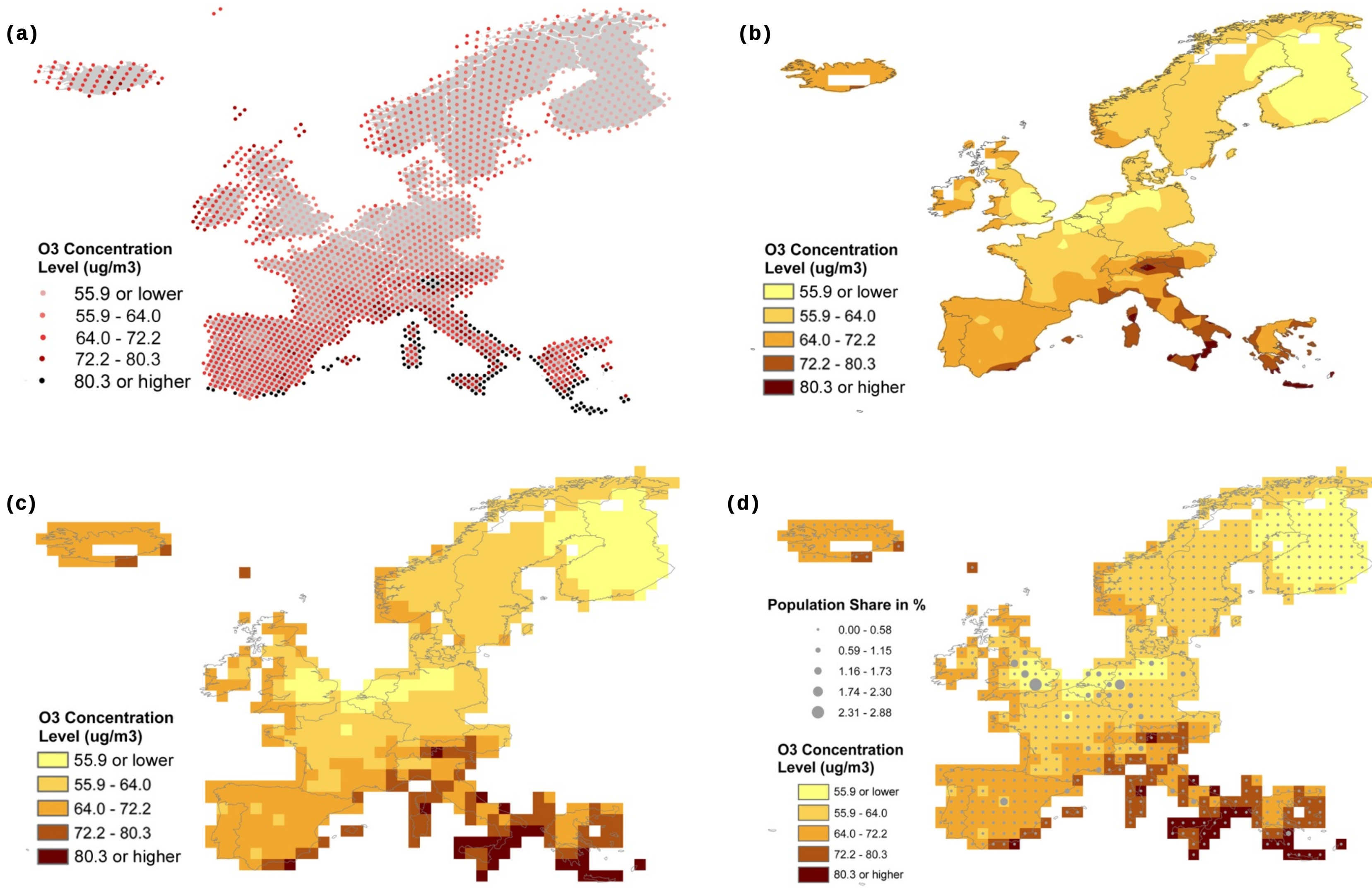

Figure 2. Procedure of Computing Population-weighted Concentration Level of Ozone, 2004: **(a)** EMEP Grids and Ozone Data for 2004, **(b)** IDW-based spatial interpolation, EMEP Data, **(c)** 1°×1° Raster-converted Ozone data, and **(d)** Compute Population-weighted Concentration Level of Ozone for 2004.

