assessment paper

AIR POLLUTION

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COPENHAGEN CONSENSUS on Human Challenges

Air Pollution

Global Damage Costs of Air Pollution from 1900 to 2050

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Abstract

This paper estimates the global damage costs of air pollution over a 150-year time period, from 1900 to 2050, focusing exclusively on air pollution of anthropogenic origin. Outdoor air pollution in urban centers and indoor air pollution from burning of solid fuel indoors are included, with damage costs made separately for developed and developing country groupings. Outdoor air pollution impacts include damages to health, crops, buildings and visibility, while indoor air pollution impacts include damages to health and additional time required for household members to collect biomass.

This study estimates the total damage costs of air pollution to be US$ 3.0 trillion in 2010, or 5.6% of Gross World Product (GWP). These losses are equivalent to US$ 430 for every person on the planet. Damage costs are divided almost equally between indoor and outdoor air pollution at the global level; while around two-thirds of the damages are to the populations of developing countries. Health-related damages account for 85% of total damages. Global damage costs are on a downward trend: starting from around 23% of GWP in the year 1900, the damage costs are predicted to fall to below 3% of GWP by 2050.

Given the pervasiveness of the current economic and energy paradigm, and the rapidly urbanizing world (further exposing populations to outdoor air pollution), mitigating damage costs in the future remains a challenge. Further decline from the current levels of economic damage will require successful implementation of policies that are environmentally sustainable, but that do not significantly compromise strategies to reduce poverty in developing countries.

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Contents

ABSTRACT 2

ACKNOWLEDGEMENT 2

CONTENTS 3

INTRODUCTION 4

PROBLEM IDENTIFICATION 4
OVERVIEW OF EXISTING RESEARCH AND AVAILABLE DATA 5

METHODS 6

AIMS 6
SCOPE 6
ESTIMATION METHODOLOGY OVERVIEW 9
HEALTH DAMAGE ESTIMATION 13
BUILDING AND OTHER MATERIALS DAMAGE ESTIMATION 17
NATURAL RESOURCES AND CROP DAMAGE ESTIMATION 18
OTHER SOCIO-ECONOMIC DAMAGE ESTIMATION 19
VISIBILITY DAMAGE ESTIMATION 19
ECOSYSTEMS 20
SENSITIVITY ANALYSIS 20

RESULTS 22

TOTAL DAMAGES 22
OUTDOOR AIR POLLUTION 25
INDOOR AIR POLLUTION 26
DEVELOPING COUNTRIES 26
DEVELOPED COUNTRIES 27
CONTRIBUTION TO IMPACTS 28
SENSITIVITY ANALYSIS 30

DISCUSSION 31

REFERENCES 34

ANNEX 1 38

Introduction

Problem identification

Air pollution is a problem as old as history itself. Air pollution can be defined broadly as the introduction of chemicals, particulate matter, or biological materials into the atmosphere that cause harm or discomfort to humans or other living organisms, or cause damage to the natural environment or built environment. Air pollution can be classified into anthropogenic and non-anthropogenic origin. The latter includes natural events such as wildfires, volcanic activity and dust/sand storms. This source of air pollution is not considered in this paper as it is largely context-specific, and since the year 1900 is likely to be relatively unimportant compared with air pollution of anthropogenic origin.

Anthropogenic, or man-made, air pollution can be traced back to when humanity discovered how to make fire. While air pollution in those days was insignificant compared to the present time, burning biomass in enclosed spaces for space heating or for cooking purposes would have exposed humans to risk of respiratory diseases and injuries. As human populations became settled and increasingly burned biomass and fossil fuels (such as coal) indoors, the exposure to air pollution and its negative consequences rose significantly. Annex 1 shows the percentage of populations in developing countries burning solid fuels indoors, ranging from 16% of households in Latin America and the Caribbean and Central and Eastern European regions, to 74% in Southeast Asian and Western Pacific regions and 77% in Africa (Rehfuess, Mehta et al. 2006).

Man-made outdoor air pollution, on the other hand, only became a health issue much more recently. The industrial revolution - which began in Great Britain and spread to the rest of Europe, the USA and Japan in the 18th century – increased significantly the combustion of biomass and fossil fuels in urban centers, leading to dangerously high levels of air pollution. Pollutants can be classified as primary or secondary. Primary pollutants are directly emitted from a process, such carbon monoxide gas from a motor vehicle exhaust or sulfur dioxide released from industrial processes. Secondary pollutants such as ozone (O_3) and particulate matter (PM) are not emitted directly, but form in the air when primary pollutants react or interact. Air pollution statistics in urban areas are available from various sources by country or by city, but not compiled globally. Air pollution maps and monitoring information are available from various internet sources[1].

Air pollution's impacts are both direct and indirect. *Direct* impacts include health, damage of materials and ecosystems, and poor visibility. *Less direct* impacts include 'acid rain' which results from chemicals being released into the atmosphere. Changes in human behavior also result from air pollution, such as inhabitants of heavily polluted urban areas relocating or tourists staying away from polluted cities. The main *indirect* impact is climate change. The biomass and fossil fuels that cause air pollution also have caused the warming of the earth's atmosphere resulting from the release of greenhouse gases (GHGs). Therefore, air pollution has many and diverse impacts. In this paper, the

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[1] For example, from European Space Agency http://www.esa.int/esaEO/SEM340NKPZD_index_0.html
the North American Space Agency http://www.nasa.gov/topics/earth/features/health-sapping.html
the US Environmental Protection Agency http://www.epa.gov/oar/oaqps/montring.html
the European Environmental Agency http://www.eea.europa.eu/maps/ozone/welcome
the European Pollutant Release and Transfer Register (EPRTR) http://prtr.ec.europa.eu/DiffuseSourcesAir.aspx

most direct and measurable impacts are captured. The costs of climate change, water resource impact, biodiversity loss and acid rain are assessed in other Assessment Papers.

In reading the findings of this paper, careful interpretation is needed. Air pollution is double-edged. On the one hand, air pollution contributes to and is the result of 'human development'. Exposure to smoke from cooking and heating stoves happened as populations built themselves stable and permanent shelter and expanded the range of edible foodstuffs through various food preparation techniques, including cooking. Thus protection from excessive heat and severe cold, easier living conditions and a better diet contributed to increased life expectancy. Exposure to outdoor air pollution several millennia later was a result of technological and economic development, which also brought about many improvements in standards of living and contributed to increased life expectancy. On the other hand, exposure to air pollution also damages peoples' health and the systems that support them. It is this latter aspect that this paper focuses on. Therefore, while this paper estimates the damage costs of air pollution, it should be kept in mind the various implications – and welfare effects – if humanity had followed a different or slower development path. In theory, mankind could have waited until 'clean' technologies came along before expanding their use for mass production and consumption – however, this would have also stalled the economic development that has taken place, and the many benefits thereof.

Overview of existing research and available data

Economic assessments of outdoor and urban air pollution have been assessed in mainly country- or city-level studies. A number of economic impact studies, also known as damage cost studies, have valued the impacts on health, aesthetics, agriculture, buildings and climate change. The data in these studies are selectively drawn on in this study, and fully referenced in the Methods section. A recent review presents a summary of the health damage cost literature – totaling 17 studies (8 from OECD countries and 9 from non-OECD countries) (Pervin, Gerdtham et al. 2008). The review describes the heterogeneity of study methodologies (components of air pollution, economic impacts included, and valuation approach) and hence widely diverging cost per capita of air pollution-related health impacts from less than one US Dollar to US$ 2,000 per capita. This finding lends support to the conduct of a global study utilizing standard methods.

A second type of economic study is cost-benefit assessment, a technique that examines the economic performance of alternative technology options and/or policy measures to reduce air pollution. This literature has been reviewed previously (Voorhees, Sakai et al. 2001; Hutton 2008; Larsen, Hutton et al. 2008). In some OECD countries such as the USA (United States Environmental Protection Agency 1999), the UK (UK Department for Environment Food and Rural Affairs 2006) and Japan (Kochi, Matsuoka et al. 2001), there have been significant efforts to quantify the benefits of different national policy measures (United States Environmental Protection Agency 2003). On climate change mitigation, several studies have examined the costs and benefits of GHG mitigation, including previous Challenge Papers of the Copenhagen Consensus Center. One of these papers explores the potential for a reduction in black carbon emissions to avert climate change (Montgomery, Baron et al.). The paper concludes that introducing measures in China would achieve reductions in black carbon emissions at considerably lower cost than other world regions.

For indoor air pollution, there are fewer economic studies. There are no damage cost studies. However, there are a handful of cost-benefit studies. One study evaluates the costs and benefits of selected indoor air quality interventions for developing world regions, comparing improved biomass cook stoves with a switch to fuels less polluting for the indoor environment (Hutton, Rehfuess et al. 2006; Hutton, Rehfuess et al. 2007). At the country level, two studies examine the costs and benefits of efficient cook stoves implemented under a cooperation of the German Government in Malawi (Habermehl 2008) and Uganda (Habermehl 2007).

Despite the cited studies, there remain major gaps in knowledge on overall global damage costs for both indoor and outdoor air pollution, and the evolution of economic damages over time. Some non-health damages have still not been evaluated at the global level, such as the impacts of outdoor air pollution on crops, biodiversity and visibility.

Methods

Aims

The aim of this paper is to generate new estimates for the global damage costs of air pollution over a 150-year time period, from 1900 to 2050. The paper focuses exclusively on air pollution of anthropogenic origin.

Scope

As is conventional practice, air pollution is split into outdoor air pollution and indoor air pollution, given that they involve different emission sources and vulnerable populations.

Outdoor air pollution is mainly a phenomenon of cities and towns, including peripheral urban areas and corridors where there is significant traffic and/or industrial activity. Outdoor air pollution remains a problem of developed countries as well as increasingly a problem of many developing countries.

Indoor air pollution results from burning of biomass and fossil fuels for the purposes of cooking and space heating. The free or low-cost availability of biomass, and the higher cost or limited availability of cleaner fuel options in rural areas (e.g. electricity, liquefied petroleum gas, or LPG), have meant that a major share (67%) of households in developing countries continue to use solid fuel (Rehfuess, Mehta et al. 2006).

While there is unarguably some overlap between indoor and outdoor air pollution[2], this study assesses them separately. At a global scale, this assumption is not expected to have a major impact on the precision of the results. The gathering and use of global epidemiological evidence by WHO and others explicitly avoids any possible double-counting of health impacts of these two sources of air pollution.

The various types of damage caused by air pollution were reviewed from the literature (Kochi, Matsuoka et al. 2001). The damage costs that are relevant for each type of air pollution and those quantified in this paper are shown in Table 1.

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[2] Smoke generated from indoor sources can lead to a critical mass in densely populated areas and hence cause outdoor air pollution, and contributes to pollution caused by industrial areas and vehicle emissions. The reverse is also true: pollution from outdoor air can easily penetrate buildings and get trapped, hence causing indoor air pollution.

Table 1. Damage costs included in this study

Impact	Outdoor		Indoor	
	Impact relevant	**Quantified in this study**	**Impact relevant**	Quantified in this study
Human health - mortality	√	√	√	**√**
Human health - morbidity	√	√	√	**√**
Aesthetics (visibility)	√	√	√	
Buildings / non-organic materials	√	√	√	
Agriculture / timber	√	√		
Climate change*	√		√	
Ecosystems / biodiversity*	√			
Water resources for human use*	√			
Acid rain*	√			
Other socio-economic (time use)			√	**√**

* These impacts are covered in the scope of other Assessment Papers

The damage costs associated with the human health impacts were included for both indoor and outdoor air pollution, due to their importance. While of relevance for indoor air pollution, the damages associated with aesthetics and buildings were only estimated for outdoor air pollution due to paucity of data for indoor air pollution. The main source of impact on the agricultural sector is from outdoor air pollution, which was estimated in this study. While of potential relevance, the climate change, ecosystem, water resource and acid rain impacts of outdoor air pollution were not estimated in this study as they are covered in the scope of other Assessment Papers. Other socio-economic impacts of indoor air pollution were included, in particular the time losses of collecting biomass fuels.

While the purpose of this paper is to present overall global damage costs, it is also instructive to show a regional breakdown, given that the current size and the time trends vary between different countries and regions based on their level of development and policy environment. However, due to data constraints, it was most feasible to make a single distinction between developed and developing countries (see Table 2). The most constraining two factors in presenting damage costs for different world regions were (1) the lack of model input data on some key damage areas, in particular the non-health related damages; and (2) the use of different regional classifications in the published literature for presenting air pollution damages, making it hard to extract the data to make damage cost estimates based on a single regional classification.

The time period indicated for this study presents problems due to the lack of global historical data on air pollution damages, as well as uncertainty of future projections 40 years ahead based on unpredictable patterns of economic growth and policy measures over that time period. Hence both geographical and time extrapolations are needed which generate significant uncertainty in the results.

Table 2. Regional classification and populations

Classification	Countries/regions	Population (billion)		
		1900	**2010**	**2050**
'Developing countries'	Asia, Africa, Latin America and the Caribbean	1.02	5.72	8.15
'Developed countries'	Europe (including ex-USSR), USA, Canada, Australia, New Zealand, Japan	0.54	1.29	1.40

An overview of the data available and the data missing is presented in Table 3. While several global databases are available, some key data sets providing a comprehensive overview of global damages are missing, thus requiring assumptions and extrapolation of data over time or across countries and regions. These data sources, and the approaches to filling the gaps, are described in the sections below.

