EEA Technical report | No 15/2011

Revealing the costs of air pollution from industrial facilities in Europe

ISSN 1725-2237

European Environment Agency

X

Revealing the costs of air pollution from industrial facilities in Europe

European Environment Agency

Cover design: EEA
Layout: EEA/Henriette Nilsson

Legal notice
The contents of this publication do not necessarily reflect the official opinions of the European Commission or other institutions of the European Union. Neither the European Environment Agency nor any person or company acting on behalf of the Agency is responsible for the use that may be made of the information contained in this report.

Information about the European Union is available on the Internet. It can be accessed through the Europa server (www.europa.eu).

Luxembourg: Publications Office of the European Union, 2011

ISBN 978-92-9213-236-1
ISSN 1725-2237
doi:10.2800/84800

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark
Tel.: +45 33 36 71 00
Fax: +45 33 36 71 99
Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

Contents

Acknowledgements

This report was compiled by the European Environment Agency (EEA) on the basis of a technical paper prepared by its Topic Centre on Air Pollution and Climate Change Mitigation (ETC/ACM, partner AEA Technology, United Kingdom).

The lead authors of the ETC/ACM technical paper were Mike Holland (EMRC) and Anne Wagner (AEA Technology). Other contributors to the report were Joe Spadaro (SERC) and Trevor Davies (AEA Technology). The EEA project manager was Martin Adams.

The authors gratefully acknowledge the technical support received from Agnes Nyiri (Air Pollution Section, Research Department, Norwegian Meteorological Institute) for providing information from the EMEP chemical transport model.

The authors also acknowledge the contribution of numerous colleagues from the EEA and the European Commission's Directorates-General for the Environment and Climate Action for their comments on draft versions of this report.

Executive summary

This European Environment Agency (EEA) report assesses the damage costs to health and the environment resulting from pollutants emitted from industrial facilities. It is based on the latest information, namely for 2009, publicly available through the European Pollutant Release and Transfer Register (E-PRTR, 2011) in line with the United Nations Economic Commission for Europe (UNECE) Aarhus Convention regarding access to environmental information.

Air pollution continues to harm human health and our environment. One of the main findings of the EEA's *The European environment — state and outlook 2010* report (EEA, 2010) was that, despite past reductions in emissions, air quality needs to further improve. Concentrations of certain air pollutants still pose a threat to human health. In 2005, the European Union's Clean Air for Europe (CAFE) programme estimated that the cost to human health and the environment from emissions of regional air pollutants across all sectors of the EU-25 economy equalled EUR 280–794 billion in the year 2000.

This report investigates the use of a simplified modelling approach to quantify, in monetary terms, the damage costs caused by emissions of air pollutants from industrial facilities reported to the E-PRTR pollutant register. In using E-PRTR data, this study does not assess whether the emissions of a given facility are consistent with its legal requirements. Nor does it assess the recognised economic and social benefits of industry (such as producing goods and products, and generating employment and tax revenues etc.).

The approach is based on existing policy tools and methods, such as those developed under the EU's CAFE programme for the main air pollutants. The CAFE-based methods are regularly applied in cost-benefit analyses underpinning both EU and international (e.g. UNECE) policymaking on air pollution. This study also employs other existing models and approaches used to inform policymakers about the damage costs of pollutants.

Together, the methods are used to estimate the impacts and associated economic damage caused by a number of pollutants emitted from industrial facilities, including:

- the regional and local air pollutants: ammonia (NH_3), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), particulate matter (PM_{10}) and sulphur oxides (SO_x);
- heavy metals: arsenic, cadmium, chromium, lead, mercury and nickel;
- organic micro-pollutants: benzene, dioxins and furans, and polycyclic aromatic hydrocarbons (PAHs);
- carbon dioxide (CO_2).

Each of these pollutants can harm human health, the environment or both. Certain of them also contribute to forming ozone and particulate matter in the atmosphere (Box ES.1).

There are differences between the selected pollutants in terms of the extent of current knowledge about how to evaluate their impacts. Understanding is most advanced in evaluating the health impacts of the major regional air pollutants, and builds on previous peer-reviewed analysis such as that undertaken to inform the CAFE Programme. This report's analysis for these pollutants thus extends to quantifying crop and building material damage but does not include ecological impacts.

Impacts of heavy metals and persistent organic compounds on human health are also quantified, primarily in terms of additional cancer incidence. In some cases this requires analysis of exposure through consumption as well as through inhalation. Again, ecological damage is not accounted for and it should be noted that the health impact estimates for these pollutants have been subject to less scientific review and debate than those generated under CAFE.

Finally, a different approach was used to quantify the damage costs arising from CO_2 emissions, based on estimated marginal abatement cost. Estimating the magnitude of costs associated with future climate change impacts is very uncertain. This uncertainty is unavoidable, as the extent of damage will be dependent on the future development of society, particularly with respect to population and economic growth, but also how much value is attached to future events. The approach used in this report, based on marginal abatement cost, is based on the existing approach used for public policy appraisal in the United Kingdom.

Box ES.1 Air pollutants included in this study and their effects on human health and the environment

Nitrogen oxides (NO_x)
Nitrogen oxides are emitted from fuel combustion, such as from power plants and other industrial facilities. NO_x contributes to acidification and eutrophication of waters and soils, and can lead to the formation of particulate matter and ground-level ozone. Of the chemical species that comprise NO_x, it is NO_2 that causes adverse effects on health; high concentrations can cause airway inflammation and reduced lung function.

Sulphur dioxide (SO_2)
Sulphur dioxide is emitted when fuels containing sulphur are burned. As with NO_x, SO_2 contributes to acidification, with potentially significant impacts including adverse effects on aquatic ecosystems in rivers and lakes, and damage to forests. High concentrations of SO_2 can affect airway function and inflame the respiratory tract. SO_2 also contributes to the formation of particulate matter in the atmosphere.

Ammonia (NH_3)
Ammonia, like NO_x, contributes to both eutrophication and acidification. The vast majority of NH_3 emissions — around 94 % in Europe — come from the agricultural sector. A relatively small amount is also released from various industrial processes.

Non-methane volatile organic compounds (NMVOCs)
NMVOCs, important ground-level ozone precursors, are emitted from a large number of sources including industry, paint application, road transport, dry-cleaning and other solvent uses. Certain NMVOC species, such as benzene (C_6H_6) and 1,3-butadiene, are directly hazardous to human health.

Particulate matter (PM)
In terms of potential to harm human health, PM is one of the most important pollutants as it penetrates into sensitive regions of the respiratory system, and can cause or aggravate cardiovascular and lung diseases. PM is emitted from many sources and is a complex mixture comprising both primary and secondary PM; primary PM is the fraction of PM that is emitted directly into the atmosphere, whereas secondary PM forms in the atmosphere following the release of precursor gases (mainly SO_2, NO_x, NH_3 and some volatile organic compounds (VOCs)).

Heavy metals
The heavy metals arsenic (As), cadmium (Cd), chromium (Cr) lead (Pb), mercury (Hg) and nickel (Ni) are emitted mainly as a result of various combustion processes and from industrial activities. As well as polluting the air, heavy metals can be deposited on terrestrial or water surfaces and subsequently buildup in soils and sediments, and can bio-accumulate in food chains. They are typically toxic to both terrestrial and aquatic ecosystems.

Organic micro-pollutants
Benzene, polycyclic aromatic hydrocarbons (PAHs), and dioxins and furans are categorised as organic pollutants. They cause different harmful effects to human health and to ecosystems, and each of these pollutants is a known or suspected human carcinogen; dioxins and furans and PAHs also bioaccumulate in the environment. Emissions of these substances commonly occur from the combustion of fuels and wastes and from various industrial processes.

Carbon dioxide (CO_2)
Carbon dioxide is emitted as a result of the combustion of fuels such as coal, oil, natural gas and biomass for industrial, domestic and transport purposes. CO_2 is the most significant greenhouse gas influencing climate change.

Key findings

The cost of damage caused by emissions from the E-PRTR industrial facilities in 2009 is estimated as being at least EUR 102–169 billion. A small number of industrial facilities cause the majority of the damage costs to health and the environment (Figure ES.1 and Map ES.1). Fifty per cent of the total damage cost occurs as a result of emissions from just 191 (or 2 %) of the approximately 10 000 facilities that reported at least some data for releases to air in 2009. Three quarters of the total damage costs are caused by the emissions of 622 facilities, which comprise 6 % of the total number.

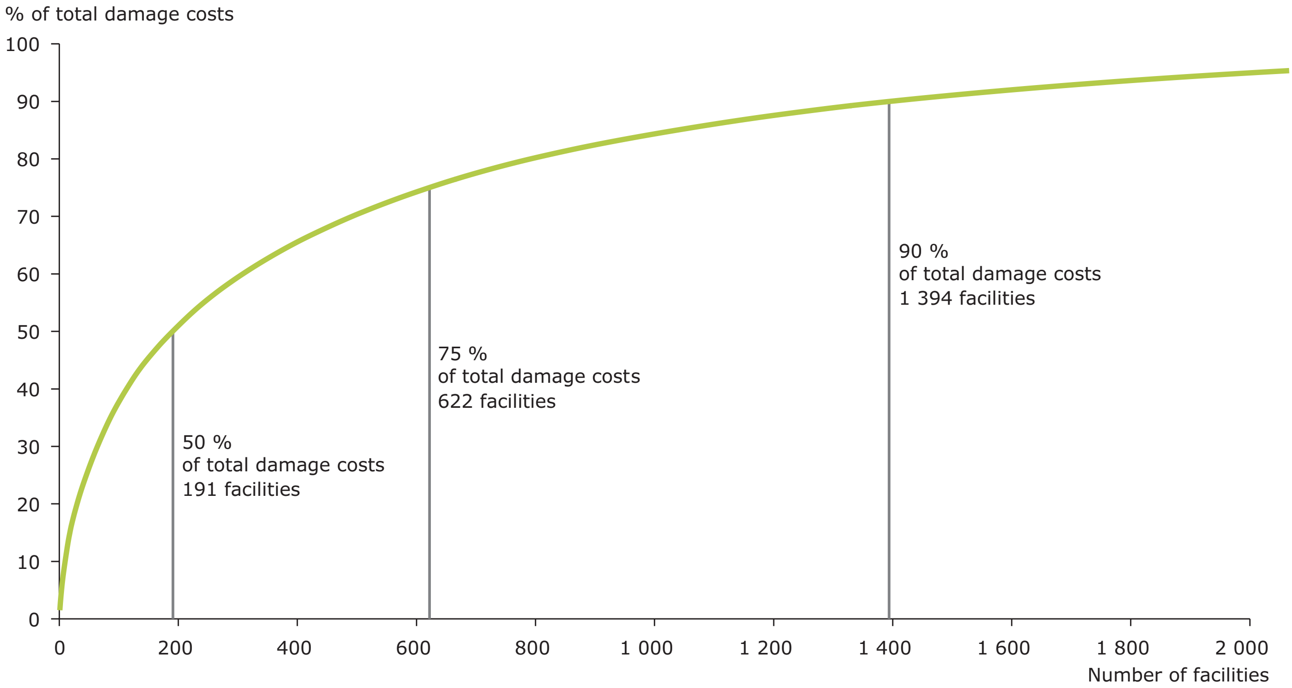
The report lists the top 20 facilities identified as causing the highest damage. Not surprisingly, most of the facilities with high emission damage costs are among the largest facilities in Europe, releasing the greatest amount of pollutants.