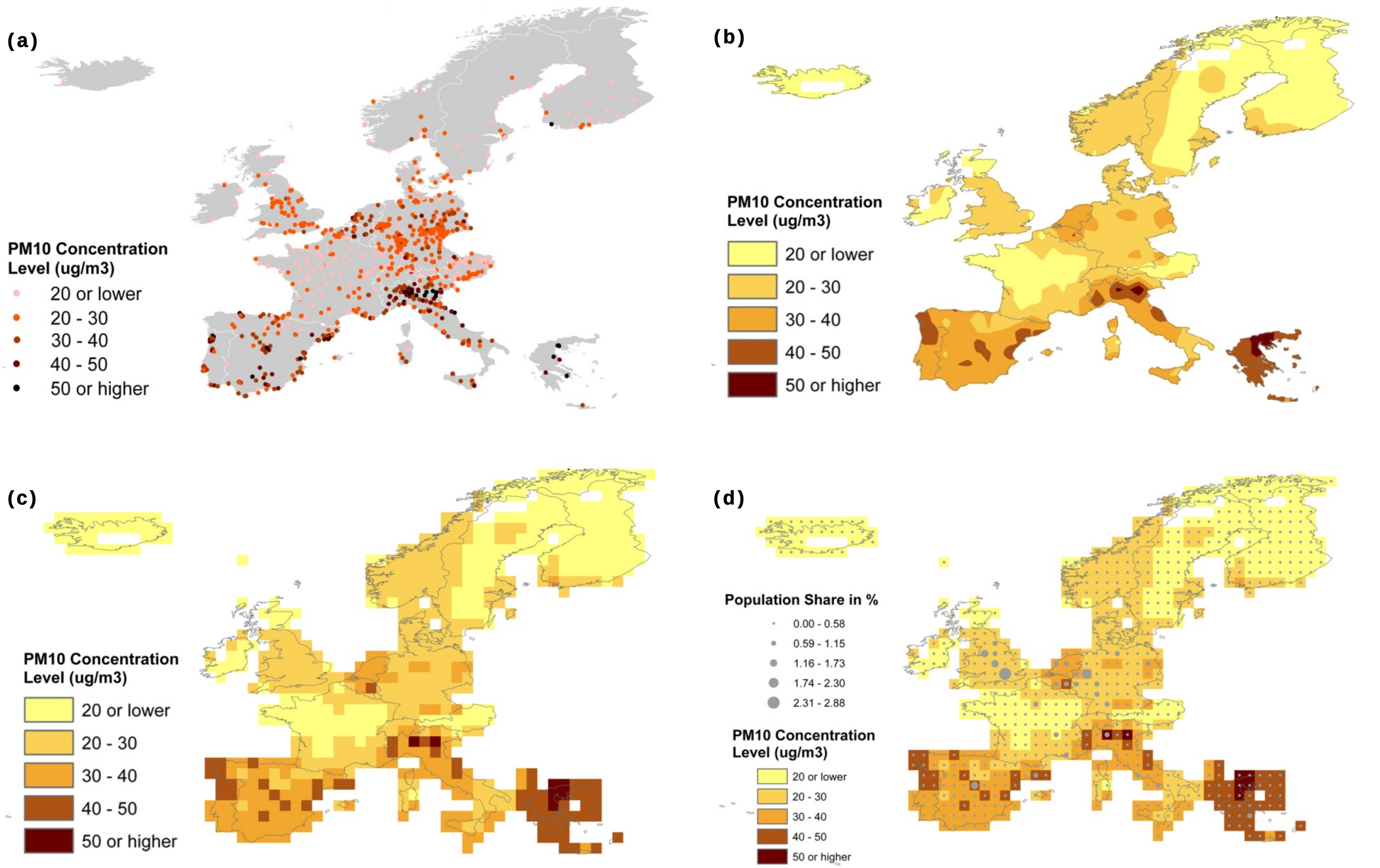

Figure 3. Procedure of Computing Population-weighted Concentration Level of PM_{10}, 2005: **(a)** AirBase PM_{10} Data for 2005, **(b)** IDW-based spatial interpolation, AirBase Data, **(c)** 1°×1° Raster Layer Converted from the Spatial Interpolation Layer, and **(d)** Compute Population-weighted Concentration Level of PM_{10} for 2005.