Table 3. Overview of data available for global damage cost study

Variable	Data available	Data not available
Coverage and exposure	• Published piecemeal data on pollutant emission and outdoor air quality in urban areas of developed and some developing countries • Global database on solid fuel use (WHO)	• Global compiled database on indoor and outdoor air quality indicators
Health benefits	• Global databases on deaths, cases, DALYs with regional and country breakdowns (1990-2010), and some projections made to 2020 for major categories of disease (WHO) • Global database on unit costs of health services in the period 2000-2010 (WHO, DCPP) • Piecemeal studies on the costs of treating selected diseases in selected countries • Value of life studies from developed countries from 1990 onwards, and few studies from developing countries	• Global updated databases on deaths, cases, DALYs with regional and country breakdowns (1900-1990 and 2010-2050) • Global compiled data on the health economic impacts of poor air quality • Global compiled data on the unit costs of treatment of air pollution-related illnesses • Value of life in developing countries, and developed countries prior to 1990
Non-health benefits	• Published piecemeal data on economic damages of outdoor air pollution (mainly developed countries) • Global study on the benefits of reducing indoor air pollution in developing countries (WHO)	• Global compiled data on the economic non-health impacts of poor outdoor air quality (aesthetics, crops, buildings, materials, etc) • Economic benefits of non-health effects of improving indoor air quality in developed countries
Other	• Global databases on historic, current and projected population size and economic product (e.g. GDP and GDP per capita) (CCC)	

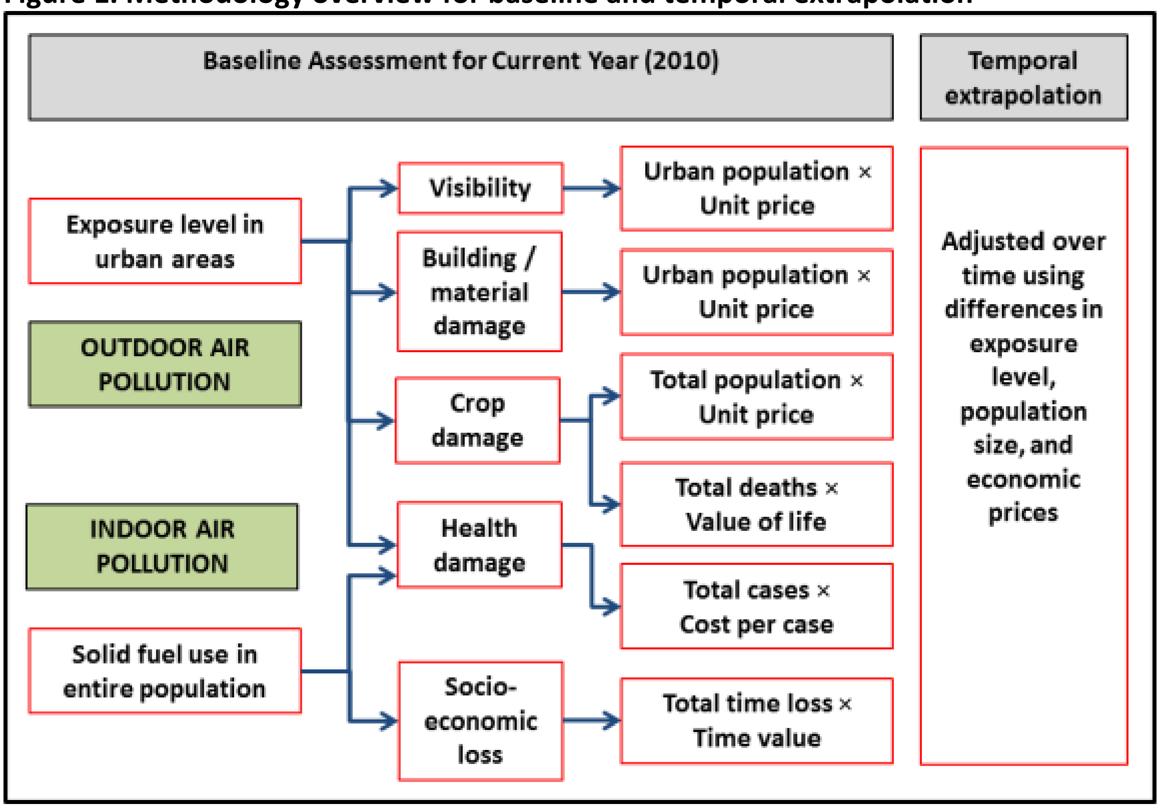
Key: WHO – World Health Organization; DCPP – Disease Control Priorities Project; CCC – provided by various United Nations agencies and adapted by the Copenhagen Consensus Center.

Studies have shown damage costs to *other* countries produced by outdoor air pollution released by the emitting country. For example, in the ExternE project funded by the European Commission, Friedrich et al show that more than half of the damage costs of pollutants released in Germany actually fall on other countries (Friedrich, Rabl et al. 2001). However, the global nature of this study means that external damage costs of pollutants released by one country in another country are incorporated in the estimates, as far as the impacts have been captured by the estimation methodology.

Estimation methodology overview

Air pollution impacts are based on exposure to air pollution. For urban air pollution, the population at risk is the urban population, except for crop damages which are estimated on a total population basis. For indoor air pollution, the population at risk is calculated at the total population level, based on solid fuel use. **Error! Reference source not found.** provides an overview of the methodology for aseline assessment for the current year, and temporal extrapolation.

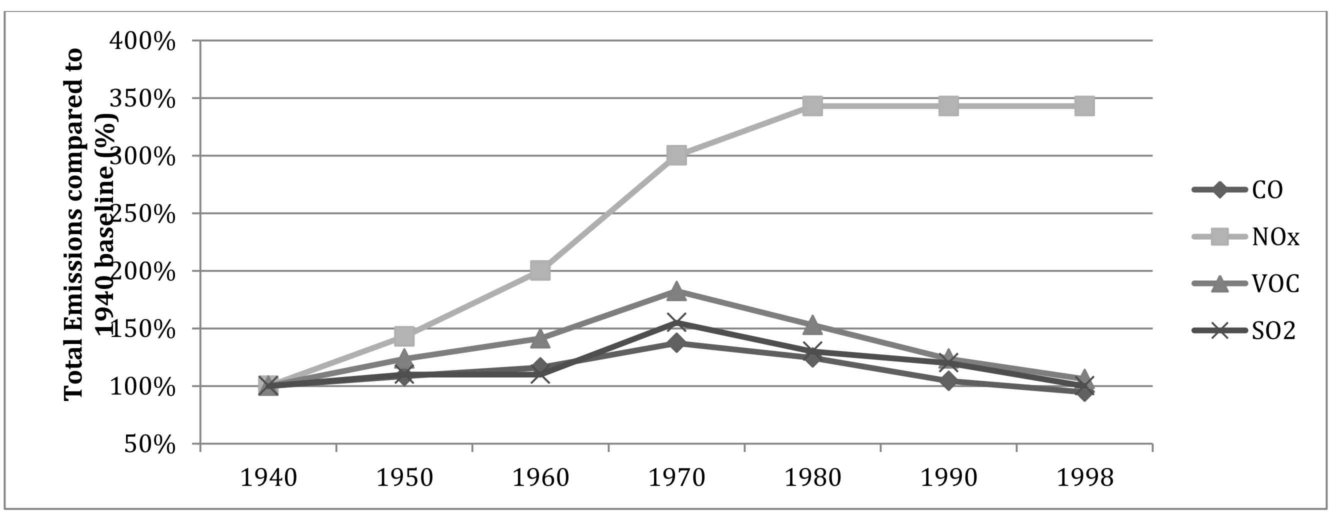
Figure 1. Methodology overview for baseline and temporal extrapolation



The assumptions on the relative exposure levels to the current time period are underpinning all intertemporal extrapolations. The comparative exposure levels over time of outdoor air pollution are assessed, based on the development stages outlined by Mage (Mage, Ozolins et al. 1996): (1) industrial development, (2) emissions controls, (3) stabilization of air quality, and (4) improvement of air quality. Figure 3 shows the average evolution in urban air quality in both developed and developing countries. In developed countries, the exposure rises from 1900 to 1970, followed by a gradual decline in exposure as public health awareness increases and legislation is adopted to reduce emissions. For example, in the USA, emissions of polluting compounds rose from 1940 to 1970 and declined to 1940 levels in 1998, as shown in Figure 2 (United States Environmental Protection Agency 2000). The same study also reports reductions of 76% in particulate matter on the order of ~10 micrometers or less (PM_{10}) from 1940 to 1998. Levels of lead emissions also declined sharply from 1970 (220 thousand tonnes) to 1990 (5 thousand tonnes), after the Clean Air Act was passed in 1963 and the first Federal emissions standards for motor vehicles in 1965. Going back further, but with weaker data, the study estimates sulfur dioxide (SO_2) and volatile organic compound (VOC) emissions doubled from 1900 to 1940, while mono-nitrogen oxides (NOx) increased by a factor of 2.5. In Europe, emissions reductions from 1990 to 2008 are reported by the European Environment Agency across 27 EU countries - the total reduction in SO_2 emissions for this period was 78%, nitrogen dioxide (NO_2) 39%, VOC 51%, and carbon monoxide (CO) 58%. PM_{10} declined from 2000 to 2008 by 8% and particulate matter on the order of ~2.5 micrometers or less ($PM_{2.5}$) by 13% (European Environment Agency 2010). In Japan, the 1967 law for environmental protection lead to a reduction in SO_2 concentrations from 0.040 parts per million in 1967 to 0.0050 parts per million in 1992 (Kochi, Matsuoka et al. 2001).

After the year 2000, the exposure is expected to decline further in developed countries, but at a much slower rate than previously. By the year 2050, air quality across the developed world is assumed to be 20% improved over current levels based on the continued implementation of clean technologies and behavior change (e.g. reduced average distance traveled per person by car). The increasing proportion of the population living in urban areas will increase the population exposed to outdoor air pollution, even if pollution levels decline.

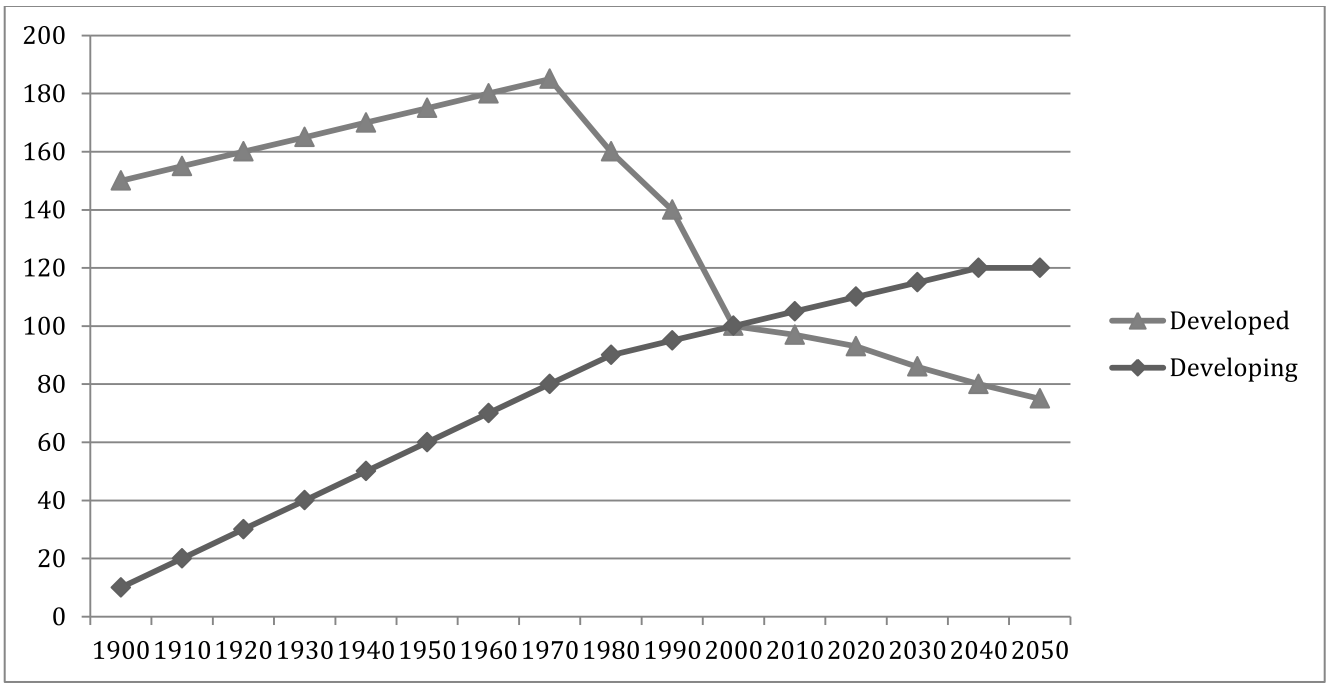
Figure 2. Trends in emissions of nitrous oxides, carbon monoxide, sulfur dioxide and volatile organic compounds in the USA from 1940 to 1998 (1940 = 100)



Source: (United States Environmental Protection Agency 2000)

The evolution of urban air pollution in developing country cities is very different to that of developed countries. In 1900 it is assumed there are very few urban centers in the developing world with serious air pollution related to burning of fossil fuels or biomass. A gradual growth is assumed from 1900 to 2000, with continued growth beyond 2000 due to economic growth, balanced by technology transfer. It is difficult to generalize across the entire developing world, given that some cities have already implemented air quality standards, and as a result are experiencing declining pollution levels. One study reports emissions in selected Asian cities, indicating a greater than 10% decline in PM_{10} and nitrogen dioxide (NO_2) concentrations, and an 80% reduction in SO_2 emissions (Clean Air Initiative for Asian Cities (CAI-Asia) Center 2010). The same report suggests declining PM_{10}, NO_2 and SO_2 levels across 243 cities of Asia.