The ranking of individual facilities is likely to be more certain than the absolute damage costs in euros estimated for each facility. Furthermore, the reporting of data to the pollutant register appears more complete for certain facilities and countries than for others, potentially underestimating damage costs at some facilities.

Ranking according to aggregate emission damage costs provides little indication of the efficiency of production at a facility. A large facility could be more efficient than several smaller facilities that generate the same level of service or output. Equally, the opposite could be true.

One weakness of the pollutant register E-PRTR is that it does not provide production or fuel consumption data, so a direct assessment of environmental efficiency is not possible. This report nevertheless seeks to illustrate the potential differences in facility efficiencies by using CO_2 emissions as a proxy for fuel consumption. The most obvious difference when damage costs from individual facilities are normalised by CO_2 emissions is that more facilities from eastern Europe appear at the top of the results, suggesting that they contribute more damage cost per unit of fuel consumption. They are less environmentally efficient, in other words.

Figure ES.1 Cumulative distribution of the 2000 E-PRTR facilities with the highest damage costs



Map ES.1 Location of the 191 E-PRTR facilities that contributed 50 % of the total damage costs estimated for 2009

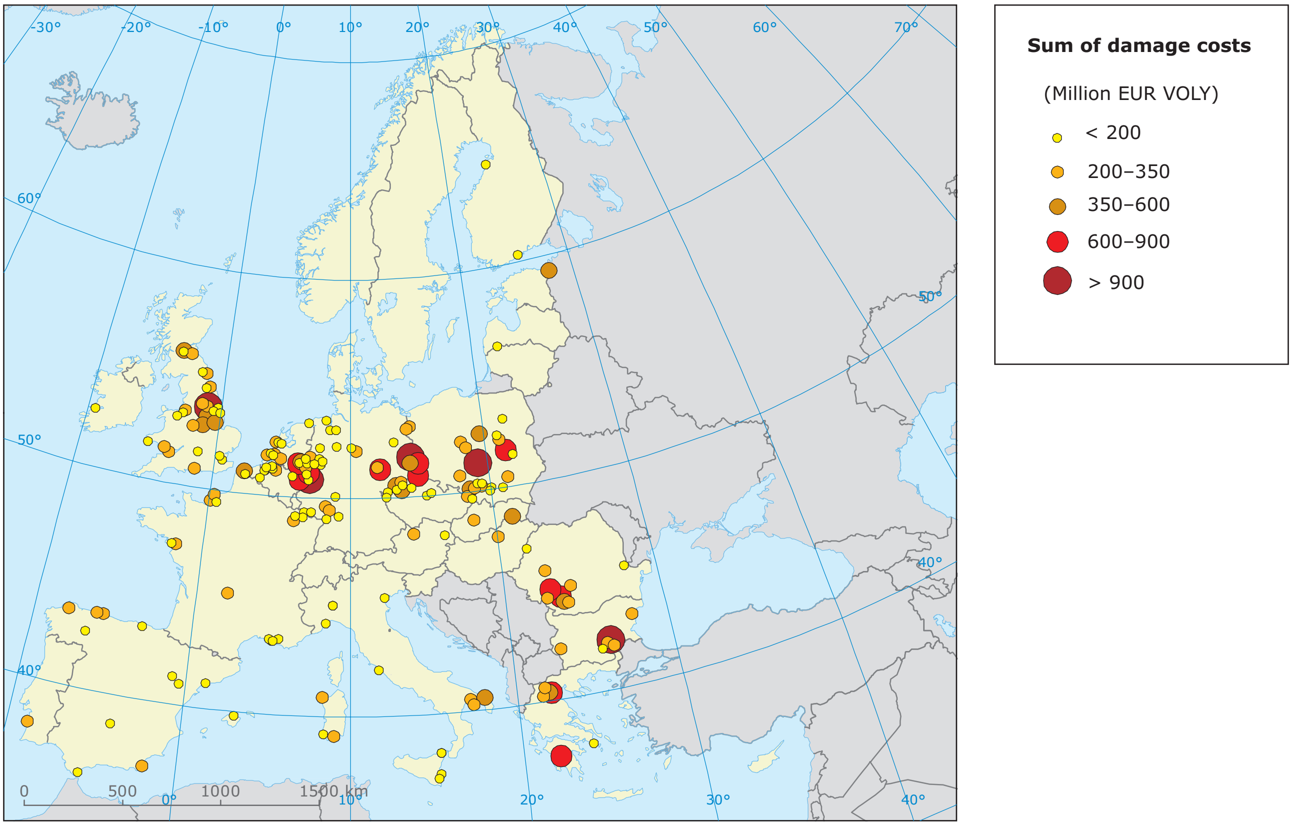
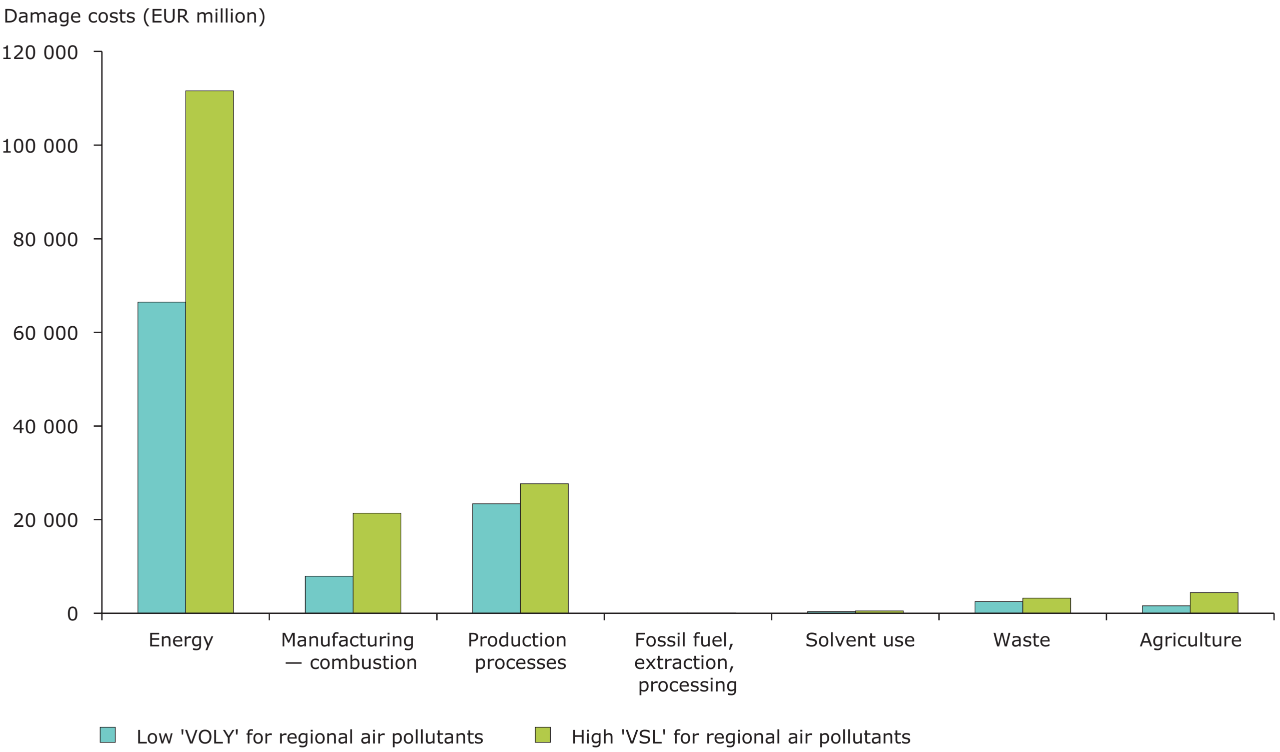


Figure ES.2 Aggregated damage costs by sector (2005 prices)



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional air pollutants.

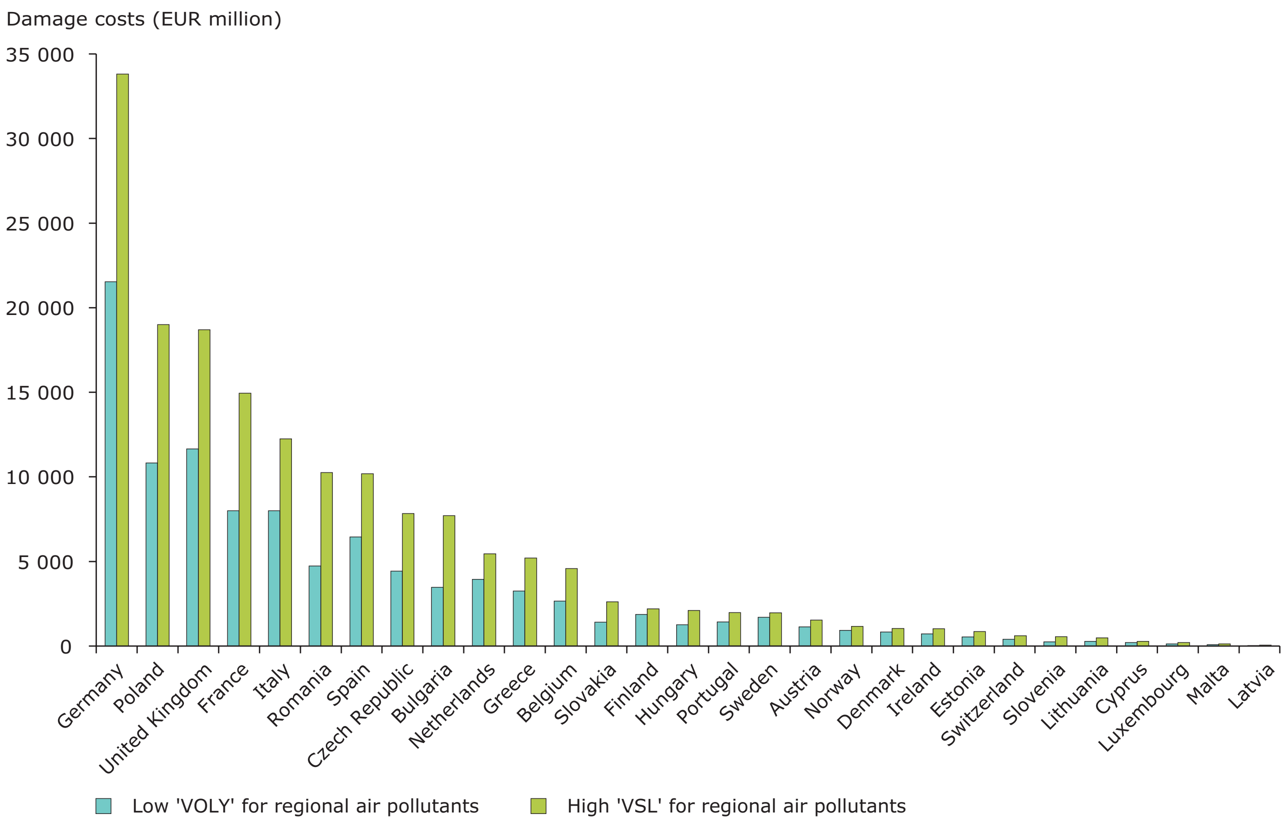
Of the industrial sectors included in the E-PRTR pollutant register, emissions from the power generating sector contribute the largest share of the damage costs (estimated at EUR 66–112 billion), (Figure ES.2). Excluding CO_2, the estimated damage costs from this sector are EUR 26–71 billion. Sectors involving production processes and combustion used in manufacturing are responsible for most of the remaining estimated damage costs.