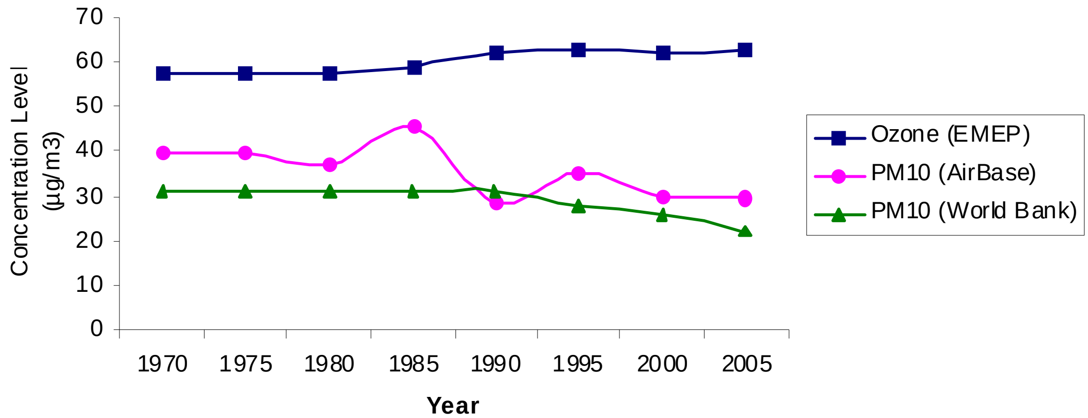

Figure 4. Concentration Levels of Ozone and PM_{10}, EUR, 1970-2005. Here, the measurement standard for ozone is annual means of 8 hour daily maximum, and that for PM_{10} is annual mean of 24 hour average.

which have data for two consecutive years, and then apply this factor to monitoring stations, which have data for either of the two years. We eliminate monitoring stations which have missing data or cannot be filled this way for two consecutive years. As data for later years are more complete, we carry out this procedure from recent years to early years. After completing this procedure, we convert AirBase data layers for each year into 1°×1° raster maps in a similar way as for the EMEP ozone data. In this case, 1970 and 1975 PM levels are assumed to be constant at the 1976 level (See **Figure 3**).

PM_{10} data from the WDI database are available between 1990 and 2005. As the database provides only nation-wide average concentration numbers, we calculate EUR-wide PM_{10} concentration numbers by using each country's population as weight. PM_{10} levels for 1985 and earlier are assumed to be constant at 1990 levels. See **Figure 4** for air quality numbers used here.

To compare these two different historical PM concentration estimates, we set up two reference case scenarios. We use AirBase-estimated PM concentrations for Reference Case Scenario A, and WDI-based estimates for Reference Case Scenario B. All other inputs for the two reference scenarios except PM concentration are identical.

5. RESULTS

We estimate pollution costs by comparing simulation outcomes for two air quality scenarios. One scenario is the *Historical* scenario, in which air quality inputs are set at historical levels and GDP growth is benchmarked to observed levels for the 1970 to 2005 period. This reference scenario reflects the fact that these air pollution levels were observed, and observed economic results were already distorted by air pollution effects. To estimate the economic impact of these observed levels, a second *Green* scenario is simulated as a counterfactual simulation where concentrations of these pollutants are set at 20 $\mu g/m^3$ for ozone and 0.001 $\mu g/m^3$ for PM_{10}, which are levels that would be observed if there were no anthropogenic sources of pollutant emissions (Seinfeld and Pandis, 1998).

5.1 Overview

We find that air pollution caused substantial socio-economic costs in the European region (**Tables 3** and **4**). First, we measure the pollution health cost in terms of consumption loss, which does not include leisure time value. In terms of consumption, we calculate that the European economy has lost annually 2.8 percent to 4.7 percent of historical consumption levels due to air pollution for the last three decades. With increasing concerns about air pollution and stricter air quality control, consumption-measured pollution-health cost shows a declining tendency, though with slight intra-period fluctuations. In absolute values, the region's consumption loss, which ranged between 169 billion Euro[4] and 229 billion Euro during the period 1975-2005, was estimated to reach its maximum of 229 billion Euro in 2000 (Reference Case A) or of 226 billion Euro in 2000 (Reference Case B). The simulation outcomes based on Reference Case B suggest that improving air quality in Europe led to lower consumption loss through the period of our analysis in terms not only of relative measure to historical consumption levels but also of absolute monetary units.