Figure 3. Exposure to outdoor air pollution, evolution from 1900 to 2050 (Year 2010 = Index 100)

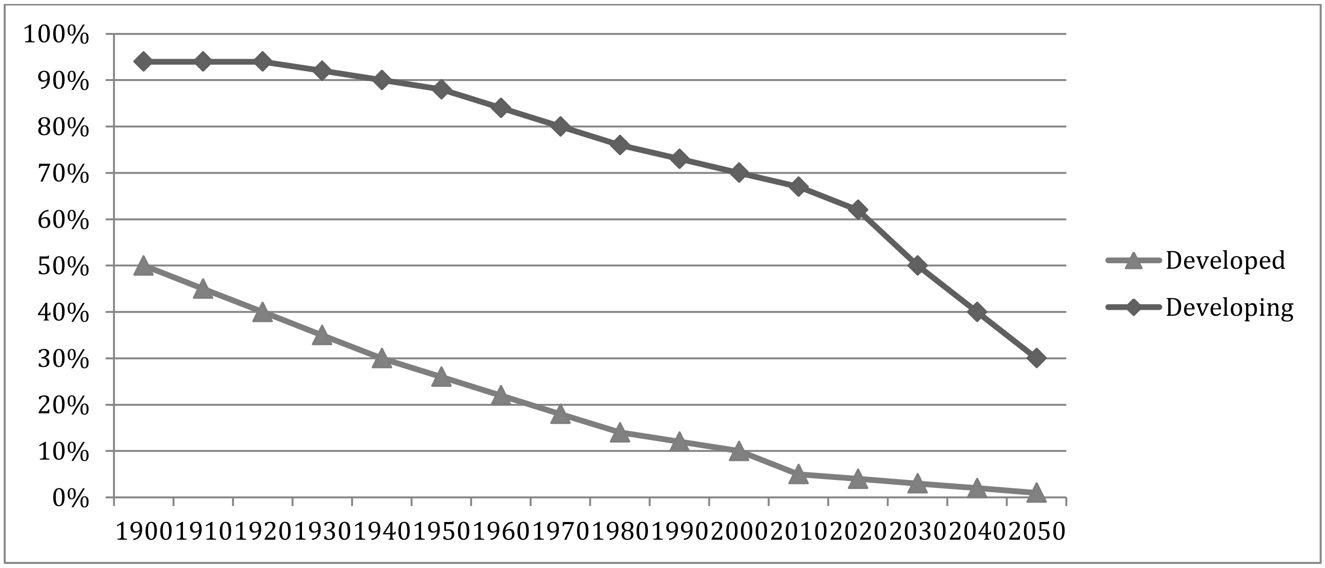


Source: authors estimates

Exposure to indoor air pollution is estimated using the rate of solid fuel use to reflect the exposure of populations to indoor air pollution. However, global monitoring of solid fuel use is a recent phenomenon, hence assumptions must be made for solid fuel use from 1900 until 1990. In developed countries, solid fuel use is estimated at 50% in 1900 (Bruce, Perez-Padilla et al. 2002)[3] with gradual and linear decline until 2010 when the rate is estimated at 5%. In developing countries, solid fuel use is assumed to be 95% in 1990, declining to 67% in 2010, and a faster decline after 2020 assuming successful implementation of ongoing and future clean cook stove and fuel switching programmes to reach 30% in 2050.

[3] It is estimated the portion of global energy derived from biofuel was 50% in 1900.

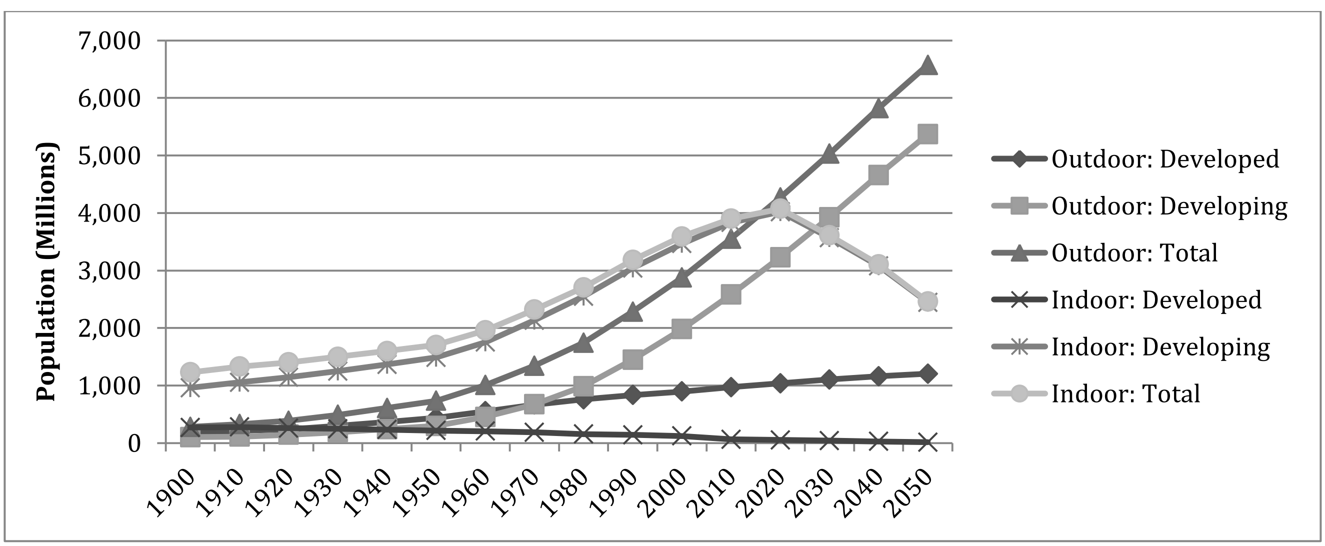
Figure 4. Exposure to indoor air pollution: solid fuel use (% of households), evolution from 1900 to 2050



Source: authors estimates. Years 1990 to 2010 based on global statistics.

Based on the urban population and the rate of solid fuel use, Figure 5 shows the total population exposed. Those living in urban centers is forecast to rise from 3.6 billion in 2010 to 6.6 billion in 2050. The severity of exposure is not reflected in these numbers. For urban areas, severity of air pollution of exposed populations is expected to decline in areas where pollution control measures are successfully implemented, and increase where urban centers where more fossil fuels are burned without accompanying pollution reduction measures. The global population exposed to indoor air pollution is predicted to decline from 3.9 billion in 2010 to 2.5 billion in 2050. If smokeless and more efficient biomass stoves are scaled up in the developing world, the exposure level will also decline, as well as the number exposed.

Figure 5. Total population exposed to air pollution



* Note, for outdoor air pollution exposure, the severity of air pollution is not reflected here (see Figure 3).

Given the high degree of uncertainty in all these assumptions, especially at the extremes of the 150-year time period covered in the study, sensitivity analysis explores high and low exposure levels (see later section).

Health damage estimation

Impacts included

Two types of health impact are valued in the damage cost assessment:

- Premature mortality – costs of lives lost due to air pollution.
- Morbidity – costs of (1) medical treatment of air pollution-related illnesses, and (2) lost time due to time spent sick.

Estimation method

For outdoor air pollution, published studies focus on cities or parts of countries (Li, Guttikunda et al. 2004; Stevens, Wilson et al. 2005; Perez, Sunyer et al. 2009) as well as selected country examples (Seethaler 1999; United States Environmental Protection Agency 1999; Zaim 1999; Kochi, Matsuoka et al. 2001; Netalieva, Wesseler et al. 2005; UK Department for Environment Food and Rural Affairs 2006). Given the comparatively rich global data set on health impacts of air pollution, and the established methods for valuing health impacts in monetary units, this paper makes a new set of calculations of health economic impact based on mortality and morbidity impacts and assigns unit cost values to each of these.

Available health impact studies

The latest global burden of disease study is from the WHO, estimating deaths and DALYs for the year 2004 (World Health Organization 2008). Data on deaths, cases and DALYs is available for the early 1990s from Smith and Mehta (Smith and Mehta 2003) for indoor air pollution in developing countries.

Methods for valuing health impacts

Values are required for three variables to estimate health-related damage costs: cost of premature death, medical cost of an illness episode and productive loss associated with an illness episode. For premature death, there are several alternative methods of valuation: (a) value-of-statistical life, using estimates of values associated with a small change in the risk of death and multiplying up to estimate the value associated with saving one equivalent life; (b) human capital approach, which values the future net value contribution of individuals to society based income over their remaining working life; and (c) values obtained from life insurance companies or court cases where members of families are compensated for the death of an individual due to accident or injury.

The most established and widely used method for valuing life in economic studies is the value-of-statistical-life (VOSL) method. Unlike the human capital approach and life insurance estimates, VOSL is based on welfare theory, as it reflects the preferences and behavior of individuals. The human capital approach, on the other hand, which values a person according to their contribution to the economic wealth of society, does not take into account the intrinsic value of life and hence may undervalue life.

Value of a life year (VOLY) is a more recently adopted technique, to give greater preference to saving lives of those with longer to live. However, there are several problems with VOLY (Krupnick, Ostro et al. 2005). The lack of global data on age-specific premature mortality from air pollution-related diseases supports the use of a single value of life, applied to all age groups equally.

There exists a rich literature, mainly from OECD countries, of VOSL studies using different valuation techniques and different industries or population groups as the basis for the estimates. Several meta-analyses exist. Table 4 shows a number of these. For high-income countries, the mean or median estimates start at US$ 1,500,000 (1998 prices) from a review conducted by Mrozek and Taylor. However, more recent reviews tend towards US$5,000,000. In several of the studies in Table 4 that estimate both mean and median values from literature studies, the mean values are usually higher than median values, as the former are upward biased by few very large willingness to pay responses. Also, different valuation methods give different VOSL results. For example, wage risk studies tend to give higher VOSL values than studies that use contingent valuation (based on responses from interviews). Dionne et al compare meta-analysis results based on different types of study, and find that transportation studies on willingness to pay for risk reduction give a VOSL on average 35% lower than all studies combined (comparing 8.3 versus 5.2 million Canadian Dollars) (Dionne and Lanoie 2002).

Given the wide variance between individual as well as meta-analytical studies and the differences observed between valuation techniques, choosing a single VOSL for this current study is more a matter of judgement than scientific assessment. It is preferable to avoid choosing a VOSL in the baseline analysis that risks overestimating the value of life. Based on the fact that the main population group likely to die prematurely from air pollution is the elderly, therefore wage risk studies are not appropriate basis for VOSL estimates. Hence the lower estimates of the published meta-analyses should be used. Taking into account deflation to 1990 Dollars, a VOSL of US$ 3 million is chosen for developed countries. In the sensitivity analysis, a range of US$ 1 million (low value) to US$ 5 million (high value) is used.

For developing countries, in their review Cropper et al for the World Bank identified 16 studies that estimate VOSL (Cropper and Sahin 2009). Most of these studies are from middle-income countries. The authors conclude: "What is clear is that the developing country literature at this point is not sufficiently mature to provide estimates for individual countries. This suggests transferring estimates from countries where better studies exist to countries for which there are no empirical estimates of the VSL" (page 18). Hence the authors adopt the 'benefits transfer' technique to estimate the VOSL in developing countries, using a VOSL from developed countries of US$ 5.4 million from Kochi et al (Kochi, Hubbell et al. 2006). This value was adjusted using the proportional difference in GDP per capita between high-, middle- and low-income countries[4]. The mean VOSL for middle-income countries was estimated at US$ 709,000 and for low-income countries it was US$ 180,000, in 2005 prices. This present study uses a similar method, transferring the value of US$ 3 million from developed countries – adjusted based on the GDP differential at official exchange rates and with an

[4] The latest World Bank classification of countries by income level uses Gross National Income in United States Dollars ($) from 2009, with the following thresholds: low income, $995 or less; middle income, $996 - $12,195; and high income, $12,196 or more. http://data.worldbank.org/about/country-classifications

income elasticity of unity. This gives an average value of US$ 685,000 (at 1990 prices) for developing countries used in this present study.

Table 4. VOSL estimates from selected meta-analyses

Regional grouping	Price year	Type of average	Value in US$	Author
High income	2005	Mean	4,271,000	(Cropper and Sahin 2009)
Middle income	2005	Mean	709,000	
Low income	2005	Mean	180,000	
High income / Europe	2004	Mean	1,520,000 – 3,280,000	(Alberini, Hunt et al. 2006)
High income (wage risk)	1996	Median	5,630,000	(Day 2007)
	1996	Mean	10,075,000	
High income	2002	Mean	2,500,000	(Abelson 2003)
High income	2003	Mean	5,400,000	(Kochi, Hubbell et al. 2006)
High income	1998	Mean	1,500,000 – 2,500,000	(Mrozek and Taylor 2002)
High income / USA (wage risk)	2002	Median	7,000,000	(Viscusi and Aldy 2003)
High income (stated preference)	2005	Mean	6,256,000	(Braathen, Lindhjem et al. 2009)
	2005	Median	2,814,000	
OECD countries Wage risk	2005	Mean	9,523,000	(Bellavance, Dionne et al. 2007)
	2005	Median	6,599,000	
USA (EPA)	2003	Mean and median	5,500,000 – 7,500,000	(Simon 2004)
Canada (road safety)	2000	Mean	5,528,000	(Dionne and Lanoie 2002)
	2000	Median	3,996,000	

The medical cost per case will vary between contexts depending in particular on (a) the type and severity of the condition; (b) the probability of seeking health care, the level and type of health facility visited, and the probability of being referred to a higher level of care; and (c) the unit costs per case treated. Given that the estimates are not based on country-specific inputs, it is necessary to make an estimate of a cost per average case of moderate severity ('moderate' being the most common medical complaint when medical advice is sought). For a moderate severity of a respiratory condition, the following assumptions are made to estimate an average unit cost (Hutton, Rehfuess et al. 2006):

- 50% of cases visit an outpatient clinic at the lowest level of care, and 20% of these require a follow-up visit.
- 10% of cases visit an outpatient clinic at secondary level of care.
- 10% of all patients are admitted for a hospital stay of an average 5 days.
- In 2010, unit costs of outpatient care are US$70 in developed countries and US$5 in developing countries at the lowest level of care, and US$100 in developed countries and US$15 in developing countries for referral outpatient care. Unit costs of inpatient care are US$200 per bed day in developed countries and US$30 per bed day in developing countries.