Care is needed in interpreting the sectoral results. The E-PRTR Regulation (EU, 2006) defines the industrial sectors that must report information to the Register. In addition, for these sectors, the Regulation includes reporting thresholds for both pollutants and activities. Only those facilities with an activity rate exceeding the defined threshold and emissions exceeding the pollutant-specific thresholds have to report information to the register. Thus the E-PRTR's coverage of each sector's pollutant emissions can vary significantly. For example, whereas the E-PRTR inventory should cover most power generating facilities, it covers only a small fraction of agricultural emissions.

Results aggregated by country are shown in Figure ES.3. Countries such as Germany, Poland, the United Kingdom, France and Italy, which have a high number of large facilities, contribute the most to total estimated damage costs.

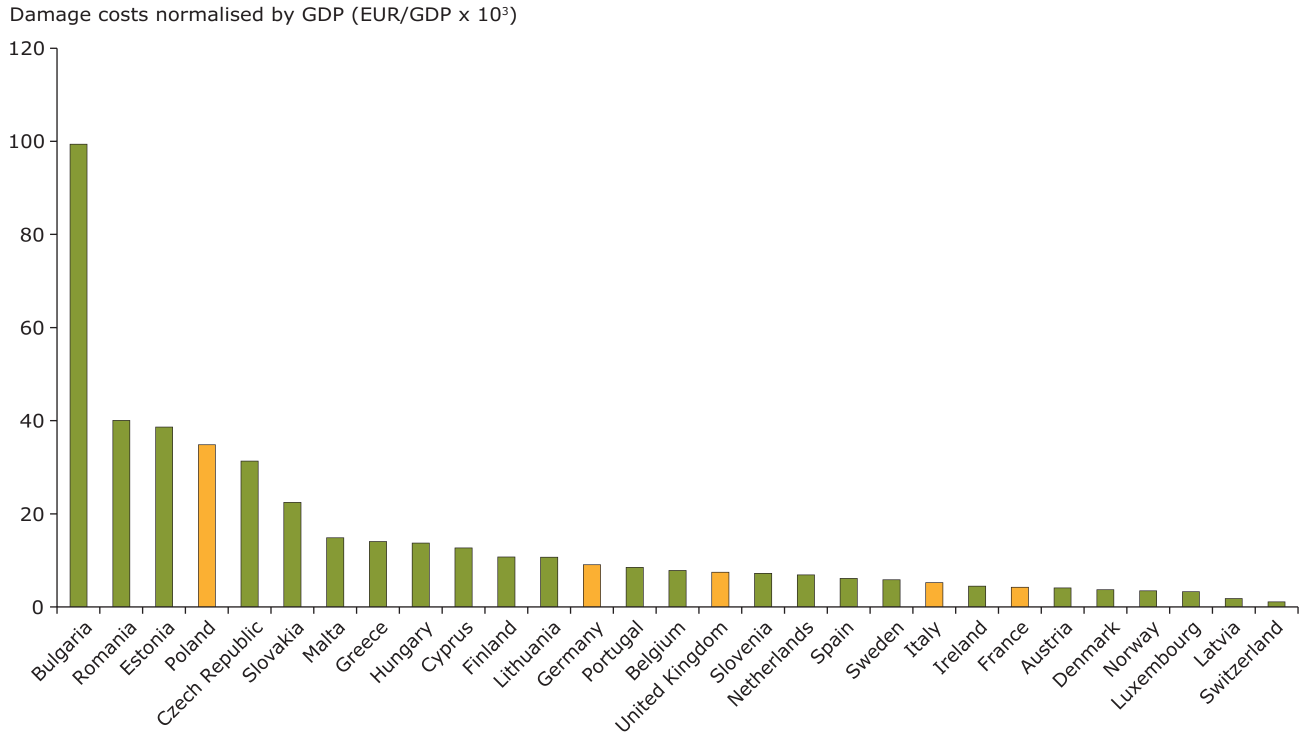
A contrasting view, offering further insights, is to incorporate a measure of the efficiency of production across the different industrial facilities. As described above, the E-PRTR does not provide facility production or fuel consumption data. As a second proxy measure, GDP was used as an indicator of national production to normalise the damage costs aggregated by country against the respective level of services provided/generated by the national economies. This alternative method of ranking countries is shown in Figure ES.4, and shows that the ordering of countries then changes significantly. Germany, the United Kingdom, France and Spain drop significantly down the ranking, whilst a number of eastern European countries (Bulgaria, Romania, Estonia, Poland and the Czech Republic) rise in position.

Figure ES.3 Aggregated damage costs by country, including CO_2



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional air pollutants.

Figure ES.4 Aggregated damage costs by country normalised against GDP



Note: The orange bars highlight the countries with the highest damage costs in Figure ES.2.

Discussion

This report only addresses damage costs derived from emissions reported by facilities to the pollutant register E-PRTR. The total cost of damage to health and the environment from all sectors of the economy (including e.g. road transport and households) and from all pollutants will therefore be higher than the estimates presented here.

Certain types of harm to health and the environment are also outside the scope of this study. For example, the model framework underpinning the assessment of regional air pollutants needs to be extended to include valuation of ecological impacts and acid damage to cultural heritage.

Since this study was completed, the available impact assessment and valuation methodologies have improved. Further refinements are expected over coming years, not least through the continuing analysis to support the revision of EU air pollution policy. While the methods employed here are therefore subject to change, it is not anticipated that the results will change substantially in terms of the relative importance of individual sectors and pollutants.

At the same time, there are acknowledged uncertainties in assessing damage costs. These extend from the scientific knowledge concerning the impact of a given pollutant, to the exposure methods applied and the models used. The report therefore highlights a number of instances where caution is needed in interpreting the results.

For example, there is no single method available to estimate the damage costs for the pollutant groups addressed in the study (i.e. the regional air pollutants, heavy metals, organic micro-pollutants and carbon dioxide). Aggregating results from the different approaches therefore poses challenges, given differences in levels of uncertainty and questions about methodological consistency. For greenhouse gases in particular, a wider debate is required on how best to estimate the economic impacts of emissions on environment and health. The report at various places addresses the uncertainty by providing damage cost estimates that have been aggregated both with and without the estimated greenhouse gas damage costs.

While caution is urged in interpreting and using estimates that are aggregated across different pollutants, it is worth underlining that there is significant value in combining damage costs based on a common (monetary) metric. Such aggregated figures provide an insight into the costs of harm to health and the environment caused by air pollution.

Finally, the report identified several important ways in which the E-PRTR might be improved for use in assessment studies. These include:

- **Providing information on the fuel consumption or productive output of individual facilities**. This would enable the efficiency of facilities to be calculated in terms of estimated damage costs per unit of production or fuel consumption.

- **More complete reporting of emissions from individual facilities**. Ideally national regulators could further improve the review of facility information before it is reported to the E-PRTR, particularly to identify outlying values and address completeness of data. The latter clearly biases any ranking of facilities on the basis of damage costs against facilities whose operators have been more conscientious in reporting complete data.

- **Improved traceability of facilities**. Comparing the present study's results with those of previous studies on a facility-by-facility basis was difficult. While some older facilities may have closed since these earlier studies were performed, part of the problem relates to differences in the annual E-PRTR datasets received by the EEA. Facilities often change ownership, name, and/or national facility identification code, creating difficulties in linking the annually reported emissions.

In summary, this report presents a simplified methodology that allows for the estimation of damage costs caused by emissions of selected pollutants from industrial facilities included in the E-PRTR. It demonstrates that, compared to using emissions data alone, these methods provide additional insights and transparency into the costs of harm caused by air pollution. Such insights are particularly valuable in the context of current discussions in Europe on how best to move towards a resource-efficient and low-carbon economy. Moreover, the analysis can be further strengthened by integrating efficiency and productivity data for individual facilities into the analysis of damage costs.

1 Introduction

1.1 Background

The European Pollutant Release and Transfer Register (E-PRTR), established by the E-PRTR Regulation (EU, 2006), provides information on releases of 91 different pollutants to air, water and land from around 28 000 industrial facilities in the 27 EU Member States, Iceland, Liechtenstein, Norway and, from 2010, Serbia and Switzerland (E-PRTR, 2011). For the EU, the Register implements the UNECE (United Nations Economic Commission for Europe) PRTR Protocol to the Aarhus Convention on Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters.

The E-PRTR register thus provides environmental regulators, researchers and the public across Europe with information about pollution released from industrial farms, factories and power plants, and demonstrates that national regulators are aware of the size of emissions from specific facilities within their jurisdictions. By focusing on releases to the environment, the E-PRTR addresses potential burdens on health and the environment in a way that can be measured directly using well-established methods. A further strength is that data is annually updated; consistency in measuring and reporting emissions should permit comparisons across years for individual facilities so that the public can see whether emissions are rising or falling.

Knowledge of the magnitude of emissions does not in itself provide information on the impacts of air pollution on human health and the environment, however, or the associated monetary costs of such damage. Significant research has been undertaken in recent years to develop scientific modelling frameworks and economic methods that allow the impacts and damage costs associated with air pollution to be estimated. Such methods have been developed through research funded by the European Commission and Member States since the early 1990s, for example, under the under the European Commission's Clean Air For Europe (CAFE) programme (Holland et al., 2005a and 2005b; Hurley et al., 2005) and have been subject to international peer review (e.g. Krupnick et al., 2005).