Table 3. Consumption and Welfare Losses Caused by Air Pollution (Reference Case A), EUR, 1975-2005.

	Consumption Loss		Welfare Loss	
Year	***Billions of year 2000 Euro***	***% of Historical Consumption Level***	***Billions of year 2000 Euro***	***% of Historical Welfare Level***
1975	169	4.7	293	3.3
1980	169	3.9	297	2.7
1985	175	3.7	260	2.2
1990	225	4.0	467	3.3
1995	219	3.6	374	2.4
2000	229	3.2	418	2.3
2005	217	2.8	354	1.8

Table 4. Consumption and Welfare Losses Caused by Air Pollution (Reference Case B), EUR, 1975-2005.

	Consumption Loss		Welfare Loss	
Year	***Billions of year 2000 Euro***	***% of Historical Consumption Level***	***Billions of year 2000 Euro***	***% of Historical Welfare Level***
1975	169	4.7	292	3.2
1980	167	3.9	278	2.6
1985	180	3.8	300	2.5
1990	216	3.8	370	2.6
1995	210	3.4	358	2.3
2000	226	3.2	393	2.1
2005	217	2.8	373	1.9

[4] We measure Euro as year 2000 Euro unless specifically noted.

The loss of welfare, which we evaluate as a loss in the sum of consumption and leisure, shows a similarly declining tendency. This simulation outcome is not surprising, given the fact that the European region's air quality has been kept constant (in the case of ozone) or improved (PM), and the changes—whether positive or negative—in air quality are small relative to the region's economic growth. For the last three decades, the European region's annual welfare loss, caused by air pollution, ranged between 1.8 percent and 3.3 percent of the historical welfare level or between 260 billion Euro and 467 billion Euro, on the basis of Reference Case A. Welfare loss estimates based on Reference Case B were similarly between 278 billion Euro and 393 billion Euro and between 1.9 percent and 3.2 percent of the historical level.

5.2 Decomposition Analysis

We decompose pollution-induced health costs below for further analysis. For simplicity, we used Reference Case Scenario B only for the following decomposition analysis, because while both Reference Case Scenario A and B produced similar simulation results, as shown in Tables 3 and 4, the latter simulations were less variable and thus produced more consistent time-series outcomes.

Table 6 displays decomposed explicit pollution health costs for year 2005, which are based on EPPA-HE-simulated pollution-induced case increases by health outcome shown in **Table 5**. We define explicit pollution health costs as the sum of (i) medical expenses, (ii) wage loss caused by illness or premature deaths, and (iii) leisure loss caused by illness or premature deaths. We estimate that explicit pollution health costs for 2005 are as much as 201 billion Euro. Around 60 percent of ozone-related costs are from leisure loss, while more than 70 percent of PM_{10}-induced costs are from medical costs to deal with illness. PM_{10} contributes more than four times as much to explicit pollution health costs as ozone: over 82 percent of the 2005 total explicit pollution health costs were caused by PM_{10}.

Table 5. Pollution-induced Health Outcomes by Pollutant (Reference Case B), EUR, Selected Years.

Unit: thousands of cases

	1975		1990		2005	
Health Outcomes	O_3	PM_{10}	O_3	PM_{10}	O_3	PM_{10}
Respiratory Hospital Admission	175	80	213	88	242	70
Cerebrovascular Hospital Admission	n/a	58	n/a	63	n/a	50
Cardiovascular Hospital Admission	n/a	50	n/a	54	n/a	43
Respiratory Symptom Days	461,420	339,789	562,187	398,383	640,103	323,005
Acute Mortality	40	66	49	72	56	58
Chronic Bronchitis	n/a	172	n/a	204	n/a	176
Chronic Cough (only for Children)	n/a	6,673	n/a	5,909	n/a	4,249
Cough and Wheeze	36,802	689,398	33,636	685,042	35,163	532,759
Restricted Activity Day	115,434	471,348	151,155	552,629	177,083	448,065
Congestive Heart Failure	n/a	28	n/a	34	n/a	31
Asthma Attacks	2,399	n/a	2,923	n/a	3,329	n/a
Bronchodilator Usage	35,023	47,968	45,772	52,162	53,021	41,515
Chronic Mortality (current year only)	n/a	221	n/a	259	n/a	307

Table 6. Decomposition of Explicit Pollution Health Costs* in 2005 (Reference Case B).