Based on these rates of health care use and unit costs, the average cost per illness episode in 2010 equals US$159 in developed countries and US$20 in developing countries. The latter is a conservative estimate of likely costs per case in developing countries. For example, a study estimated the population is willing to pay US$44 in 1990 US$ for averting cases of lower respiratory infection in Mumbai, India (Lvovsky 1998). Unit costs in 2010 are adjusted to other time periods based on the proportional difference in GDP per capita compared to 2010.

The loss in economic value due to loss of productive time will depend on two main factors: (a) the time taken off productive activities by the sick person, and (b) the opportunity cost of that time, which depends, among other things, on the person's age, education level and the activity that could not be carried out due to sickness.

a) Respiratory illnesses vary in their severity, and the time to become well again and return to normal functioning will also depend on whether the right treatment was given. Some illness cases will last a short time – maximum 1 or 2 days – while the more severe cases may last for several weeks such as pneumonia, or be a permanent disability such as asthma, chronic obstructive pulmonary disease (COPD) and cancer. A conservative estimate of 5 days per case lost from productive activities is used in this study, which is the same for all time periods (Hutton, Rehfuess et al. 2006).
b) Being an economic analysis, this study considers broader welfare implications of time lost from illness than just wage losses (for paid employees) or lost production time (e.g. for subsistence farmers). Hence, other activities than paid employment are considered in the assessment of opportunity cost of time. For one, leisure time is also valued by adults (Feather and Douglass Shaw 1999). Also, children of school age will miss education time, and these children – as well as children of 0-5 years – will require the care of a family member of other carer. Previous studies have commented that the value of time lost at the wage rate would overstate the actual losses, due to the substitutability of labor. A differential valuation of time of different age groups is not possible due to the lack of age breakdown of respiratory diseases at a global level. Therefore, to avoid overestimation, a more conservative value of time at the rate of 30% of the GDP per capita is used (Senhadji 2000).

<u>Time extrapolation of available data sets</u>

There are some but limited disease burden estimates before 1990, and projections after 2010. The problem inherent in using past and future values from other studies is that the methods and data sources may be different, hence leading to estimates that are inconsistent with the best current estimates for 2004. Therefore, disease burden estimates are scaled according to the average population exposure to main risk factors (see Figure 3 for outdoor air pollution exposure and

Figure 4 for solid fuel use).

Building and other materials damage estimation

Impacts included

Various impacts have been previously evaluated:

- Acid corrosion of stone, metals and paints due to SO_2 and NO_X.
- Ozone damage to polymeric materials, particularly natural rubbers.
- Soiling of buildings and materials including both “utilitarian” and historic buildings and causes economic damages through cleaning and amenity costs.
- Acid impacts on materials of cultural merit (including stone, fine art, and medieval stained glass).

The impacts included are limited to those impacts where there have been damage costs expressed in total terms for an identifiable population (typically at country level).

Estimation method

From available studies, the cost per person in urban areas is calculated based on overall economic damages divided by the urban population.

Available impact studies

Lee et al estimated annual damages to the UK of £170 to £345 million for impacts on surface coatings (paints) and elastomers and the cost of antiozonant protection used in rubber goods (Lee, Holland et al. 1996). The cost is equivalent to US$ 5 to US$ 9 per capita/year in 1990 prices. Damage to rubber goods from ozone exposure in the UK was estimated at between £35 to 189 million, with a best estimate of £85 million/year, or US$ 2 per capita/year.

A series of studies from France, summarized in Rabl, estimated the air pollution contribution to damage of historical buildings at US$ 2.4 per person/year and to utilitarian buildings US$4 per person/year in 1990 (Rabl 1999), totaling US$ 7.4 per person/year in 2000 prices.

Some studies estimate cost savings of SO_2 control policies, such as in Budapest (US$50 per inhabitant) (Aunan, Patzay et al. 1998), Prague (US$110 per inhabitant) and Stockholm (US$20 per inhabitant) (Kucera, Henriksen et al. 1993).

Based on the available studies, and taking account that the damages studied only cover part of the overall damages to buildings and materials, the damage cost used in this study is US$20 per capita/year in urban areas of developed countries. Based on the higher estimates found in the literature, this is likely to be an underestimate of average actual damages per person.

Fewer studies are available from developing countries. In Colombo, Sri Lanka, the average property damage cost due air pollution is US$118 per year per household, or approximately US$20 to US$25 per capita/year (Batagoda and Shanmuganathan 2004). From the same study, the average willingness to pay of the population to avoid property damage was estimated at US$5 per household/year, compared to US$14 to improve overall air quality.

Extrapolation of available data set

The unit costs per person living in urban areas from country- or city-level studies are extrapolated to other countries, world regions and time periods based on population exposed (based on the proportion of population living in urban areas), relative pollution level and economic levels (GDP per capita).

Natural resources and crop damage estimation

Impacts included

Ozone is recognized as the most serious regional air pollution problem for the agricultural and horticulture sectors (Delucchi 2000). The impact of acid rain on natural resources and crops is the subject of a separate Assessment Paper.

Estimation method

Studies in the literature on economic loses due to crop damages use either a mathematical approach (based on dose-response relationships from experimental studies) or they use an econometric model (based on observed changes in actual farm output due to a change in pollution). These estimates are extracted from studies and converted to average loss per capita per year, and are extrapolated to other time periods and geographical zones based on air pollution levels and economic level (GDP per capita).

Available impact studies

The US EPA (1999) reports a total annual benefit to the US commercial timber sector of approximately $800 million and to grain crop producers of about $700 million in 2010 from improved yields due to ozone reductions as a result of the 1990 Clean Air Act Amendments (CAAA) (Chestnut and Mills 2005). Other studies have shown significantly greater impacts. Several studies were published during the 1990s on losses to US agriculture due to ozone. Losses due to vehicular pollution alone were estimated at between US$2 billion and US$3.9 billion by Murphy (Murphy, Delucchi et al. 1999), between US$ 2.6 and US$ 5.3 billion by Delucchi et al in 1990 (Delucchi, Murphy et al. 1996), while US$ 1.2 billion was estimated by Muller and Mendolsohn (Muller and Mendolsohn 2007). Hence, the cost in the US ranges from US$5 to US$20 per capita/year.

European countries have also been the focus of other crop loss studies. In Hungary, as much as US$716 million losses due to ozone-induced crop losses, or US$100 per capita (Aunan, Patzay et al. 1998). The PESETA[5] study estimated crop losses of €6.7 billion across 47 European countries, or €12 per capita (US$16 per capita) (Ciscar and Soria 2009). A UNECE study estimated £4.3 billion (US$6.8 billion) across 36 European countries, or US$12 per capita, in 1990 (Holland, Mills et al. 2002). A cost-benefit analysis carried out under the Clean Air For Europe (CAFE) programme estimates damage costs in EU countries in the year 2000 for crop damages (€2.8 billion) and materials (€1.1 billion), equal to €8 per capita, or US$11 (Pye and Watkiss 2005). A study from the mid-1980s in the Netherlands estimated crop losses at US$320 million per year, or US$22 per capita (van der Eerden,

[5] Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis

Tonneijck et al. 1988). Therefore, adjusting to 1990 Dollars, this study uses US$20 per capita for developed regions, and US$5 per capita for developing countries.

Other socio-economic damage estimation

Impacts included

The time losses from collecting biomass and the time spent cooking with inefficient and polluting stoves or fuel are valued in this study.

Estimation method and available study

A global study was conducted by the World Health Organization in 2006 which estimated the health, environmental and time gains from measures to reduce exposure to indoor air pollution (Hutton, Rehfuess et al. 2006). The study covered only non-OECD countries. The value of the time lost per year of US$88 billion is used for developing countries for the year 2000, and also extrapolated to non-OECD countries adjusting for population sizes, economic prices (GDP per capita) and rates of solid fuel use.

Visibility damage estimation

Impacts included

Particulate matter in the air absorbs and scatters light as it passes through the atmosphere, reducing the clarity of viewed objects and visual range. Analyses of visibility often use a measure of haziness called the 'Deciview'. Visibility conditions directly affect people's enjoyment of a variety of daily activities. Individuals value visibility where they live and work, where they go for recreation, and at sites of unique aesthetic value such as national parks.

Estimation method and available impact studies

This study identifies economic impact studies in the literature and extrapolates them across time and geographical location. Economic studies have estimated monetary values held by the visitors to facilities (such as historical monuments or national parks) and of the general public in their place of abode for changes in visibility. Most work has been conducted in the USA. For example, the estimate of the total annual value for visibility improvement at all national parks and wilderness areas is about $3 billion (Chestnut and Mills 2005). Adding to this value the WTP estimates of households for visibility improvements in locations where they live brings the total value of related Title IV (also known as the acid rain program) visibility improvements to about $5 billion, or US$17 per capita. A comprehensive damage cost study from the US estimates visibility as having a value of US$2.7 billion annually (Muller and Mendolsohn 2007), or US$10 per capita. Delucchi estimates visibility losses at between US$5 and US$37 billion per year, or US$20 to US$150 per capita/year (Delucchi 2000), and in a later paper US$8 to US$31 billion (Delucchi, Murphy et al. 2002).

This study uses an estimate of US$10 per capita/year for loss of visibility in developed countries, applied to the urban populations where the major loss of visibility takes place. This value is extrapolated to developing countries adjusting by differences in GDP per capita. Extrapolations are made over time adjusting for economic prices (GDP per capita), population size and pollution levels.

Ecosystems

Damage costs to ecosystems are estimated in another Assessment Paper, so estimates are not included within this paper. Table 5 presents a range of different impacts on ecosystems identified by the United States EPA. A study produced by the EPA estimated annual economic losses avoided from implementing the clean air act by 2010, which included: estuarine ecosystems (US$2.7 billion), acidification of freshwater fisheries (US$88 million), aesthetics of 2 selected forests (US$250 million), timber production losses (US$600 million), and net surplus on crop production (US$1.1 billion) (United States Environmental Protection Agency 1999). With a population of 312 million in 2010, this gives a benefit of US$15 per capita/year. As these figures reflect damages avoided from a partial reduction in emissions, the total damages are likely to be considerably more than these figures.

Table 5. Ecological impacts with identifiable human service flows

Pollution source	Causal pathway of impact	Activity impacted
Acidification (H_2SO_4, HNO_3)	High-elevation forest acidification resulting in dieback	Forest aesthetics
	Freshwater acidification resulting in aquatic organism (e.g. fish) population decline	Recreational fishing
	Changes in biological diversity and species mix in terrestrial and aquatic systems	Existence value for maintenance of biological diversity
Nitrogen Saturation and Eutrophication (NOx)	Freshwater acidification resulting in aquatic organism (e.g. fish) population decline	Recreational fishing
	Estuarine eutrophication causing oxygen depletion and changes in nutrient cycling	Recreational and commercial fishing
	Changes in biological diversity and species mix in terrestrial and aquatic systems	Existence value for maintenance of biological diversity
Toxics Deposition (Mercury, Dioxin)	Terrestrial bioaccumulation of mercury and dioxin	Hunting, wildlife aesthetics
	Aquatic bioaccumulation of mercury and dioxin	Recreational and commercial fishing
	Changes in biological diversity and species mix in terrestrial and aquatic systems	Existence value for maintenance of biological diversity
Tropospheric Ozone (O_3)	Terrestrial plant foliar damage causing lower productivity	Commercial timber productivity and reduced competitiveness forest aesthetics, existence value
Multiple Pollutant Stress	Ecosystem deterioration resulting in visual effects habitat loss, and changes in biological diversity and species mix caused by synergistic action of several pollutants	Ecosystem aesthetics, and ecosystem existence value

Source: US EPA (United States Environmental Protection Agency 1999)

Sensitivity analysis

While this study has used a number of assumptions, the sensitivity analysis focuses on two single variables that are expected to influence the results. These are (a) the economic value of life and (b) the historical and projected pollution levels. The latter leads to changes in estimates in the years before and after the baseline, but no changes in the actual baseline years. For both these variables, high and low values are used. The ranges on the pollution level variables are shown in Figure 6 (outdoor air pollution) and Figure 7 (indoor air pollution). For VOSL, a low value of US$ 1 million and a high value of US$ 5 million are used for the year 2010 in developed countries. For developing countries, a low value of US$ 228,560 and a high value of US$ 1,142,800 are used for the year 2010. For pollution levels, high and low assumptions are used to provide a range around the baseline assumptions from 1900 to 1990 and from 2020 to 2050. For other variables such as health care unit costs, GDP values, population sizes and health impacts (deaths and cases), there is less uncertainty in their values and hence are not tested in the sensitivity analysis.