In 2005, the CAFE programme, for example, estimated that the annual cost to human health and the environment from emissions of regional air pollutants across all sectors of the then EU-25 economy was EUR 280–794 billion for the year 2000.

In addition to the CAFE programme, such methods have been applied to inform the development of a considerable amount of European environmental legislation and a number of international agreements, including:

- The National Emission Ceilings Directive (EU, 2001b), setting total emission limits for SO_2, NO_X, NH_3 and NMVOCs for EU Member States, and the related Gothenburg Protocol to the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP Convention) (UNECE, 1999; Pye et al., 2007, Holland et al., 2011);

- The Air Quality Directives (EU, 2004a and 2008), setting concentration limits for pollutants in the ambient air (AEA Technology, 1997; Holland and King, 1998, Entec, 2001; Holland et al., 2001; Holland et al., 2005c);

- The Titanium Dioxide Directives (EU, 1978, 1982 and 1992) and the Large Combustion Plant Directive (EU, 2001a), feeding into the Industrial Emissions Directive (EU, 2010; Stewart et al., 2007);

- The Fuel Quality Directives (EU, 1999 and 2003; Bosch et al., 2009);

- Investigations of economic instruments for pollution control (e.g. Lavric et al., 2010).

There are acknowledged uncertainties in the scientific knowledge and modelling framework that underpins the assessment of damage costs. For example, it cannot yet provide quantification for all types of damage, particularly those relating to ecosystems. Methods are also still evolving, so calculated estimates of damage costs are not considered to be as 'accurate' as the emissions data. However, it is nevertheless possible to quantify a number of impacts and subsequent damage costs for a range of pollutants.

Box 1.1 General principles in assessing environmental externalities

In order to account for the external costs of air pollution, an individual pollutant's adverse impacts on human health and the environment are expressed in a common metric (a monetary value). Monetary values have been developed through cooperation between different scientific and economic disciplines, linking existing knowledge in a way that allows external costs to be monetised.

Damage costs incorporate a certain degree of uncertainty. However, when considered alongside other sources of information, damage costs can support decisions, partly by drawing attention to the implicit trade-offs inherent in decision-making.

1.2 Objectives

The present report describes a simplified modelling approach developed to assess, in monetary terms, the cost of damage to health and the environment from selected air pollutants released in 2009 from industrial facilities reporting to the pollutant register E-PRTR. The approach developed is based upon existing models and tools used to inform policymakers. The pollutants included within the scope of study include:

- the main regional and local air pollutants;
- certain heavy metals and organic micro-pollutants;
- the main greenhouse gas — carbon dioxide.

Applying the methodology to the E-PRTR dataset used in this study makes it possible to address various questions, for example:

- which industrial sectors and countries contribute most to air pollution's estimated damage costs in Europe?
- how many facilities are responsible for the largest share of estimated damage costs caused by air pollution?
- which individual facilities reporting to the E-PRTR pollutant register are responsible for the highest estimated damage costs?

On the last point, it is clear that some facilities will have high damage cost estimates simply because of their size and production or activity levels. It is possible that a large facility may be more efficient and cleaner than a number of smaller facilities that together deliver the same level of service or output. The opposite may also be true. However, as the E-PRTR does not routinely provide information on output by facilities it is not possible to use it to assess the environmental efficiency of production directly. To try to address this problem, the report investigates the use of proxy data to normalise the estimated damage costs per unit of production.

Finally, in using E-PRTR data and calculating damage costs from individual facilities, the report does not assess whether the emissions of a given facility are consistent with its legal conditions for operating. Furthermore, while presenting the damage costs for human health and the environment from industrial facilities, the report does not assess the recognised benefits of industrial facilities (such as the production of goods and products, and generating employment and tax revenues etc.). It is important that such benefits of industrial activity are also properly recognised.

2 Methods

This chapter provides an overview of the methods used and further detail on the approaches employed to quantify the benefits of reducing emissions of regional air pollutants, heavy metals and organic compounds, and greenhouse gases.

There has been extensive past debate about the methods used to estimate impacts and associated damage costs of regional air pollutants under the CAFE Programme, and some consensus (though not universal) has been reached in this area. There has been less debate, however, about the approach used for the heavy metals, trace organic pollutants and CO_2, so the methodology for these pollutants may be considered less robust.

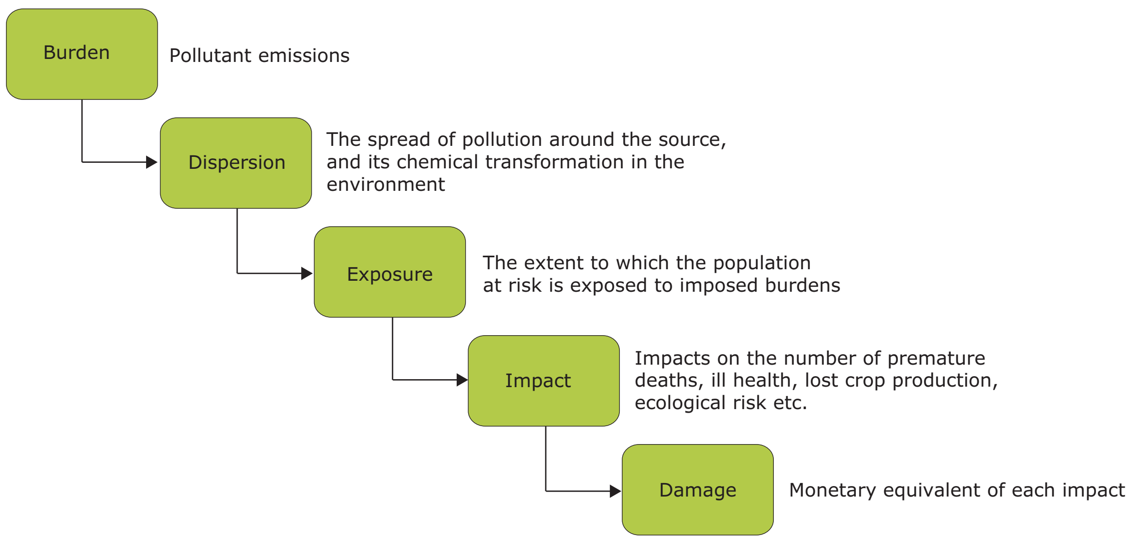
2.1 The impact pathway approach

The analysis presented here for all pollutants except CO_2 is based on the Impact Pathway Approach (IPA). This was originally developed in the 1990s in a collaborative programme, ExternE, between the European Commission and the US Department of Energy to quantify the damage costs imposed on society and the environment due to energy use (e.g. Bickel and Friedrich, 2005). It follows a logical, stepwise progression from pollutant emissions to determination of impacts and subsequently a quantification of economic damage in monetary terms (Figure 2.1).

Some pathways are fully characterised in a simple linear fashion as shown here. A good example concerns quantification of the effects on human health of particulate matter emissions, for which inhalation is the only relevant exposure route. In this case, it is necessary to quantify the pollutant emission, describe its dispersion and the extent to which the population is exposed, apply a concentration-response function and finally evaluate the economic impact. Pathways for other pollutants may be significantly more complex.

Figure 2.2 illustrates the case for pollutants such as some heavy metals and persistent organic

Figure 2.1 The impact pathway approach



compounds, where estimating total exposure may require information not just on exposure to pollutant concentrations in air but also on consumption of various types of food and drinks. In these cases it is possible that the inhalation dose may be only a small part of the total, with most impact associated with exposure through consumption.

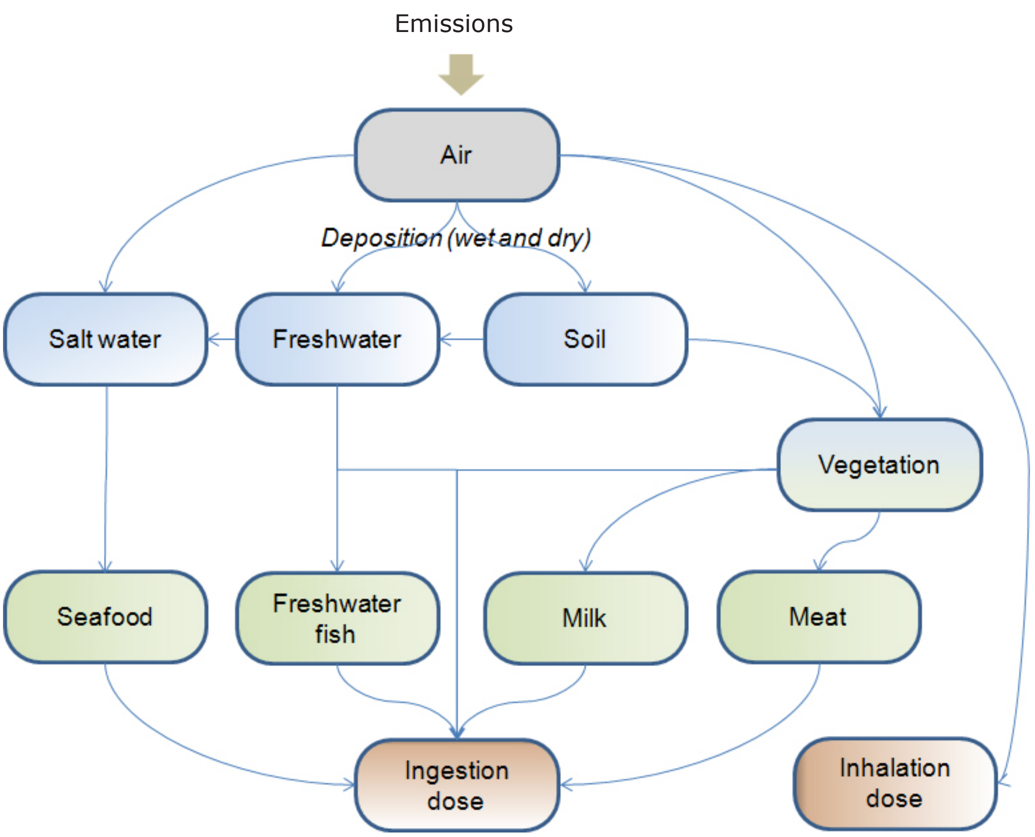
2.2 E-PRTR emissions data

The damage costs determined in this report are based upon the emissions to air of selected pollutants reported by 9 655 individual facilities to the pollutant register E-PRTR for the year 2009. The most recent version of the E-PRTR database available at the time of writing was used in the study (EEA, 2011). The pollutants selected were:

- the regional and local air pollutants: ammonia (NH_3), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), particulate matter (PM_{10}) and sulphur oxides (SO_x);
- heavy metals: arsenic, cadmium, chromium, lead, mercury and nickel,
- organic micro-pollutants: benzene, dioxins and furans, and polycyclic aromatic hydrocarbons (PAHs ([1]);
- carbon dioxide (CO_2).