Unit: millions of year 2000 Euro

Health Outcome Category	Ozone: Medical Expenses	Ozone: Wage Loss	Ozone: Leisure Loss	PM_{10}: Medical Expenses	PM_{10}: Wage Loss	PM_{10}: Leisure Loss
Non-fatal Health Outcomes	13,384	20	19,172	106,748	10,429	30,806
Acute Mortality	n/a	436	1,452	n/a	447	1,490
Chronic Mortality (Year 2005 Only)	n/a	n/a	n/a	n/a	2,666	13,459
Sub-total	13,384	456	20,624	106,748	13,542	45,755
Sub-total by Pollutant	34,463 (17.2 %)			166,045 (82.8 %)		
Total	200,508 (100 %)					

* Explicit pollution health costs do not include pollution-induced residual cumulative impacts.

Table 7 displays decomposed total welfare loss in 2005, caused by air pollution. Estimates shown in the table consider two counterfactual economic outcomes. One is estimated output loss due to chronic mortalities in the past and current years, and the other is residual impact, which shows how aggregate social welfare changes when resource allocation is not distorted by air pollution. We decomposed the 2005 welfare loss into three categories: (i) wage loss in the current year only, (ii) wage loss due to chronic mortality in the past, and (iii) residual impact. One notable conclusion from this analysis is that a large fraction of the total welfare loss is from pollution-induced distortions in resource allocation. We estimate that over 45 percent of the 2005 total pollution health cost was from the residual cumulative impact. It is clear that point estimation techniques, which fail to capture this residual cost, can substantially underestimate the pollution health cost. The remaining 20 percent and 35 percent of the cost is attributable to the first and the second categories, respectively.

Table 7. Decomposition of Welfare Loss* in 2005 (Reference Case B).

	Total Pollution Health Cost	Pollution Health Cost, 2005 Only: *Non-fatal Outcomes and Acute Mortality*	Pollution Health Cost, 2005 Only: *Chronic Mortality*	Chronic Mortality in the Past	Residual Impact
In billions of year 2000 Euro	373.8	59.4	14.8	130.4	169.3
In % to Total Welfare Loss	100.0	15.9	4.0	34.9	45.3

* Welfare Loss is defined as sum of Consumption Loss and Leisure Loss; ** Non-fatal diseases + Acute Mortality + Chronic Mortality in 2005.

5.3 Sensitivity Analysis

Given that E-R relationships can vary by time and place, even for the same pollutant and health outcome, a substantial degree of uncertainty may come from the E-R functions. In this section, we conduct two sets of sensitivity analysis on E-R functions to evaluate the robustness of the results presented above. The first analysis compares reference simulation outcomes with those using upper and lower bound values of E-R functions, acquired from the 95 percent confidence interval. For the second analysis, we run the model by replacing reference E-R functions by E-R functions from the 1998 ExternE study. We compared both sets of sensitivity analysis simulation results with those from Reference Case Scenario B, which employs WDI-based estimates for historical PM_{10} concentration levels.

When we used lower bound values of E-R functions, EPPA-HE not surprisingly produced lower estimates of air pollution-driven health costs than the reference case (**Table 8**). Compared with estimates in Table 4, both consumption and welfare loss fell by more than half. However, lower bound E-R values also produce non-trivial estimates for consumption and welfare loss from air pollution, which reach 1.4-2.1 percent of historical levels. In contrast, upper bound E-R values raised pollution-caused health damage estimates to 4.9-7.4 percent of consumption or 3.2-5.0 percent of welfare with a declining trend over time (**Table 9**). From this result, we can conclude that although uncertainty involved in E-R functions themselves widens the range of our pollution health cost estimates substantially, it does not undermine our general conclusions that substantial socio-economic burdens result from air pollution, and that relative pollution health costs have declined over time.

Table 8. Sensitivity Analysis 1-1: Lower Bound Values (95% C.I.) of E-R Functions.

	Consumption Loss		**Welfare Loss**	
Year	***Billions of year 2000 Euro***	***% of Historical Consumption Level***	***Billions of year 2000 Euro***	***% of Historical Welfare Level***
1975	76	2.1	143	1.6
1980	78	1.8	144	1.3
1985	85	1.8	158	1.3
1990	101	1.8	192	1.3
1995	101	1.7	192	1.2
2000	110	1.6	215	1.2
2005	107	1.4	209	1.1

Table 9. Sensitivity Analysis 1-2: Upper Bound Values (95% C.I.) of E-R Functions.