Figure 6. Uncertainty range tested in pollution exposure in urban centers

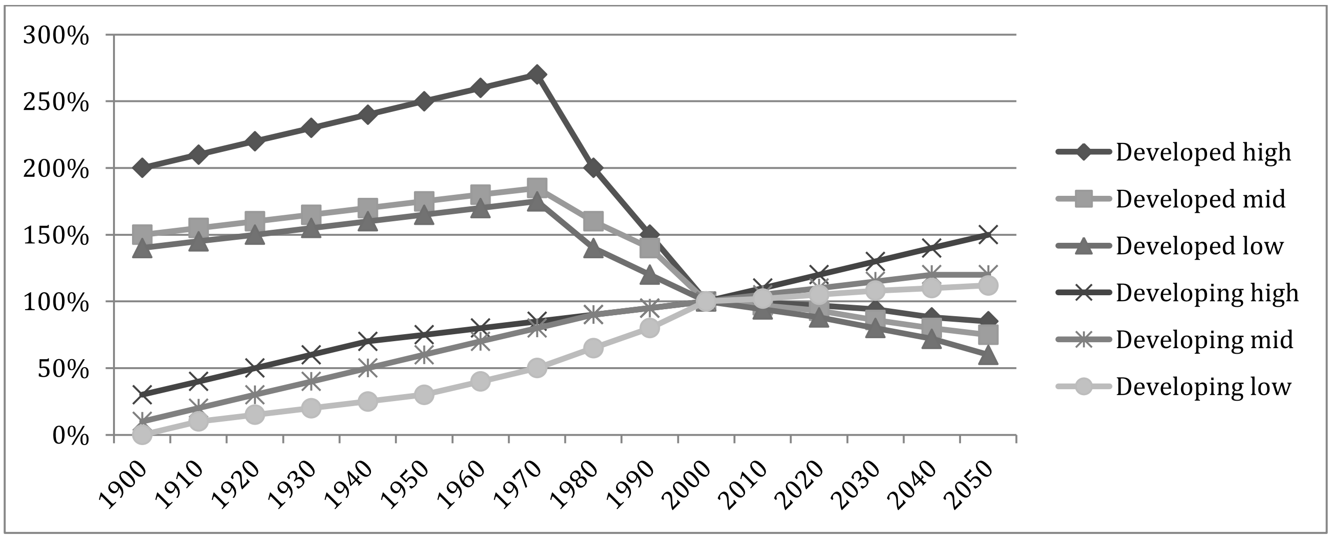
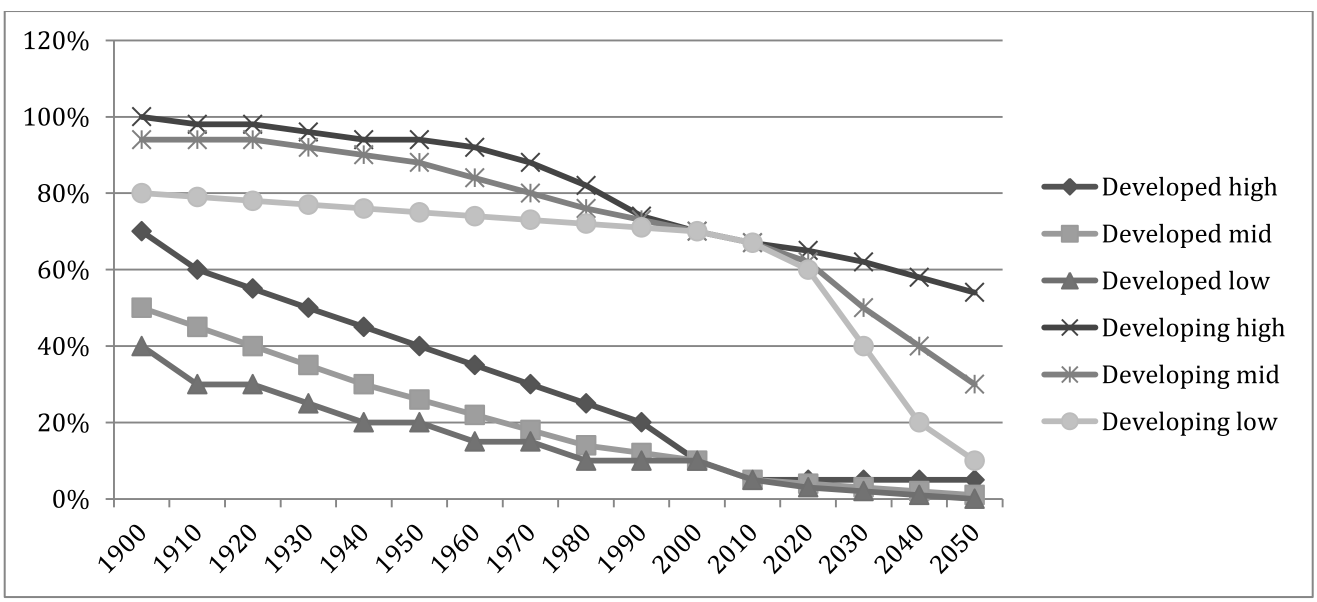


Figure 7. Uncertainty range tested in solid fuel use



Results

Total damages

This study estimates the total damage costs of air pollution to be US$ 3.0 trillion in 2010, or 5.6% of Gross World Product (GWP). Table 6 shows the evolution over time at five time points. At present, in 2010, the damages are shared equally between developed and developing countries for outdoor air, but for indoor air the major share of damages falls on developing countries. Over the next 40 years, the relative impact of overall air pollution damages is expected to fall to under 4% of GWP by 2050.

Since the start of the last century, damage costs to developed countries of outdoor air pollution have been falling from 5.2% of GDP, predicted to be 2.5% of GDP in 2050. Developing countries on the other hand have seen a major growth in damages due to outdoor air pollution, stabilizing at 2.8% of GDP in 2050.

Damages due to indoor air pollution started high for developed countries in 1900 at 7.7% of GDP, falling rapidly to 2.6% in 1950 and 0.3% in 2010 as households switched from solid fuels to kerosene, electricity and gas. In developing countries, a high number of deaths due to indoor air pollution lead to very high economic losses at 42% of GDP, falling to 24% in 1950, 5.4% in 2010 and falling further to 1.7% in 2050 as solid fuels are phased out.

Table 6. Evolution of air pollution damage costs over time – absolute (US$ billion, 1990 prices) and as % of GDP

Impact	1900		1950		2010		2030		2050	
	Cost	**% GDP**	**Cost**	**% GDP**	**Cost**	**% GDP**	**Cost**	**% GDP**	**Cost**	**% GDP**
Outdoor air										
Developed	69	5.2%	238	6.1%	828	3.1%	1,113	2.8%	1,521	2.5%
Developing	2	0.3%	26	1.8%	644	2.4%	1,515	2.5%	3,681	2.8%
Total	71	3.6%	265	5.0%	1,472	2.7%	2,628	2.6%	5,202	2.7%
Indoor air										
Developed	103	7.7%	102	2.6%	87	0.3%	74	0.2%	36	0.1%
Developing	272	42.4%	347	23.9%	1,467	5.4%	1,933	3.2%	2,259	1.7%
Total	375	19.0%	449	8.4%	1,554	2.9%	2,007	2.0%	2,295	1.2%
Total air										
Developed	172	12.9%	340	8.8%	915	3.4%	1,187	3.0%	1,558	2.6%
Developing	274	42.7%	373	25.8%	2,111	7.8%	3,448	5.8%	5,940	4.5%
Total	446	22.6%	713	13.4%	3,026	5.6%	4,635	4.6%	7,498	3.9%

Figure 8 shows the growth in damage costs in Billion US Dollars (at constant 1990 proces). It can be seen that indoor and outdoor air had similar costs globally until 2020, when declining deaths from indoor air pollution are expected to be halved from 1.7 million to 0.8 million annually, and outdoor air pollution deaths are expected to increase in the developing world. While overall health risks and deaths are expected to fall from air pollution over time, the growth in economic costs seen in the figure is due to the higher relative prices that economic growth gives rise to, especially in the developing world.

Figure 8. Global damage costs from air pollution - outdoor versus indoor, US Dollars (1990 prices)

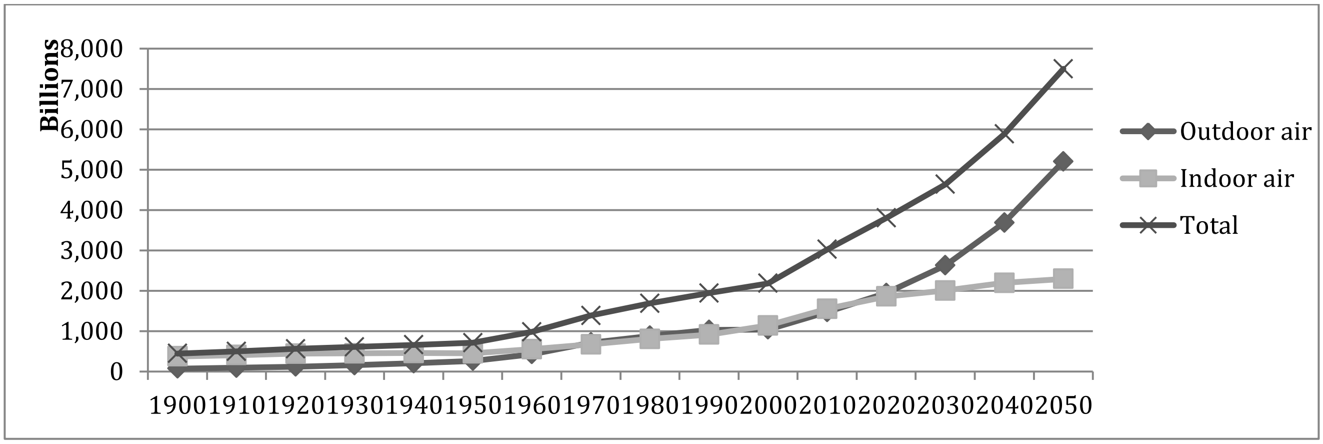


Figure 9 shows the declining damage costs as a proportion of gross world product (GWP) for both indoor air and outdoor air pollution. For indoor air, the damages have been decreasing substantially since 1900, while for outdoor air pollution the decline has been mainly since 1970. After around 2020, outdoor air will have higher damage costs than indoor air, reversing the trend of the past century.

Figure 9. Global damage costs from air pollution - outdoor versus indoor, as % of GDP

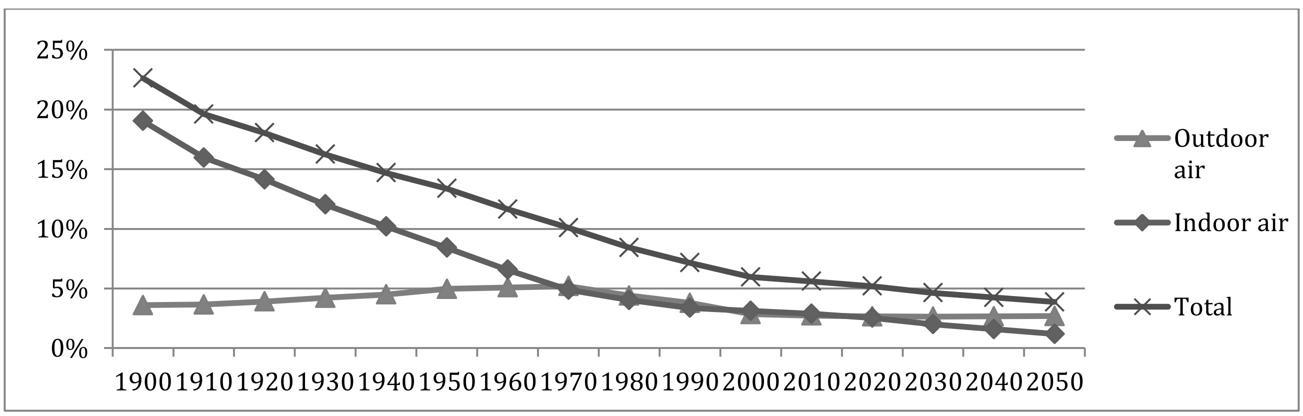


Figure 10 shows the damage costs from air pollution are significantly increasing in developing countries, compared to developed countries. The rise is almost totally from rising real prices (i.e. economic growth) in the developing world.

Figure 10. Global damage costs from air pollution, US Dollars (1990 prices)

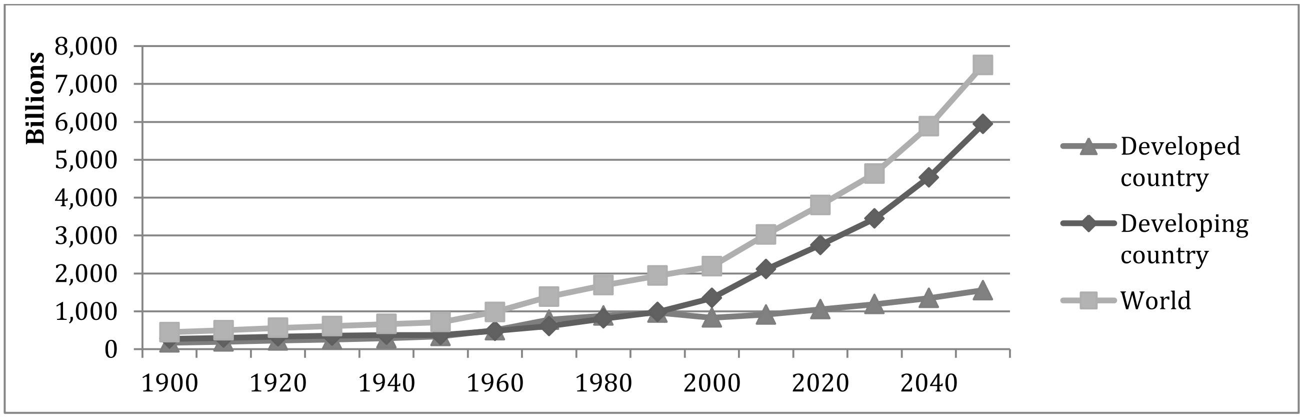


Figure 11 shows the convergence of developing with developed countries of overall air pollution damage costs, when expressed as a proportion of GDP. From a global average of close to 23% of GWP, the damage costs have fallen to little over 4% of GWP.