The E-PRTR register contains information for 32 countries — the 27 EU Member States and Iceland, Liechtenstein, Norway, Serbia and Switzerland. Country-specific damage costs (see Section 2.3) were not available for Iceland or Serbia, and so information for these countries was not included in the analysis.

Figure 2.2 Pathways taken into account for estimating health impacts of toxic air pollutants



([1]) The derived damage costs for PAHs assume that PAH emissions are available as benzo-a-pyrene (BaP)-equivalents. In actuality, the E-PRTR Regulation (EU, 2006) requires emissions to be estimated for 4 PAH species, including BaP, on a mass basis.

The reliability of E-PRTR data is considered in Chapter 4, particularly with respect to completeness of information from facilities. One data point from the E-PRTR database was corrected prior to analysis as it appeared to have been reported incorrectly by three orders of magnitude when compared to the reported emissions of the other pollutants from the facility. This was the value for SO_X emissions from the 'Teplárna Strakonice' plant (facility ID 14301) in the Czech Republic for which the reported estimate of 1 250 000 tonnes of SO_X was taken to be 1 250 tonnes.

As described in Chapter 1, the E-PRTR provides information from specific industrial facilities. The E-PRTR Regulation (EU, 2006) defines the industrial sectors that must report information to the register. In addition, for this defined list of sectors, the Regulation includes reporting thresholds for both pollutants and activities. Facilities only have to report information to the register if their rate of activity exceeds the defined threshold and emissions of a given pollutant exceed the pollutant-specific thresholds.

In practice, this means that many smaller facilities do not report emissions to E-PRTR, and all facilities regardless of their size need only report emissions of those pollutants that exceed the respective thresholds. The E-PRTR register is therefore not designed to capture all emissions from industrial sectors.

To provide an illustration of the 'completeness' of the E-PRTR register, Table 2.1 provides a comparison of the aggregated emissions data for the selected pollutants in 2009 reported to E-PRTR, with the national total emissions for the same year reported by countries to the UNECE LRTAP Convention (UNECE, 1979) and for CO_2 under the EU Greenhouse Gas Monitoring Mechanism (EU, 2004b). The national totals include emission estimates for those sectors not included in E-PRTR, such as small industrial sources as well as 'diffuse' sources such as transport and households. Sources such as these, not included in the E-PRTR, can make a very substantial contribution to the overall population exposure. With the exception of SO_2, Table 2.1 shows that for most pollutants other sources not included in E-PRTR produce the majority of emissions. The damage costs estimated in this study therefore clearly do not represent the total damage costs caused by air pollution across Europe.

Table 2.1 Comparison of the emissions data reported to E-PRTR that were used in this study with national total emissions reported for the year 2009 by countries to the UNECE LRTAP Convention and, for CO_2, under the EU Greenhouse Gas Monitoring Mechanism

Pollutant	Emissions reported to E-PRTR (tonnes)	Aggregated national total emissions (tonnes)	% E-PRTR emissions of national totals
CO_2 ([a])	1 881 831 000	42 568 284 670	44 %
NH_3	189 100	3 862 436	5 %
NMVOC	504 695	7 992 914	6 %
NO_X	2 567 861	9 631 276	27 %
PM_{10}	146 715	2 040 806	7 %
SO_X	3 360 553	5 044 091	67 %
Arsenic	31	188	16 %
Cadmium	13	96	14 %
Chromium	80	323	25 %
Lead	315	2 083	15 %
Mercury	31	75	41 %
Nickel	298	998	30 %
Benzene	3 477	N.A. ([b])	–
PAHs	85	1 463	6 %
Dioxins and furans	0.00086	0.0020	43 %

Notes: ([a]) CO_2 reported to E-PRTR by facilities must include emissions from both fossil fuel and biomass. The value for the aggregated national total of CO_2 reported by countries to UNFCCC has thus had biomass CO_2 emissions added. These latter emissions are reported separately by countries, but are not included in the official national total values.

([b]) 'N.A.' denotes 'not available'.

2.3 General approach

It is possible to model the pollution impacts arising from specific industrial facilities in detail. The ExternE Project has undertaken this type of work extensively since the early 1990s (CIEMAT, 1999). However, such intensive analysis would be extremely resource intensive and costly if the aim were to model simultaneously and in detail the individual emissions, dispersion and impacts from the approximately 10 000 facilities covered by the E-PRTR. Some methodological simplification is thus necessary.

The simplified analysis developed in this study applies the following approach:

1. Damage costs per tonne of each pollutant were quantified as a national average;

2. Factors to account for any systematic variation in damage cost per tonne between the national average and specific sectors were developed (e.g. to account for differences in the height at which emissions are released, which will affect dispersion and hence exposure of people and ecosystems);

3. E-PRTR emissions data for each facility were multiplied by the national average damage cost per tonne estimates for each reported pollutant, with the sector-specific adjustment factors applied where available.

The main modelling work undertaken in this study addressed the first of these steps. A detailed description of the modelling undertaken to develop national average damage costs per tonne of pollutant is provided in Annex 1 (for the regional and local air pollutants) and Annex 2 (for the heavy metals and organic micro-pollutants).

For the regional air pollutants NH_3, NO_X, NMVOCs, $PM_{2.5}$, and SO_2, the first step followed the approach described by Holland et al. (2005d) in developing marginal damage costs for inclusion in the BREF of Economics and Cross Media Effects (EIPPCB, 2006). Results in terms of damage cost per tonne of pollutant emission are different to those calculated earlier by Holland et al. (2005d), as updated dispersion modelling from the EMEP model has been used in the present analysis (see Annex 1).

The second step — introduction of sector-specific factors — used information from the Eurodelta II study (Thunis et al., 2008). Eurodelta II compared air quality modelling results from a number of European-scale dispersion models, including assessment of emission sources by sector. This enabled derivation of adjustment factors for four countries: France, Germany, Spain and the United Kingdom. For the present study, therefore, country-specific adjustment factors were applied to these four countries, and a sector-specific average value used to make adjustment for the other countries. This requires that the E-PRTR facilities are mapped onto the sector descriptions used by Eurodelta II. Further details are provided in Annex 3.

The Eurodelta II analysis is subject to certain limitations, for example:

- the geographic domain of the models used does not cover the full area impacted by emissions from countries included in the E-PRTR;

- assumptions on stack height for the different sectors appear simplistic.

However, using the Eurodelta II national sector adjustment values in this report addresses the concern that a blanket application of national average data would overestimate the damage costs attributed to industrial facilities.

In the final step — multiplying emissions data by the estimates of damage cost per tonne to quantify the total damage costs — PM_{10} data from the E-PRTR are converted to $PM_{2.5}$ by dividing by a factor of 1.54. This conversion is necessary for consistency with the damage functions agreed under the CAFE programme and the dispersion modelling carried out by EMEP.

Uncertainty is explicitly accounted for with respect to two main issues. The first concerns the method used for valuing mortality resulting from the regional and local pollutants. The second relates to inclusion or exclusion of damage cost estimates for CO_2. While there are numerous other uncertainties that could be accounted for these two issues are considered dominant for the present assessment.

Sections 2.3.1–2.3.3 describe in more detail the approaches used to determine the country-specific damage costs for the regional and local air pollutants, heavy metals and organic micro-pollutants, and CO_2. For the former two pollutant groups, additional methodological details are provided in the annexes to this report.

2.3.1 *Regional and local air pollutants*

Analysis of the impacts of regional and local air pollutant emissions (NH_3, NO_x, PM, SO_2 and NMVOC) (hereafter referred to as the regional pollutants) addresses effects on human health, crops and building materials assessed against exposure to $PM_{2.5}$, ozone and acidity. The health effects of SO_2, NO_X, NH_3 and NMVOCs result from the formation of secondary particulate matter and ozone through chemical reactions in the atmosphere. The possibility of direct health effects occurring as a result of direct exposure to NO_X and SO_2 is not ruled out but such effects are considered to be accounted for by quantifying the impacts of fine particulate matter exposure. Quantifying them separately would therefore risk a double counting of their effects.

An important assumption in the analysis is that all types of particle of a given size fraction (e.g. $PM_{2.5}$ or PM_{10}) are equally harmful per unit mass. Alternative assumptions have been followed elsewhere (e.g. in the ExternE project) but here the approach used in the CAFE analysis was employed, following the recommendations of the Task Force on Health (TFH) coordinated by WHO Europe under the Convention on Long-range Transboundary Air Pollution (LRTAP Convention). Some support for the TFH position comes from a recent paper by Smith et al. (2009), which suggested significant effects linked to sulphate aerosols.

This report does not quantify certain types of impact, for example ecosystem damage from acidic and nitrogen deposition and exposure to ozone, and acid damage to cultural heritage such as cathedrals and other fine buildings. This should not be interpreted as implying that they are unimportant. Rather, they are not quantified because of a lack of data at some point in the impact pathway.

Included in the estimation of damage costs of regional air pollutants is an extensive list of health impacts, ranging from mortality to days with respiratory or other symptoms of ill health. In economic terms the greatest effects concern exposure to primary and secondary particulate matter leading to mortality, the development of bronchitis and days of restricted activity including work-loss days.

Recognising methods developed elsewhere, a sensitivity analysis has been performed using two commonly applied methods for the valuing mortality — the value of statistical life (VSL) and the value of a life year (VOLY). The former is based on the number of deaths associated with air pollution while the latter is based upon the loss of life expectancy (expressed as years of life lost, or YOLLs). The values used in this report for VOLY and VSL are consistent with those used in the earlier CAFE programme. Use of the two methods follows the approach developed and discussed with stakeholders during the CAFE programme and used in the best available techniques reference document (BREF) on economics and cross media effects (EIPPCB, 2006).

The debate about the correct approach to use for mortality valuation does not extend to the other pollutants considered here — heavy metals and organic micro-pollutants. For these two pollutant groups, it is considered that exposure causes the onset of cancers or other forms of serious ill health that lead to a more substantial loss of life expectancy per case than for the regional air pollutants and hence that the use of the value of statistical life is fully appropriate.

The analysis of crop damage from exposure to ozone covers all of the main European crops. It does not, however, include assessment of the effects on the production of livestock and related products such as milk. Material damage from deposition of acidic or acidifying air pollutants was one of the great concerns of the acid rain debate of the 1970s and 1980s. Analysis here accounts for effects of SO_2 emissions on a variety of materials, the most economically important being stone and zinc/galvanised steel. Rates of damage have, however, declined significantly in Europe in recent decades in response to reduced emissions of SO_2, particularly in urban areas. Unfortunately it is not yet possible to quantify the damage costs caused by air pollution's impact on monuments and buildings of cultural merit.