	Consumption Loss		**Welfare Loss**	
Year	***Billions of year 2000 Euro***	***% of Historical Consumption Level***	***Billions of year 2000 Euro***	***% of Historical Welfare Level***
1975	269	7.4	452	5.0
1980	262	6.0	420	3.9
1985	281	6.0	451	3.8
1990	338	6.0	557	3.9
1995	328	5.3	533	3.4
2000	352	4.9	581	3.2
2005	335	4.3	550	2.8

Table 10 summarizes simulation outcomes based on the 1998 ExternE study-proposed E-R functions instead of the updated values from the 2005 ExternE study. When 1998 E-R functions were used, pollution health cost estimates were reduced to 1.3-2.6 percent of consumption and 0.8-1.7 percent of welfare. This outcome, though lower in magnitude, does not contradict our general conclusion that air pollution has generated substantial socio-economic costs to the European economy.

Table 10. Sensitivity Analysis 2: Old E-R values from the 1998 ExternE Study.

	Consumption Loss		Welfare Loss	
Year	***Billions of year 2000 Euro***	***% of Historical Consumption Level***	***Billions of year 2000 Euro***	***% of Historical Welfare Level***
1975	93	2.6	151	1.7
1980	93	2.2	146	1.3
1985	104	2.2	169	1.4
1990	126	2.3	213	1.5
1995	117	1.9	190	1.2
2000	117	1.7	186	1.0
2005	102	1.3	154	0.8

6. COMPARISON WITH THE CAFE STUDY

There are several studies that attempt to estimate health impacts of air pollution in Europe (e.g., Krupnick *et al*., 1996; Olsthoorn *et al*., 1999; Holland *et al*., 2005). It is difficult, however, to compare their estimates directly with ours due to different pollutants of interest, target years, target air quality, and geographical boundaries. Nonetheless, we concluded that the 2005 Clean Air for Europe (CAFE) study of Holland *et al*. took the most analogous approach with ours in estimating pollution health costs, and thus we present here a comparison to their results. For comparison, we modified EPPA-HE to simulate economic and health outcomes up to year 2020.

6.1 Additional Inputs and Emission Scenarios

Emission scenarios, used by Holland *et al*. (2005), are summarized in **Table 11**. Their 2020 Baseline scenario is consistent with that of the Regional Air pollution Information and Simulation (RAINS) model, which was also employed for other CAFE studies. EU-25's emission levels for policy alternative scenarios are set at around 11 to 43 percent-reduced levels from the Baseline emission levels. Among them, Policy Scenario C has the most ambitious emission reduction target, while Policy Scenario A has the least ambitious target.

Table 11. Emission Scenarios for the CAFE Study, EU-25.

Unit: kt

	Year 2000	Year 2020			
		Baseline	***Scenario A***	***Scenario B***	***Scenario C***
SO_2	8,735	2,806	1,814	1,700	1,594
NO_x	11,581	5,886	4,560	4,136	3,923
VOC	10,661	5,907	5,232	4,867	4,743
NH_3	3,824	3,683	n/a	n/a	n/a
Primary PM	37	27	23	22	22

Source: Adopted and computed from Amann *et al*. (2005: 20-24) and Holland *et al*. (2005: 17).

As explained in previous sections, EPPA-HE needs concentration data of ozone and PM for the computation of health end point cases. Thus, emission-based scenarios shown in Table 11 should be converted into concentration-based ones. Holland *et al*. (2005) clarify that their PM and ozone concentration data are taken from the RAINS model and the EMEP model, respectively. We obtained country-specific PM and ozone concentration data that were used for their CAFE reference and three policy scenarios (C. Heyes, pers. comm.). For PM_{10}, we computed population-weighted average for EPPA region EUR directly from the provided numbers. However, an additional step was necessary for the case of ozone, as the provided data was measured as the sum of excess of daily maximum 8 hour means over the cut-off of 35 ppb (SOMO35). To approximate year 2020 ozone concentration numbers without thresholds, we first computed the ratio between year 2000 and year 2020 SOMO35 numbers, and then applied the ratio to year 2000 ozone concentration numbers without thresholds.[5] Annual means of ozone concentration for a large region are highly correlated (r = 0.99) with SOMO35 (Dentener *et al*., 2006). **Table 12** displays PM and ozone concentration numbers for 2020 by scenario. In addition, EPPA-HE's future projection assumes annual GDP growth rates of 1.8 percent for 2006-2015 and of 2.0 percent for 2016-2020 (Paltsev *et al*., 2005).