Figure 11. Global damage costs of all-cause air pollution, as % of GDP and GWP

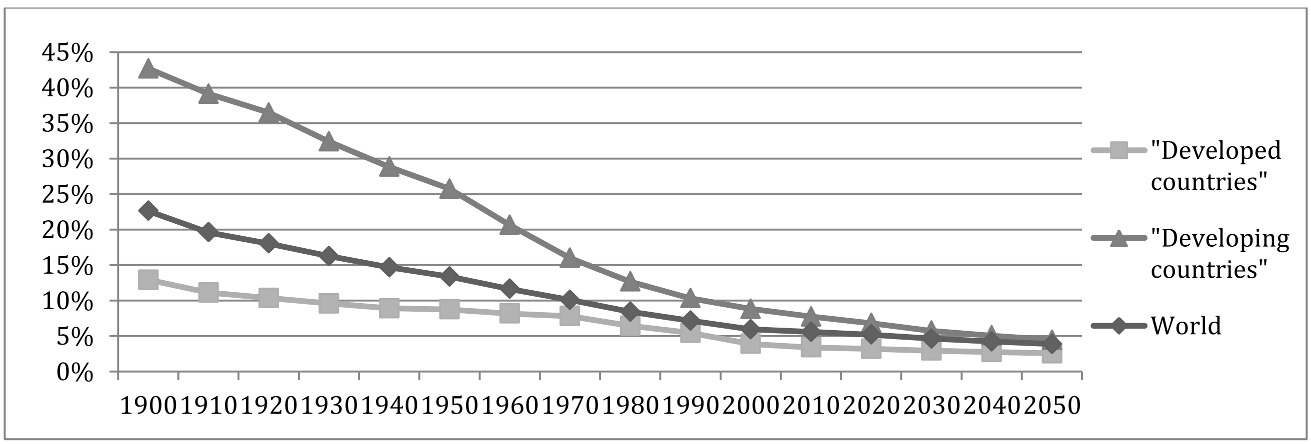


Table 7 shows the per capita costs for selected time points. Despite the overall declining levels of pollution, the per capita costs are rising over time. This phenomenon is largely due to rising real prices resulting from continued economic growth. By 2050, the total damage cost is between US$700 and US$800 per capita/year. The major share of overall damage costs are incurred in the developing world due to 85% of the global population being located in countries defined by this study as belonging to the developing country region. As shown in Table 7, the overall damage costs are dominated by health costs, and of these, health damage costs from outdoor air exceed indoor air pollution by more than two times. The disaggregated findings are presented further below.

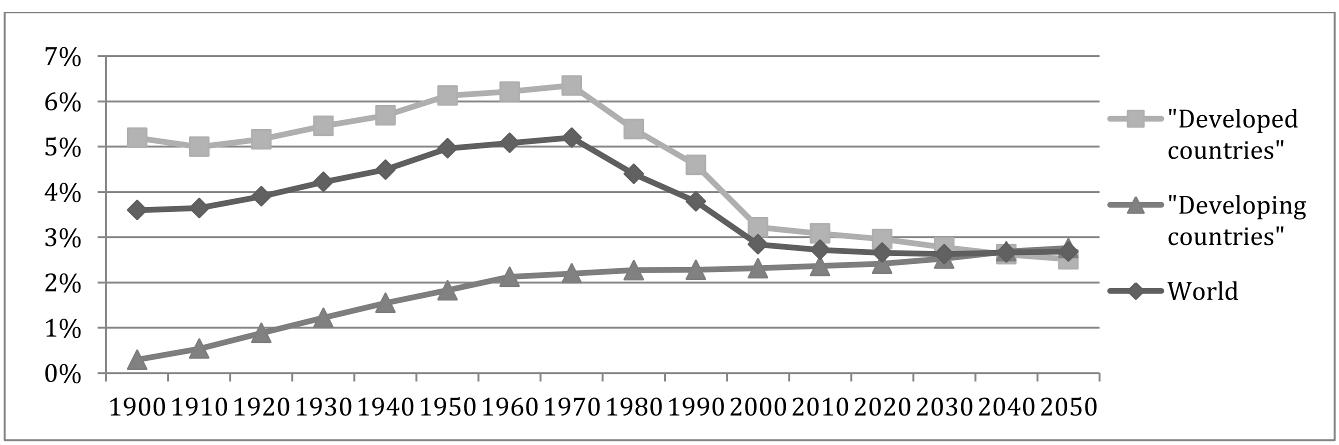
Table 7. Per capita damage costs of air pollution (US$, 1990 prices)

Variable	1900	1950	2000	2010	2050
Health impacts of outdoor air					
Developed country	111	258	510	585	999
Developing country	2	14	64	101	408
World	**40**	**94**	**153**	**190**	**495**
Non-health impacts of outdoor air					
Developed country	16	29	49	56	90
Developing country	0	2	7	11	44
World	**6**	**11**	**16**	**20**	**50**
Health impacts of indoor air					
Developed country	167	108	104	60	23
Developing country	243	187	183	234	253
World	**217**	**161**	**167**	**202**	**219**
Non-health impacts of indoor air					
Developed country	23	15	14	8	3
Developing country	24	18	18	23	24
World	**23**	**17**	**17**	**20**	**21**
Outdoor and indoor air					
Developed country	317	410	677	709	1,116
Developing country	269	220	273	369	729
WORLD	**285**	**283**	**353**	**431**	**786**

Outdoor air pollution

Figure 12 shows the converging damage costs of developing countries with developed countries, as a % of GDP. Starting at under 0.5% of GDP in 1900, damage costs have grown to almost 3% of GDP in developing countries. In developed countries, damage costs have been falling since 1970 in developed countries, from over 6% of GDP to the current levels of 3.5% of GDP.

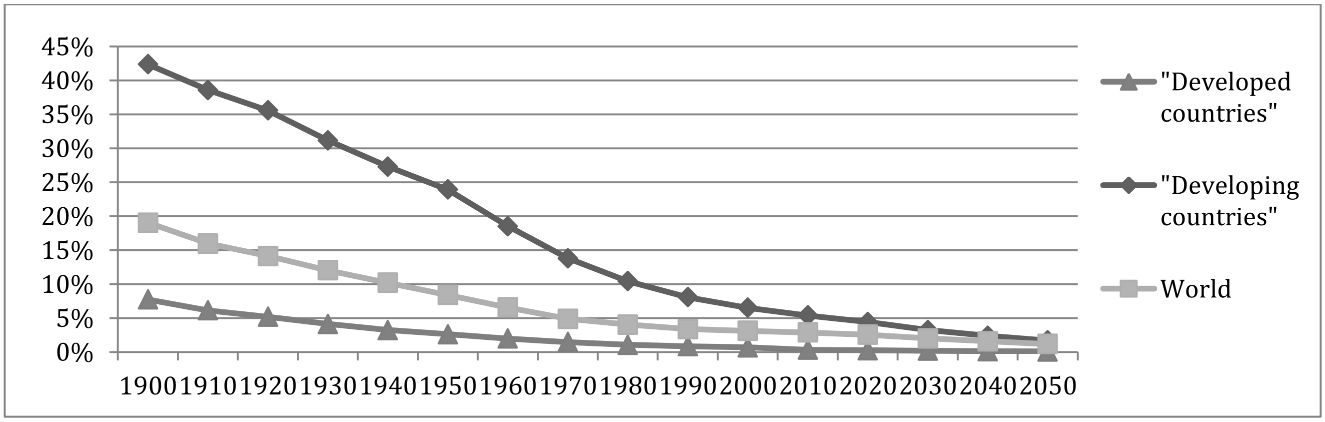
Figure 12. Damage costs of outdoor air pollution, as % of GDP



Indoor air pollution

Figure 13 shows falling damage costs associated with indoor air pollution, due to gradually falling rates of solid fuel use since 1900. In developed countries, damages of below 3% of GDP were achieved as early as the 1950s, whereas for developing countries, damage costs of 3% are expected to be achieved by 2050 – assuming continued declines in solid fuel use.

Figure 13. Damage costs of indoor air pollution, as % of GDP



Developing countries

Figure 14 shows the damage costs in developing countries are increasing significantly due to outdoor air pollution, while the growth is smaller from indoor air pollution. The results are largely being driven by the number of deaths, which are increasing from outdoor air pollution and decreasing from indoor air pollution. By 2050, almost US$ 6 trillion will be lost from air pollution.

Figure 14. Damage costs to developing countries from air pollution, US Dollars (1990 prices)

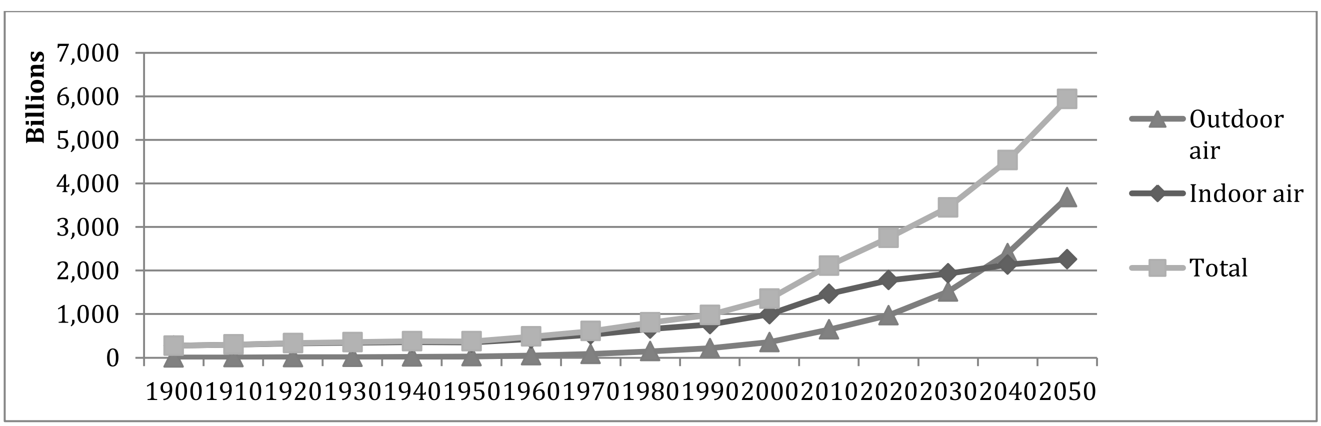
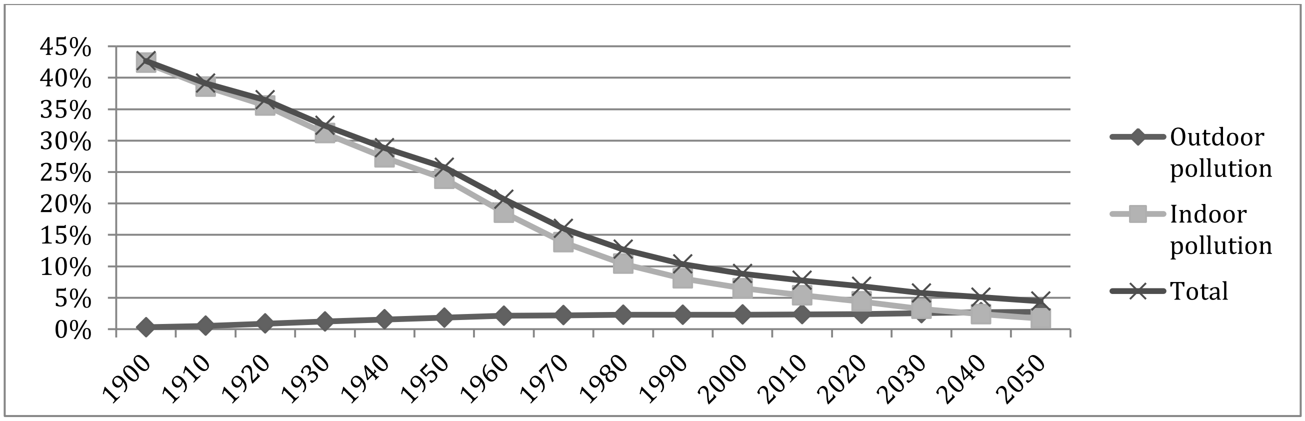


Figure 15 shows the drastic fall in damage costs from indoor air pollution from 1900 to 2050, while there is an increasing trend for damage costs from outdoor air pollution. After 2040, and at projected indoor and outdoor air pollution paths in developing countries, the deaths and damage costs from outdoor air pollution will exceed indoor air pollution.

Figure 15. Damage costs of air pollution in developing countries, as % of GDP



Developed countries

Figure 16 shows that from similar damage costs in 1900, there is now a wide divergence in damage costs between indoor and outdoor air pollution. There is an apparent dip in damage costs between 1990 and 2010 due to the continued large fall in the number of deaths from 1990 to 2000, after which the marginal rate of decline in deaths falls (due to lower proportional declines in air pollution). The growth of damage costs after 2000 is due to the increase in real prices (from to economic growth) outstripping the continued decline in the number of deaths.

Figure 16. Damage costs to developed countries from air pollution, US Dollars (1990 prices)

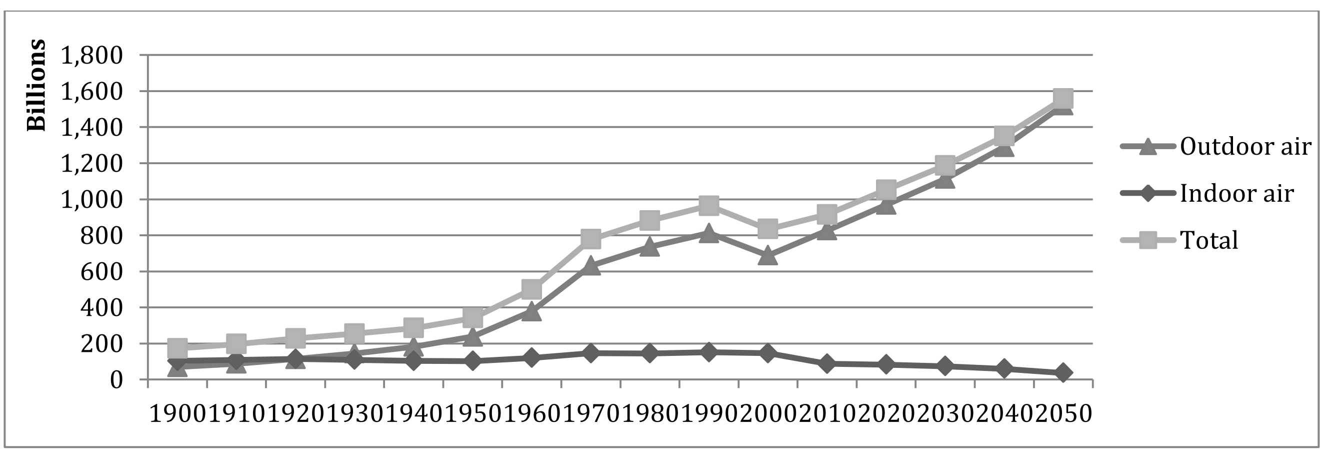
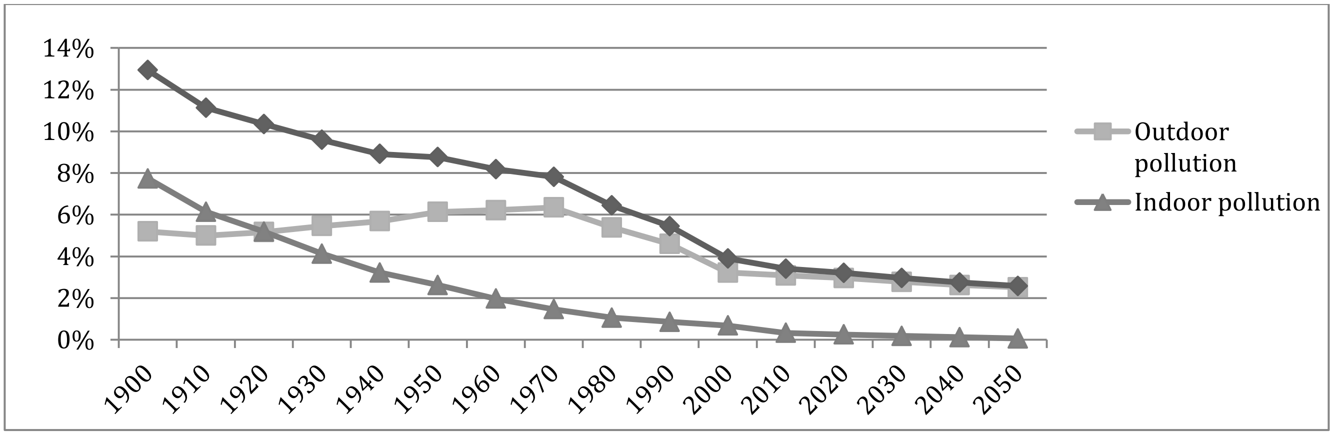