Analysis of the effects of these regional pollutants is performed using the ALPHA-2 model, which is used elsewhere to quantify the benefits of European policies such as the Gothenburg Protocol and National Emission Ceilings Directive (e.g. Holland et al., 2005c; Holland et al., 2011). Further information on the methods used to quantify the effects of the regional air pollutants is given in Annex 1.

2.3.2 *Heavy metals and organic micro-pollutants*

As is the case for the major regional pollutants, assessment of the damage costs of heavy metals and organic micro-pollutants is incomplete, particularly with respect to quantifying ecosystem damage costs. Direct analysis for these pollutants focuses on health effects, particularly cancers but also, for lead and mercury, neuro-toxic effects leading to IQ loss and subsequent loss of earnings potential. The RiskPoll model has been adopted for this part of the work (Spadaro and Rabl, 2004, 2008a, 2008b). Further details of this part of the analysis are given in Annex 2. The Annex contains information on a more extensive list of pollutants than those covered in this report, demonstrating that the methods can be extended beyond the current scope of work.

Where appropriate, the analysis takes account of the types of cancer identified for each pollutant in developing the impact pathways for each. Exposure only comprises inhalation where lung cancer is the only observed effect of a particular substance. For others it is necessary to estimate total dose through consumption of food and drink as well as inhalation as shown in Figure 2.2. The valuation process takes account of the proportion of different types of cancer being fatal and non-fatal.

A complication arises because many of these pollutants are associated with particulate matter upon release. By taking account only of their carcinogenic and neuro-toxic properties and ignoring their possible contribution to other impacts of fine particulate matter it is possible that the total impact attributed to heavy metal and organic micro-pollutant emissions is underestimated. However, quantifying effects of particulate matter and some effects of the trace pollutants separately may imply a risk of double counting, at least with respect to fatal cancers ([2]). This issue is discussed further in Chapter 4, where it is concluded that the overall effect of any double counting on the final results is very small, and that knowledge of the carcinogenic impact of these pollutants is useful.

2.3.3 Greenhouse gases

Monetisation of greenhouse gas emissions follows a different approach to that adopted for the other pollutants considered, using an estimate of marginal abatement costs. There are two reasons for using a control cost approach for greenhouse gas (GHG) emissions:

1. There are concerns over the very high uncertainty in estimates of climate costs. This uncertainty is unavoidable as damage is dependent on the future development of society, particularly with respect to population and economic growth, neither of which can be forecast with great confidence, and the extent to which value is attached to future events.

2. Where national emission ceilings effectively exist for GHGs (as under the Kyoto Protocol), the marginal effect of a change in emissions is not to alter the amount of damage that is done to health, infrastructure and the environment, but to change the cost of reaching the national ceiling. To assume otherwise assumes that countries are very willing to exceed the agreed emission reduction targets (abating emissions more than they are legally required to do). The difficulty in gaining international consensus on effective GHG controls suggests that this is unlikely at present.

There are issues with this approach in that the marginal costs of abatement for GHGs are subject to their own significant uncertainties, and that they are specific to a certain level of emission control. However, the use of an approach involving use of marginal abatement costs can be considered a pragmatic response to the problems faced in this part of the analysis.

The valuation adopted here for CO_2 emissions is EUR 33.6 per tonne, based on a methodology developed by the UK government for carbon valuation in public policy appraisal. The latest update of this methodology provides a central short-term traded price of carbon of GBP 29 per tonne CO_2-equivalent in 2020 (DECC, 2011). The present day exchange rate was used to convert the value in GBP to EUR. A value for the year 2020 was selected rather than, for example, the current spot trading price for carbon, to remove one element of uncertainty with respect to short-term price fluctuations affecting the value of the marginal abatement cost. The year 2020 is also the end of the phase III period of the EU Emissions Trading System. While it is stressed that this figure reflects the views of the United Kingdom government rather than a consensus-based estimate widely recognised across Europe, it is considered reasonably representative and consistent with other figures that have been discussed, either in relation to damage costs or abatement costs. For illustrative purposes, the UK methodology further recommends an increased value of carbon by 2030, with a central price of GBP 74 per tonne CO_2-equivalent.

([2]) This does not apply to damage from neuro-toxic effects or the non-mortality costs of cancers related to healthcare, pain and suffering and loss of productivity.

As an illustration of the valuation for CO_2 used in this report with other approaches based upon the social cost of carbon (SCC), in its fourth assessment report, the Intergovernmental Panel on Climate Change (IPCC, 2007) highlighted both the uncertainties associated with estimating SCC and the very wide range of values that is available in the present literature. They identified a range for SCC between USD 4–95 per tonne CO_2 (equivalent at present-day exchange rates to approximately EUR 3–70 per tonne CO_2). The valuation adopted in this report of EUR 33.6 per tonne, reflecting the marginal costs of abatement, is therefore around mid-range of the IPCC's suggested range even through the two valuations are based on very different valuation approaches.

Recognising the uncertainties surrounding the valuation of damage costs from CO_2, the results in Chapter 3 are therefore presented both with and without CO_2-related impacts. One advantage of doing this is that it gives better recognition of operators that have taken action to reduce emissions of other air pollutants, such as acidic gases, particulate matter and heavy metals. It is clear, however, that a wider debate is required on how better to estimate the economic impacts of greenhouse gas emissions on the environment and health.

3 Results

The results of this work are described in three parts. The first set of results (Section 3.1) describes the national damage cost per tonne of emission determined for each of the selected pollutants. These results are the stepping stone linking emissions and the final damage cost estimates. Section 3.2 presents the damage cost estimations at the level of individual facilities. Section 3.3 then provides results aggregated in various ways, for example by pollutant, sector and country.

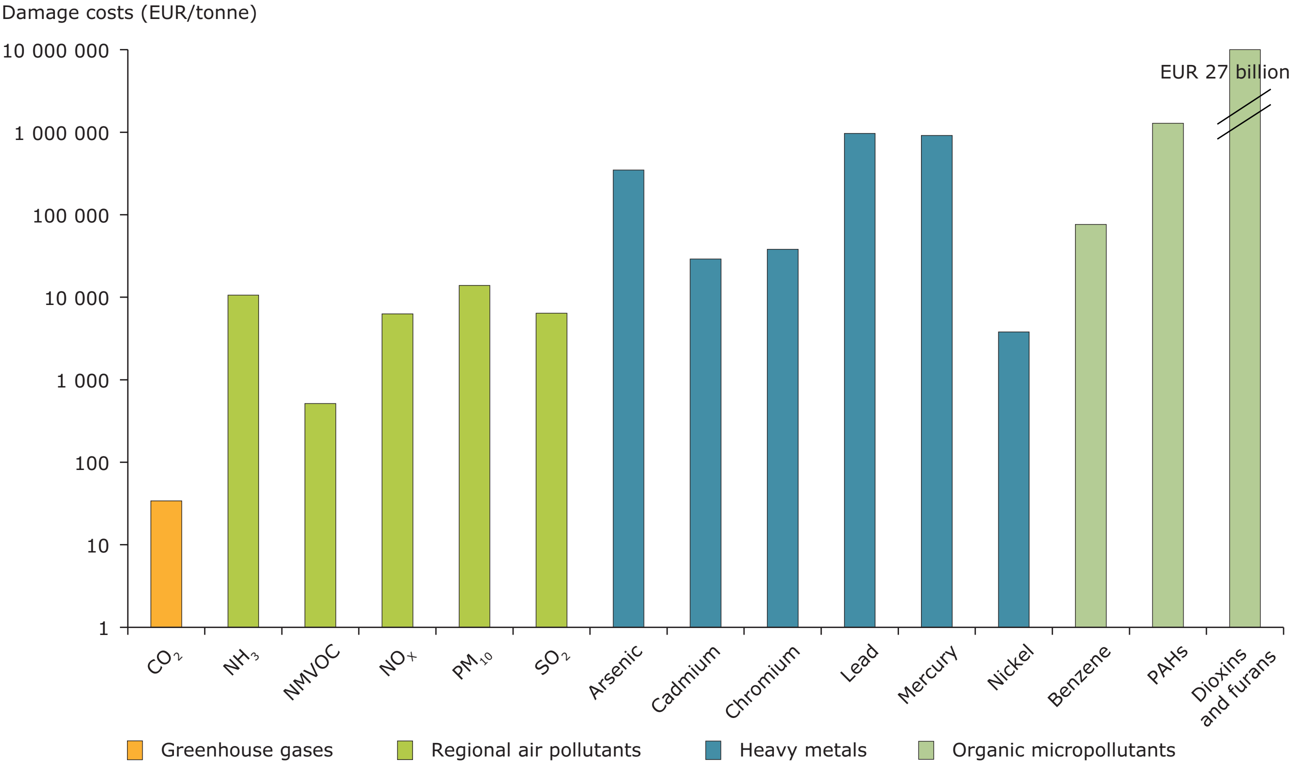
3.1 Damage cost per tonne of pollutant

This section provides an overview of the average damage cost per tonne of pollutant emitted from each country. Full results for each country are provided in Annexes 1 and 2.

Figure 3.1 shows how the quantified damage costs per unit of emission vary between pollutants. For illustrative purposes, data have been averaged across countries for those pollutants where the location of release strongly influences the damage caused (i.e. for all of the selected pollutants except CO_2, lead and mercury).

Taking the logarithmic scale into account, Figure 3.1 shows, not surprisingly, that the damage cost per tonne emitted values vary substantially between pollutants with nine orders of magnitude difference between the values for CO_2 and dioxins. There is a rough ordering of the different pollutant groups, with the organic micro-pollutants the most hazardous per unit of emission, followed by the heavy metals, regional pollutants, and finally CO_2. Issues relating to the scale of the damage per tonne estimates for arsenic, cadmium, chromium and nickel, relative to estimates for fine particulate matter, are discussed further in Chapter 4.

Figure 3.1 Estimates of the European average damage cost per tonne emitted for selected air pollutants (note the logarithmic scale on the Y-axis)



For several pollutants, the country-specific estimated damage costs per unit of emission provided in Annexes 1 and 2 vary significantly among emitting countries for various reasons. For example:

- The density of sensitive receptors (people, ecosystems) varies significantly around Europe. Finland, for example, has a population density of 16 people/km^2, compared to Germany with 229/km^2.
- Some emissions disperse out to sea and do not affect life on land, an issue clearly more prominent for countries with extensive coastlines such as the United Kingdom or Ireland compared to landlocked countries such as Austria or Hungary.

For some pollutants the site of release is relatively unimportant in determining the magnitude of damage costs. Persistent pollutants, CO_2 and mercury are good examples, although their impacts are differ greatly.

Figure 3.2 illustrates these issues, showing variation in the average damage costs attributed to PM_{10} in each country, with a factor six difference between the country with the lowest damage cost per tonne (Estonia) and the highest (Germany). The countries with the lowest damage cost per tonne estimates tend to be at the edges of Europe, particularly the eastern edge, while the countries with the highest damage costs are close to the centre of the continent.