Table 12. Air Quality Inputs, EUR, 2020.

Unit: μg/m^3

Ozone				**PM_{10}**			
Reference	***Policy A***	***Policy B***	***Policy C***	***Reference***	***Policy A***	***Policy B***	***Policy C***
52.5	48.7	47.5	46.7	9.0	7.4	7.0	6.8

6.2 Results and Analysis

Holland *et al*. (2005) provides two sets of estimates for net welfare benefits of CAFE-proposed emission regulation scenarios. One is a low set of estimates based on the value of a life year (VOLY) of 52,000 Euro, and the other is a high set of estimates based on the VOLY of 120,000 Euro. As EPPA-HE uses ExternE-proposed health end point valuation tables, which are based on the VOLY of 50,000 Euro, we compare our estimates with their low estimates. As shown in **Table 13**, we estimate that CAFE-proposed emission regulation measures will bring a welfare gain of 34 billion to 48 billion Euro. Our estimates are very close to those of Holland *et al*. (2005), which are between 37 billion and 49 billion Euro. Perhaps, part of the estimates difference is from dissimilar geographical boundaries of interest for each study as well as from difference in methodology. While EPPA region EUR includes EU-15 member states and three non-EU high-income countries (Switzerland, Norway, and Iceland), the CAFE study embraces the whole EU-25 member countries. As of 2000, the population of the former region was no more than 86 percent of EU-25's total.

Table 13. Net Welfare Gains from CAFE-proposed Emission Control, Year 2020 Only.

Unit: billions of year 2000 Euro

Holland *et al*. (2005)			**EPPA-HE**		
Policy A	***Policy B***	***Policy C***	***Policy A***	***Policy B***	***Policy C***
37	45	49	34	43	48

[5] This calculation procedure can be expressed as the following equation, where Ozone_t indicates annual means of 8 hour daily maximum (without threshold) in time t.

$$\text{Ozone}_{t+1} = \frac{\text{SOMO35}_{t+1}}{\text{SOMO35}_{t}} \times \text{Ozone}_{t}$$

7. CONCLUSIONS

Our results show that air pollution has generated substantial economic burdens for the European region. Although air quality in Europe has been controlled, we estimate that the region still lost 3 percent of consumption (or 2 percent of welfare) due to air pollution in 2005, even when only human health-related aspects and two key air pollutants (ozone and PM_{10}) were considered. This suggests that policy measures formulated to improve air quality can benefit society, though they may cause explicit economic costs in the short term. A set of sensitivity analysis shows us that our general conclusion is robust even in the presence of substantial degrees of uncertainty embedded in key parameters such as E-R functions and PM concentration levels.

Our benchmark analysis to the 2005 CAFE study makes this point clearer. We modified EPPA-HE to run simulations for the future and incorporated CAFE-proposed emission scenarios. From this analysis, we obtain results very close to those of the 2005 CAFE study. A Europe-wide reduction from the 2020 baseline scenario of 10 to 40 percent of key air pollutants such as SO_2, NO_x, VOC, NH_3, and PM is estimated to bring a net welfare gain of 34 billion to 48 billion Euro for year 2020 alone.

Finally, we emphasize from our CGE analysis the cumulative nature of pollution-induced health cost. Pollution from one period can affect economic welfare of the future for quite a long time, as the level of welfare is a function of the stock of economic and human capital rather than of their flows. Our estimates of pollution health cost for Europe may be greater than most other studies, because we include the residual cumulative impacts of air pollution, which are often omitted by others. We find from the decomposition analysis of year 2005 pollution-induced welfare loss that roughly half the total cost is attributable to the residual cumulative impacts. Studies that consider only pollution costs that happened in the year of analysis or fatal and non-fatal health outcomes, although they may take chronic mortality of the past into account, are likely to underestimate the real economic burdens to the society generated by air pollution. In this sense, a CGE-based approach is a more reasonable approach than the point estimation method used in other studies of health costs of air pollution.

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