Figure 17 shows a gradually declining trend in air pollution damage costs as a proportion of GDP in developed countries, from 13% in 1900 to 2.5% in 2050. This declining trend is being driven by reductions in solid fuel use – and the associated reductions in health damage costs. However, these reductions are accompanied by a gradual increase in damage costs from outdoor air pollution rising from 1900 to 1970, followed by a rapid decline to below 5% of GDP from 1990 onwards.

Figure 17. Damage costs of air pollution in developed countries, as % of GDP



Contribution to impacts

Figure 18 and

Figure 19 show that for both developed and developing countries the major contributor to overall damage costs of outdoor air pollution is mortality cost, accounting for over 80% of overall damages. Making up the remaining costs are health productivity, health care costs, crop production, material damages and visibility.

Figure 18. Contribution to outdoor air pollution damage costs in developed countries

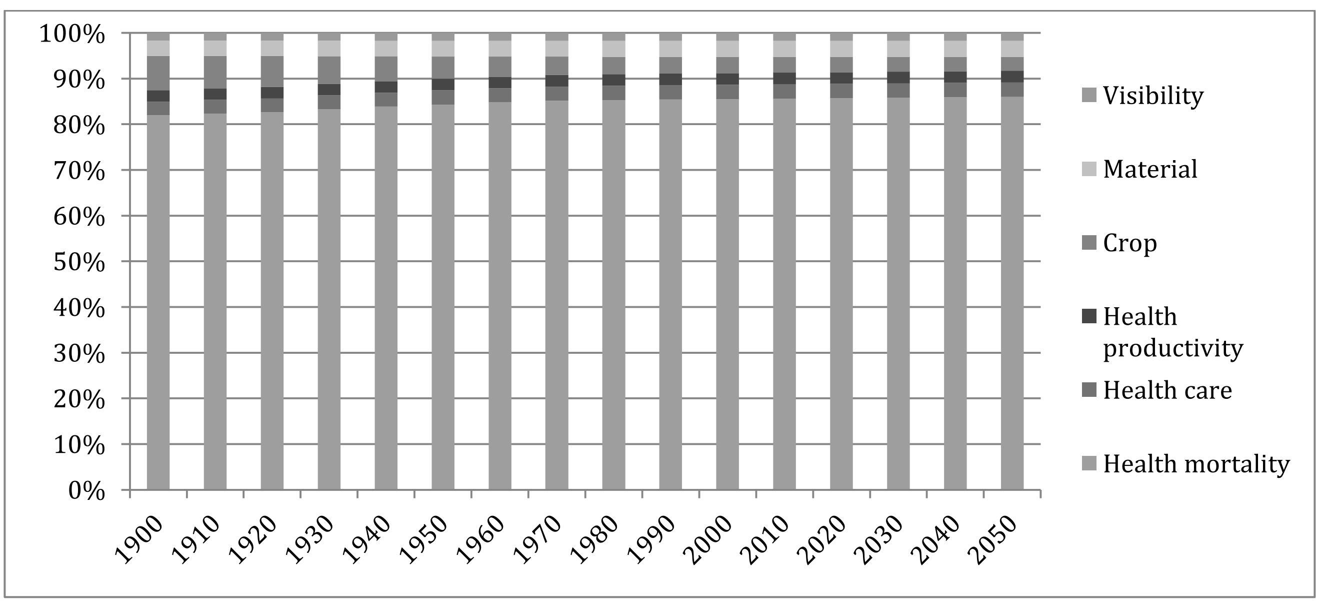


Figure 19. Contribution to outdoor air pollution damage costs in developing countries

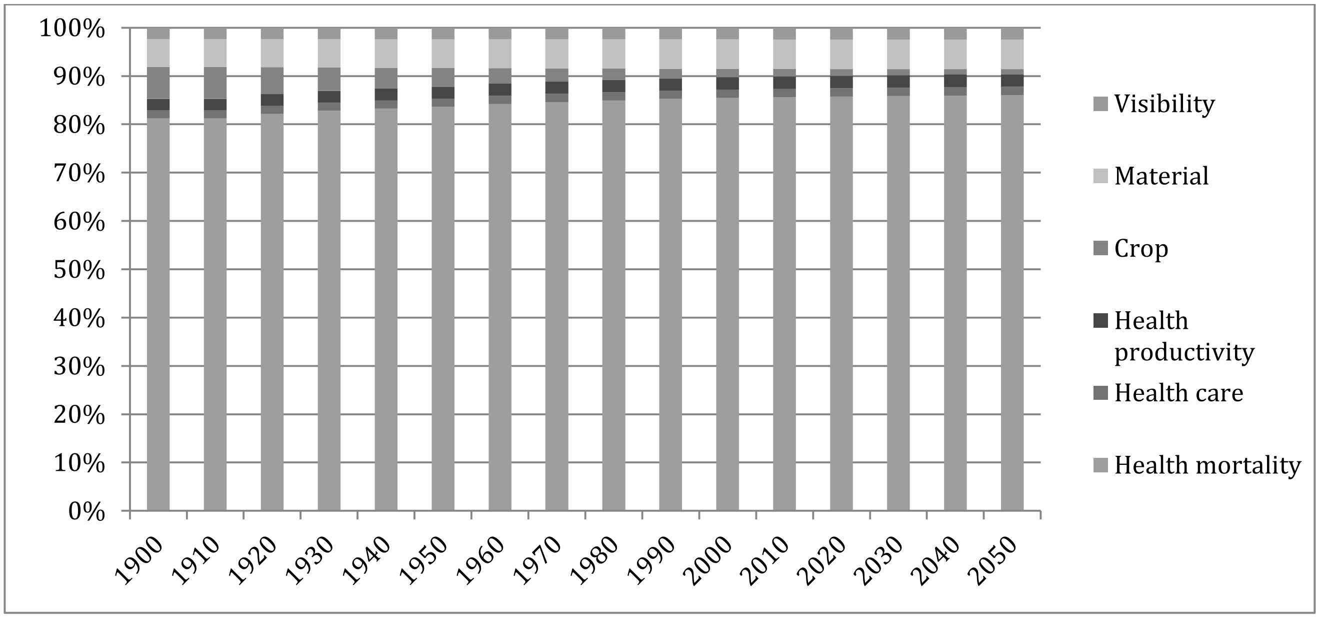
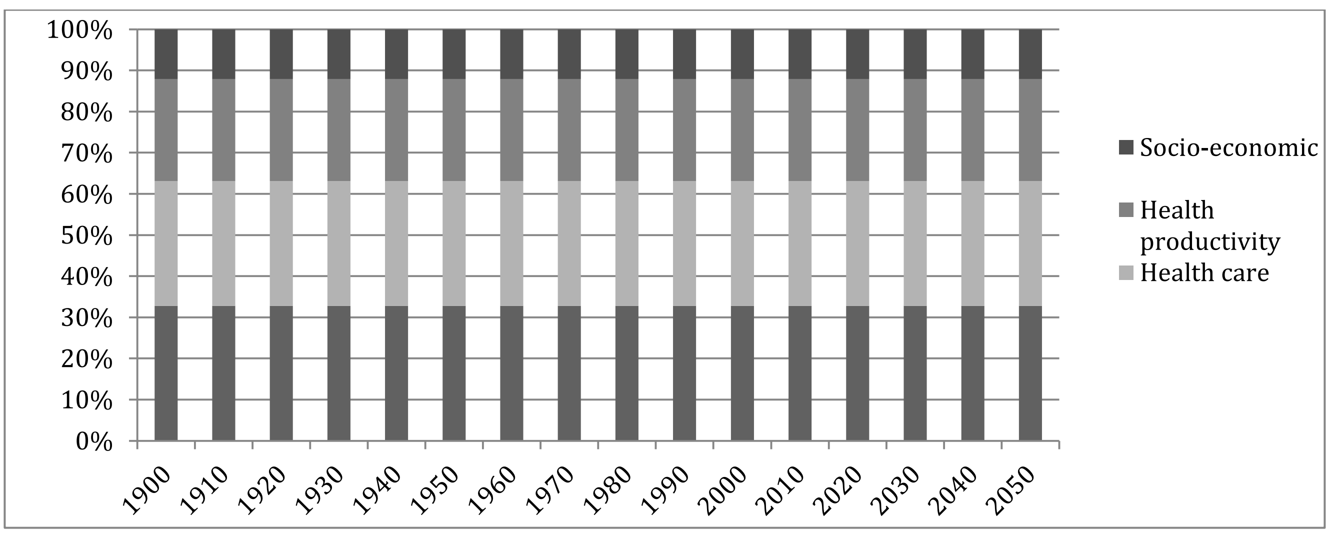


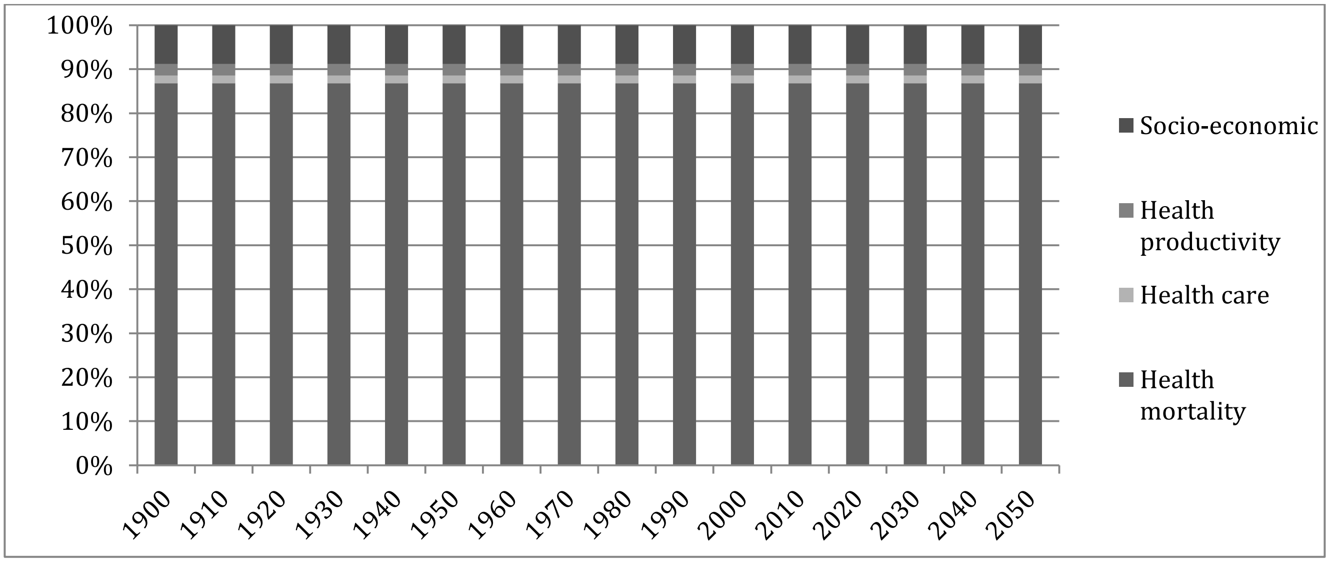
Figure 20 shows that the overall damage costs of indoor air pollution in developed countries are shared between premature mortality, health-related productivity and health care costs. A smaller share, a little over 10%, is contributed by access time to collect biomass (or equivalent cost if purchased).

Figure 20. Contribution to indoor air pollution damage costs in developed countries



Error! Not a valid bookmark self-reference. shows that the mortality cost is the major contributor in developing countries, at 85-90% of overall damage cost. Collection time losses account for almost 10% of overall solid fuel use losses, a proportion which is stable over time.

Figure 21. Contribution to indoor air pollution damage costs in developing countries



Sensitivity analysis

The sensitivity analysis made adjustments to the pollution levels used in the baseline analysis. Figure 22 shows the variation in overall damage costs under pessimistic (top line) and optimistic (bottom line) pollution scenarios, as a % of world GDP. Under high pollution levels, the damage costs reach little over 25% of GWP in 1900, while under low pollution levels the damage cost remains over 18% of GWP. In 2050, even under pessimistic assumptions, the total damage cost is around 5% of GWP. In conclusion, although quite significant adjustments were made to the pollution levels, the impact on the over results is not major. Hence the results are sensitive to the assumptions on pollution levels, but do not change the results by any order of magnitude. Hence, a stable or continued declining trend in global losses is confirmed by this analysis.