Figure 3.2 also shows the sensitivity of results to the methods (VOLY and VSL) used for valuing mortality — producing a factor 2.8 difference between the two sets of values.

3.2 Damage cost estimates for E-PRTR facilities

Using the country-specific damage costs per unit emission as described in the preceding section, it is possible to quantify the damage costs caused by each facility reported under the E-PRTR by multiplying the emissions of the selected pollutant from each facility by the respective damage cost per tonne for each pollutant.

Table 3.1 lists the 20 facilities estimated to cause the greatest damage costs for the selected pollutants. All facilities are categorised within E-PRTR as being

Figure 3.2 Variation across Europe in national average damage cost per tonne PM_{10} emission and illustrating the alternative approaches used for valuing mortality

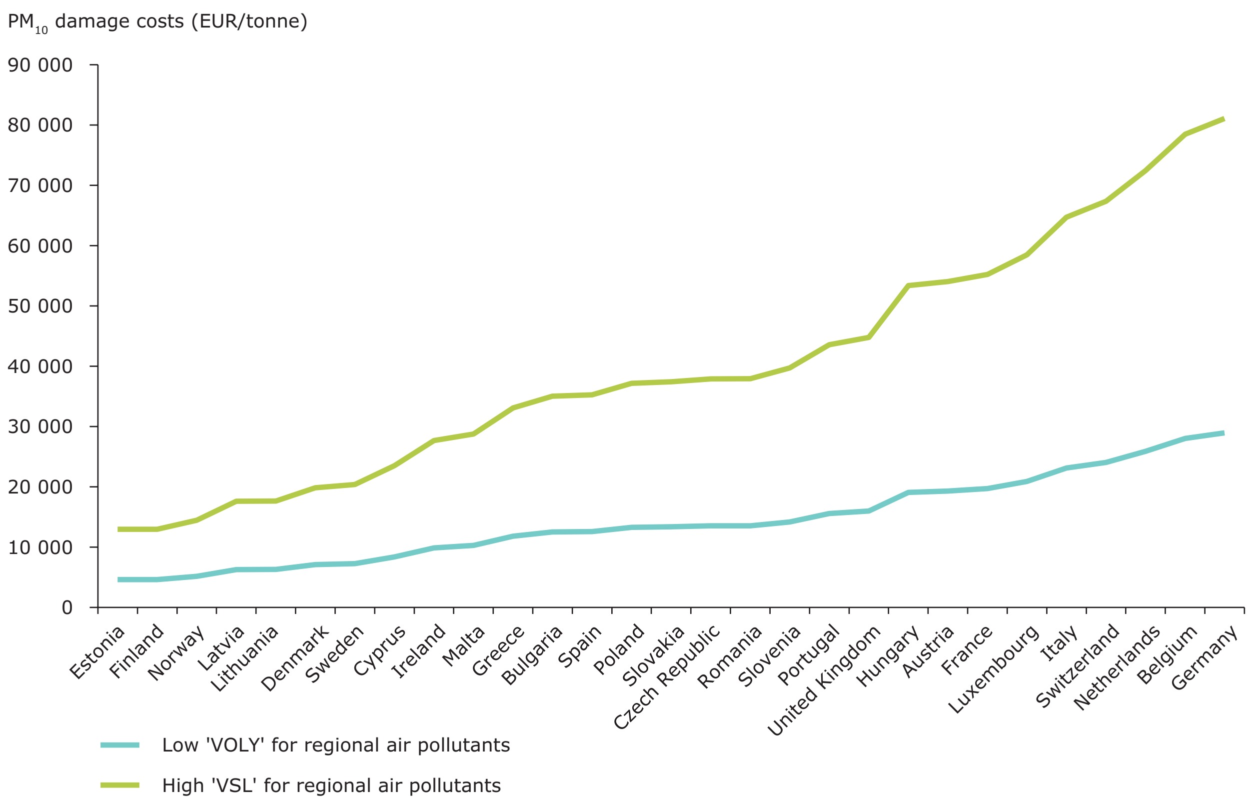


Table 3.1 The top 20 E-PRTR facilities (all of which are power generating facilities) estimated as having the greatest damage costs from emissions of selected pollutants to air, based on data for 2009

No	E-PRTR facility ID	Facility name	Country	Emissions (tonnes)				Estimated damage cost per pollutant group (million EUR)				Aggregated damage cost (million EUR)	
				CO_2	NO_x	SO_x	PM_{10}	CO_2	Regional air pollutants VOLY low	Regional air pollutants VSL high	Heavy metals and organic micro-pollutants	VOLY low	VSL high
1	1298	PGE Elektrownia Bełchatów S.A.	Poland	29 500 000	42 900	50 700	1 810	991	557	1 525	1.9	1 550	2 518
2	99010	TETs Maritsa Iztok 2, EAD	Bulgaria	9 630 000	11 700	290 000	N.R.	324	1 108	3 015	N.R.	1 432	3 339
3	143123	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Germany	23 600 000	18 200	21 400	675	793	439	1 209	0.3	1 232	2 002
4	140663	RWE Power AG Bergheim	Germany	26 300 000	15 400	6 420	440	884	246	676	0.4	1 130	1 560
5	13777	Drax Power Limited	United Kingdom	20 500 000	38 400	27 800	362	689	337	935	0.2	1 026	1 625
6	149935	Complexul Energetic Turceni	Romania	6 070 000	15 400	106 000	1 320	204	684	1 878	0.4	889	2 082
7	140709	RWE Power AG Eschweiler	Germany	19 200 000	12 300	3 360	396	645	178	490	0.3	824	1 135
8	140418	RWE Power AG Kraftwerk Neurath	Germany	17 900 000	12 300	3 630	281	601	180	493	0.2	781	1 095
9	140358	RWE Power AG Kraftwerk Frimmersdorf	Germany	16 800 000	10 500	5 280	289	564	177	487	0.2	742	1 051
10	198	PGE Elektrownia Turów S.A.	Poland	11 700 000	11 800	40 600	1 400	393	329	906	N.R.	722	1 299
11	144585	Vattenfall Europe Generation AG Kraftwerk Boxberg	Germany	15 300 000	9 790	8 170	180	514	198	545	0.5	713	1 059
12	14192	PPC S.A. SES Megalopolis A'	Greece	4 460 000	3 090	184 000	5 590	150	541	1 459	1.0	692	1 609
13	4951	Elektrownia 'Kozienice' S.A.	Poland	10 900 000	21 200	32 200	711	366	320	878	1.6	688	1 246
14	144664	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Germany	12 800 000	8 590	14 000	95.3	430	245	675	1.9	677	1 107
15	14245	PPC S.A. SES Agioy Dhmhtrioy	Greece	12 900 000	24 800	58 000	471	433	194	509	1.8	629	944
16	149936	Complexul Energetic Rovinari	Romania	5 110 000	11 800	63 500	2 400	172	439	1 204	0.3	611	1 376
17	12825	Elektrárny Prunéřov	Czech Republic	9 070 000	17 100	15 800	628	305	236	644	0.7	541	949
18	118084	Centrale Termoelettrica Federico II (BR Sud)	Italy	13 000 000	7 300	6 540	473	437	99	270	0.4	536	707
19	155619	Longannet Power Station	United Kingdom	7 390 000	15 200	32 200	459	248	278	769	0.4	527	1 018
20	143135	Vattenfall Europe Generation AG Kraftwerk Schwarze Pumpe	Germany	10 700 000	4 190	8 200	91.1	360	135	371	0.3	495	731

Notes: 'N.R.' denotes 'not reported'.
For the regional air pollutants, the low-high range shows the differing results derived from the alternative approaches to mortality valuation.
Heavy metal and organic micro-pollutants are not shown. Two facilities in the top 20 list, 'TETs Maritsa Iztok 2, EAD' and 'PGE Elektrownia Turów S.A.' did not report emissions of these pollutants; all other facilities reported emissions of at least one of the individual pollutants within these categories.
Emissions of NMVOC and NH3 not shown. Just two facilities,' Drax Power Limited' and 'Elektrownia KOZIENICE S.A.' reported emissions of these pollutants. It is noted, however, that emissions of these pollutants from power generating facilities may not always be above the E-PRTR reporting threshold.

thermal power stations (i.e. power plants generating electricity and or heat). Eight of these facilities are located in Germany, three in Poland, two each in Greece, Romania and the United Kingdom, and one in Bulgaria, the Czech Republic and Italy. Emissions data confirm that all of the facilities listed are large, with CO_2 emissions of between 4.4 million and 30 million tonnes per year.

It is also clear from Table 3.1 that the facilities do not always appear to be reporting complete emissions data to E-PRTR. For example, the Bulgarian facility ranked second in terms of its overall damage costs, 'TETs Maritsa Iztok 2, EAD', has not reported emissions of PM_{10} to E-PRTR for the year 2009; all other facilities did. Similarly of the top 20 facilities, neither 'TETs Maritsa Iztok 2, EAD' nor 'PGE Elektrownia Turów S.A.' reported emissions of the individual heavy metals or organic micro-pollutants, despite all other facilities having reported emissions for at least one pollutant within these groups. Likely omissions such as these clearly bias any ranking of facilities against facilities whose operators have been more conscientious in reporting complete data.

Table 3.2 shows that these 20 facilities were among the total of only 69 facilities that emitted more than 4.5 million tonnes in 2009 (of the 2 204 facilities that reported CO_2 emissions within the E-PRTR). All 14 facilities emitting more than ten million tonnes of CO_2 per year are included in the list of the 20 facilities with highest damage costs. Their presence in this top 20 list is therefore attributable in significant part to their size.