Figure 22. Variation in pollution exposure and resulting impact on baseline estimates of air pollution damage costs, developed and developing countries combined (% of GWP)

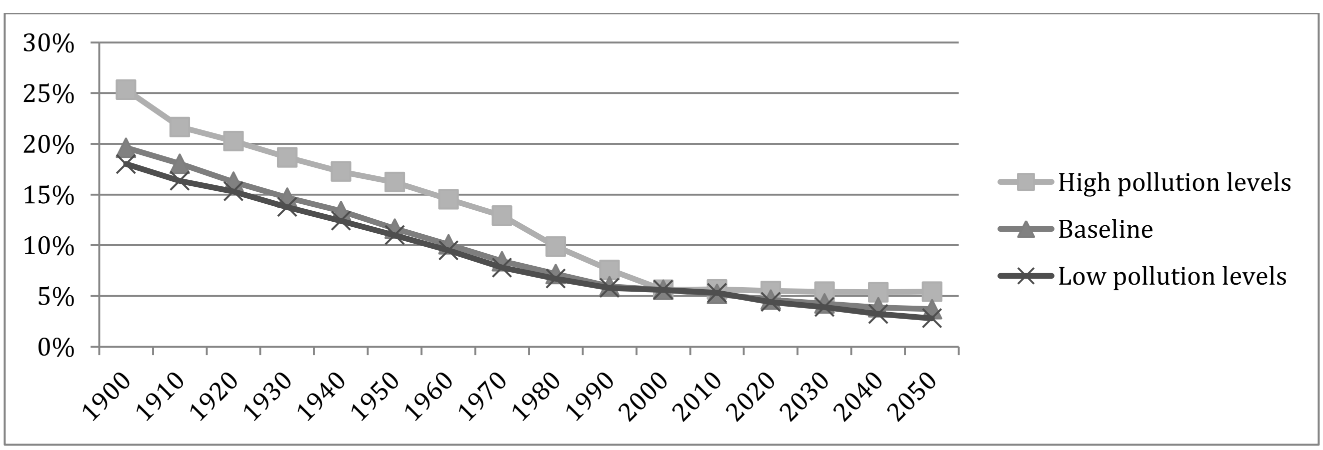
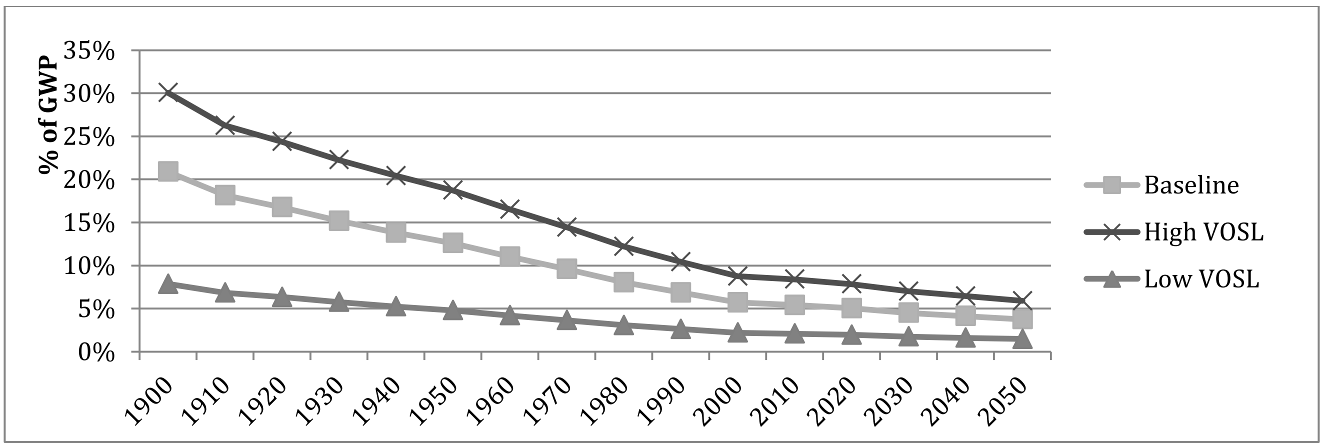


Figure 23 shows the influence of high and low value of saved lives (VSL) on the global damage costs of air pollution. Given that the value of premature deaths accounted for at least 80% of total damage costs for all time periods of the analysis, the alternative VOSL values chosen had a major impact on the results. The high VOSL value of US$5 million per death in developed countries in 2010 lead to almost twice the damage costs at 8.4% of GWP in 2010 compared to 5.4% in the baseline. Likewise, the low VOSL value of US$1 million lead to a major cut in damage costs to 2.1% of GWP. Hence the choice of VOSL is critical to the size of impact and the resulting conclusions.

Figure 23. Variation in value of life and resulting impact on baseline estimates of air pollution damage costs, developed and developing countries combined (% of GWP)



Discussion

This study has faced several challenges in estimating the global damage costs of air pollution from 1900 to 2050. Even since 1990, when many scientific articles on damage costs of air pollution have been published, there is a lack of evidence, especially studies from developing countries, to estimate global health and non-health damages from air pollution. The resulting estimates are not precise. Prior to 1990, and post 2010, this study faced many challenges in estimating input values within the damage cost function. Hence, both geographical and temporal extrapolation of available research studies has lead to some weaknesses in the results. Using best available extrapolation techniques of damage functions and expert judgement, this study gives a global overview on relative size of damage costs for two main causes of air pollution – indoor and outdoor – and two categories of country – developed and developing. One-way sensitivity analysis on important determining variables – pollution levels and value of life – has indicated a probable range of global damage costs between 2.1% to 8.4% of GWP in 2010. In 1900, the damage costs ranged between 8% and 30% of GWP; with a decline to between 1.5% and 6% of GWP in 2050. Hence, the overall and continuing trend of declining global damage costs is encouraging from a human development perspective. However, it is important to bear in mind that the projected reductions in damage costs (as % of GWP) beyond 2010 depend on the success of current and future policies to reduce exposure to air pollution in both urban and indoor environments. The estimates of future pollution exposure assume appropriate policies are pursued and implemented, supported by sustainable economic growth which increases the available funds for households, governments and private sector to make the necessary investments in pollution abatement technologies, different fuels and measures to reduce exposure.

The health damage costs account for a large proportion of overall damage costs. This is partly because health damages are easier to quantify due to the availability of global data on burden of disease. Other non-health benefits are likely to have been significantly underestimated. First, few economic data exist on the non-health impacts that were included such as crop and material damage. It is indeed possible that the unit cost estimates that were chosen are very conservative estimates, and hence damage costs could be significantly higher. Second, some non-health impacts were omitted as they have been included in other Assessment Papers.

In interpreting the overall damages, it should be noted whom the health impacts fall on. Air pollution generally affects those most vulnerable to poor air quality such as those with underlying (respiratory) health conditions, the elderly and the young. Some types of worker are also more exposed to urban air pollution than others, being located in the outdoor environment, such as street sellers and construction workers. Poor and rural families are more likely to use solid fuel for cooking or for indoor heating, and not have access to improved stoves, than richer households. Women and (young) children are most exposed to indoor air pollution, as the home is where their lives are based. Also, those who are poorer are less able to take avertive measures to protect themselves from air pollution (such as using an air conditioning in homes or in a car in cities), and these same low-income groups are least able to afford adequate medical care when they fall sick. Hence, while it was not within the scope of this paper to perform an equity analysis, it is important to be aware of whom these impacts most fall on.

The distinction between developed and developing regions has been instructive – indicating different air pollution exposure patterns and different strength of trends over time. However, the economic analysis has also given different values to the physical impacts felt by those living in developed compared to developing countries. Such an approach is justified from the perspective of national or regional policy makers who need to make decisions based on a comparison of the actual costs and benefits of different policy choices. For example, if national policy from developing countries used evidence based on an average world price for medical cost savings or deaths averted, they would be misled into allocating too many resources to a pollution reduction activity, as the actual gains would be lower. On the other hand, when damage costs from developed and developing regions are compared in the same currency unit, but based on different underlying prices, the implicit assumption is that pollution reduction measures are worth more to those in developed countries. This is clearly wrong from a global equity perspective. Hence, when considering the global allocation of pollution control resources, it is fairer to compare damage costs between developed and developing countries as a percentage of GDP (e.g. Figure 11) rather than in currency units (e.g. Figure 10). Importantly, globally available resources – such as the Green Climate Fund - should be allocated to where consumers have least ability to pay for pollution control measures, and/or countries where the private sector is least likely to invest their funds. In particular, where the private sector is willing to invest, it is important to avoid 'crowding out' private investment potential with public subsidies, the latter which could be used more efficiently elsewhere.

As was mentioned in the introduction, air pollution is double-edged. Economic growth has unarguably lead to increased levels of income and improved standards of living, while this economic growth has been possible because of longer life expectancies and technological progress such as the combustion engine and industrial development, which compromise air quality. Governments and citizens alike, while they may not have been fully aware of the health and other impacts of air pollution, have been shown to be willing to trade off the health of the population for other gains in quality of life. These decisions have been made without the offer of cleaner technologies, nor (often) the ability to choose a different paradigm of economic growth. However, in the latter part of the 20th Century, greater environmental knowledge combined with technological development and freer trade regimes – which have themselves enabled the multinational private sector to reach almost every household on the planet – have together given rise to many new possibilities for sustainable living. The damage costs of air pollution in the coming decades could be significantly more or significantly less than those presented here, depending on which development pathway is chosen. This is a decision that needs to be made collectively, based on developments in science and technology, improved delivery mechanisms for green technology, and sustainability concerns placed at the center of economic planning.

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Annex 1

Annex Table 1. Percentage of population using solid fuels, by country and WHO region.

Region/country	Percentage	Region/country	Percentage	Region/country	Percentage
Africa	77	Colombia	15	Hungary	< 5
Algeria	< 5	Costa Rica	23	Kazakhstan	5
Angola	> 95	Cuba	< 5	Kyrgyzstan	76
Benin	95	Dominican Republic	14	Latvia	10
Botswana	65	Ecuador	< 5	Lithuania	< 5
Burkina Faso	> 95	El Salvador	33	Poland	< 5
Burundi	> 95	Grenada	48	Republic of Moldova	63
Cameroon	83	Guatemala	62	Romania	23
Cape Verde	36	Guyana	59	Serbia and Montenegro	ND
Central African Republic	> 95	Haiti	> 95	Slovakia	< 5
Chad	> 95	Honduras	57	Tajikistan	75
Comoros	76	Jamaica	45	TFYR of Macedonia	30
Congo	84	Mexico	12	Turkey	11
Cote d'ivoire	74	Nicaragua	58	Turkmenistan	< 5
Democratic Republic of the Congo	> 95	Panama	33	Ukraine	6
Equatorial Guinea	ND	Paraguay	58	Uzbekistan	72
Eritrea	80	Peru	33	Russian Federation	7
Ethiopia	> 95	Saint Kitts and Nevis	< 5	**Southeast Asia**	74
Gabon	28	Saint Lucia	63	Indonesia	72
Gambia	> 95	St Vincent and the Grenadines	31	Sri Lanka	67
Ghana	88	Suriname	ND	Thailand	72
Guinea	> 95	Trinidad and Tobago	8	Bangladesh	88
Guinea-Bissau	95	Uruguay	< 5	Bhutan	ND
Kenya	81	Venezuela	5	India	74
Lesotho	83	**Eastern Mediterranean**	36	Korea, Democratic People's Republic of	ND
Liberia	ND	Afghanistan	>95	Maldives	ND
Madagascar	> 95	Bahrain	< 5	Myanmar	95
Malawi	> 95	Cyprus	< 5	Nepal	80
Mali	> 95	Djibouti	6	Timor-Leste	ND
Mauritania	65	Egypt	< 5	**Western Pacific**	74
Mauritius	< 5	Iran, Islamic Republic of	< 5	Cambodia	> 95
Mozambique	80	Iraq	< 5	China	80
Namibia	63	Jordan	< 5	Cook Islands	ND
Niger	> 95	Kuwait	< 5	Fiji	40
Nigeria	67	Lebanon	< 5	Kiribati	ND
Rwanda	> 95	Libyan Arab Jamahiriya	< 5	Korea, Republic of	< 5
Sao Tome and Principe	ND	Morocco	5	Lao People's Democratic Republic	> 95
Senegal	41	Oman	< 5	Malaysia	< 5
Seychelles	< 5	Pakistan	72	Marshall Islands	ND
Sierra Leone	92	Qatar	< 5	Micronesia, Federated States of	ND
South Africa	18	Saudi Arabia	< 5	Mongolia	51
Swaziland	68	Somalia	ND	Nauru	ND
Togo	76	Sudan	> 95	Niue	ND
United Republic of Tanzania	> 95	Syrian Arab Republic	32	Palau	ND
Uganda	> 95	Tunisia	5	Papua new Guinea	90
Zambia	85	United Arab Emirates	< 5	Philippines	47
Zimbabwe	73	Yemen	42	Samoa	70
Latin America and the Caribbean	16	**Central and Eastern Europe**	16	Singapore	< 5
Antigua and Barbuda	46	Albania	50	Solomon Islands	95
Argentina	< 5	Armenia	26	Tonga	56
Bahamas	< 5	Azerbaijan	49	Tuvalu	ND
Barbados	< 5	Belarus	19	Vanuatu	79
Belize	43	Bosnia and Herzegovina	51	Viet Nam	70
Bolivia	25	Bulgaria	17		
Brazil	12	Estonia	15		
Chile	< 5	Georgia	42	**World**	52

ND, no data. Data from United Nations (2005b). For a more detailed explanation of WHO regions and epidemiologic subregions based on mortality strata, see WHO (2002). Source: (Rehfuess, Mehta et al. 2006).