Table 3.2 Distribution of CO_2 emissions reported in the E-PRTR for the 20 facilities with the highest damage costs

Emission (tonne)	Number of the 20 facilities with the highest damage costs	Total number from the 2 204 facilities reporting CO_2 in E-PRTR
> 4.5 million	20	69
> 10 million	14	14
> 15 million	8	8
> 20 million	4	4
> 25 million	2	2

Figure 3.3 Cumulative distribution of damage costs for the 2 000 E-PRTR facilities with the highest estimated damage costs (including CO_2)

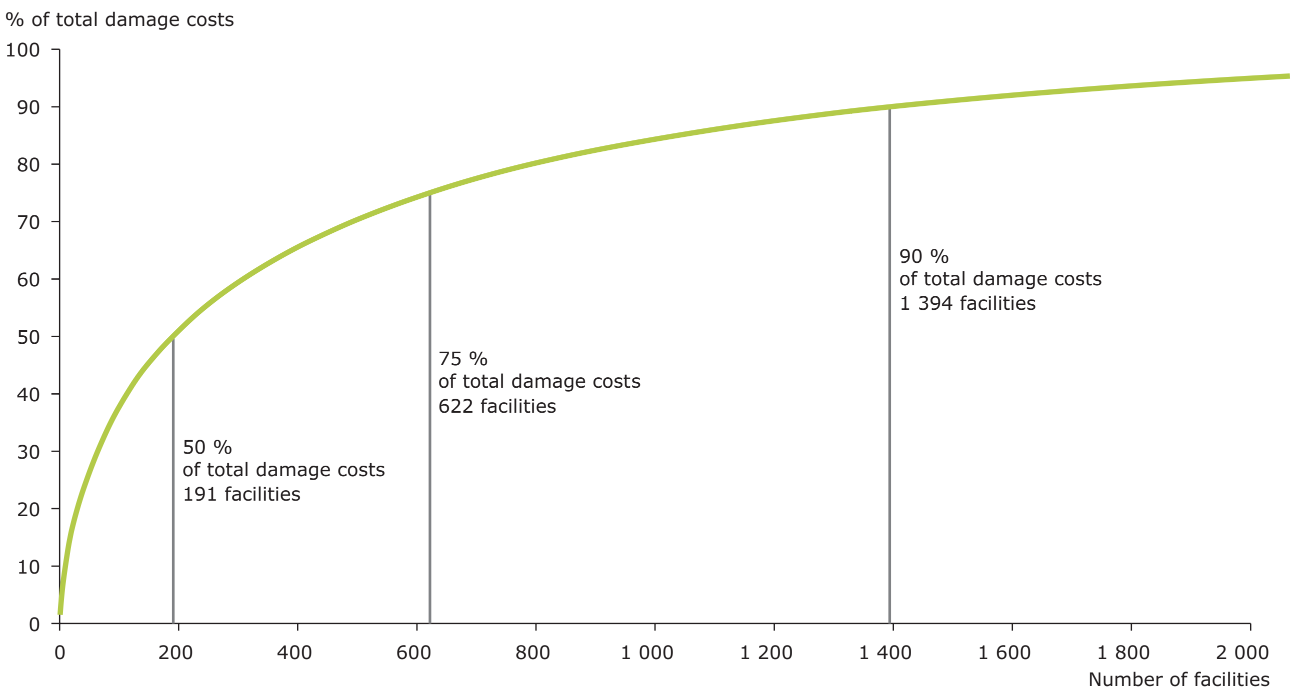


Figure 3.3 shows the cumulative distribution of the estimated damage costs for the 2 000 E-PRTR facilities with the highest estimated damage costs. A small number of individual facilities cause the majority of the damage costs. Fifty per cent of the total damage cost occurs as a result of emissions from just 191 (or 2 %) of the approximately 10 000 facilities that reported data for releases to air.

Map 3.1 shows the geographical distribution of these 191 facilities. Three quarters of the total damage costs are caused by the emissions of 622 facilities, which is 6 % of the total number, and 90 % of damage costs are attributed to 1 394 facilities.

Another factor that needs to be considered to gain a proper understanding of these results is the efficiency of production at different sites. The E-PRTR does not provide production or fuel consumption data so a direct assessment of the environmental efficiency of facilities relative to output (or fuel consumption) is not possible. For the purposes of the present report, CO_2 emissions are taken to be a proxy for fuel consumption because (accepting that efficiency will vary between facilities) CO_2 emissions will have a closer relationship with power production and productivity than any of the other data available.

Table 3.3 presents the same 20 facilities as before, ordered according to the estimated damage costs per tonne of CO_2. The most obvious difference between the rankings in Table 3.1 and Table 3.3 is that all except one of the eight German facilities now fall into the lower half of the second table, suggesting that they contribute less damage cost per unit fuel consumption or, in other words, they are more environmentally efficient within this group of 20 facilities. Conversely, more facilities from Eastern Europe now appear among the 10 facilities with the highest damage costs.

Map 3.1 Location of the 191 E-PRTR facilities that contributed 50 % of the total damage costs estimated for 2009

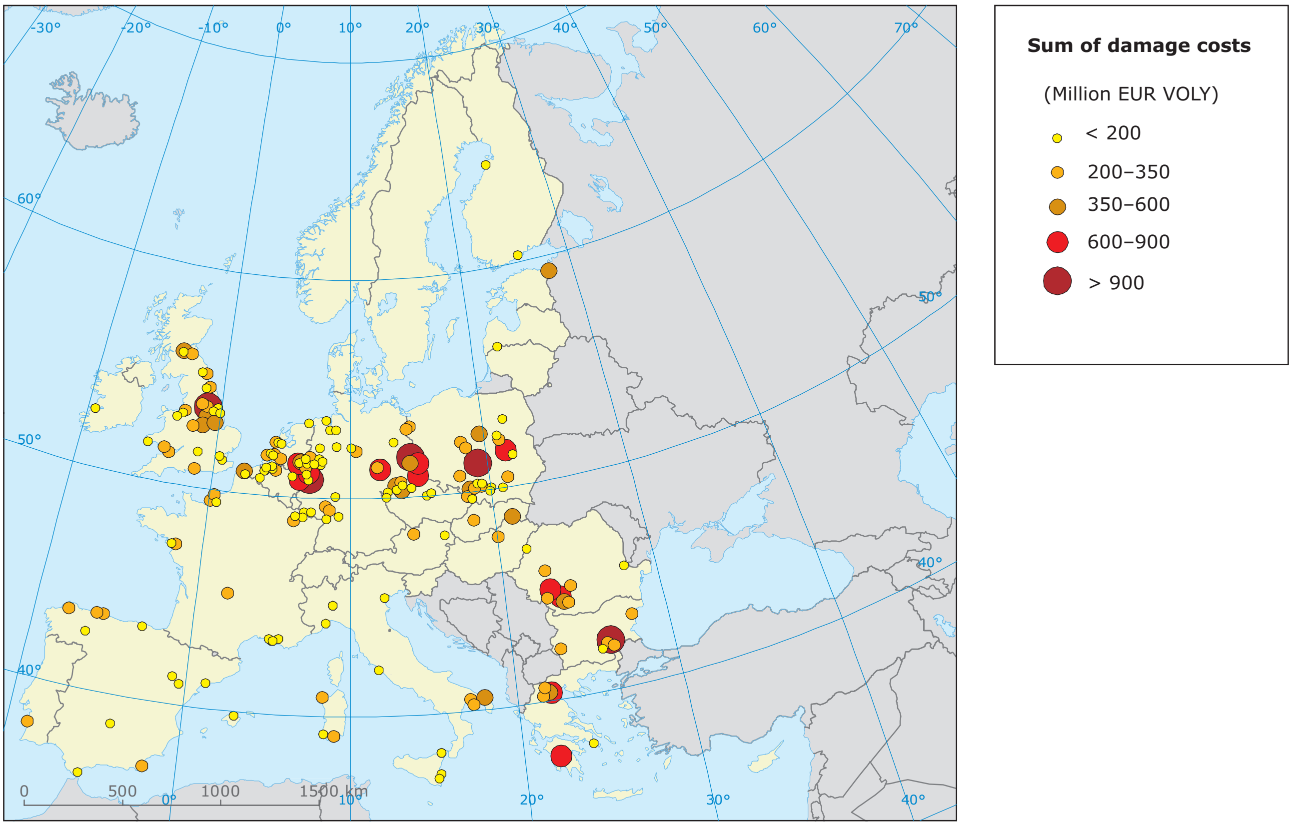


Table 3.3 Aggregated damage costs by facility for the top 20 facilities normalised per unit CO_2 emission (as a proxy for output)

No	E-PRTR facility ID	Facility	Country	Aggregated damage cost per tonne CO_2 (EUR/tonne CO_2)	
				VOLY low	VSL high
1	14192	PPC S.A. SES Megalopolis A'	Greece	155	361
2	99010	TETs Maritsa Iztok 2 – EAD	Bulgaria	149	347
3	149935	Complexul Energetic Turceni	Romania	146	343
4	149936	Complexul Energetic Rovinari	Romania	120	269
5	155619	Longannet Power Station	United Kingdom	71	138
6	4951	Elektrownia Kozienice S.A.	Poland	63	114
7	198	PGE Elektrownia Turów S.A.	Poland	62	111
8	12825	Elektrárny Prunéřov	Czech Republic	60	105
9	144664	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Germany	53	86
10	1298	PGE Elektrownia Bełchatów S.A.	Poland	53	85
11	143123	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Germany	52	85
12	13777	Drax Power Limited, Drax Power Ltd	United Kingdom	50	79
13	14245	PPC S.A. SES Agioy Dhmhtrioy	Greece	49	73
14	144585	Vattenfall Europe Generation AG Kraftwerk Boxberg	Germany	47	69
15	143135	Vattenfall Europe Generation AG Kraftwerk Schwarze Pumpe	Germany	46	68
16	140358	RWE Power AG Kraftwerk Frimmersdorf	Germany	44	63
17	140418	RWE Power AG Kraftwerk Neurath	Germany	44	61
18	140663	RWE Power AG	Germany	43	59
19	140709	RWE Power AG	Germany	43	59
20	118084	Centrale Termoelettrica Federico II (BR SUD)	Italy	41	54

Table 3.4 Aggregated damage costs for all E-PRTR facilities normalised per unit CO_2 emission (as a proxy for output)

No	E-PRTR facility ID	Facility	Sector	Country	Aggregated damage cost per tonne CO_2 (EUR/tonne CO_2)	
					VOLY low	VSL high
1	13067	Hanson Building Products Limited, Whittlesey Brickworks	Manufacture of ceramic products incl. tiles, bricks, etc.	United Kingdom	526	1 385
2	7831	Centrale électrique de pointe des carrières	Power generation	France	307	764
3	7689	Central de Escucha	Power generation	Spain	285	722
4	143993	Aurubis AG	Production of smelting of non-ferrous crude metals	Germany	263	641
5	99009	TETs 'Maritsa' AD Dimitrovgrad	Power generation	Bulgaria	241	598
6	4884	EDF — Centrale Thermique du PORT	Power generation	France	236	574
7	132431	Central Diesel de Melilla	Power generation	Spain	218	511
8	98893	Gorivna instalatsias nominalna toplinna moshtnost	Power generation	Bulgaria	216	530
9	7808	Centrale De Jarry-Nord	Power generation	France	210	506
10	99021	TETs 'Republika'	Power generation	Bulgaria	207	514
11	7832	Centrale De Bellefontaine	Power generation	France	197	473
12	149940	Regia Autonoma Pentru Activitati Nucleare — Sucursala Romag Termo	Power generation	Romania	197	482
13	149945	SC CET Govora SA	Power generation	Romania	185	449
14	149973	SC Electrocentrale Oradea SA	Power generation	Romania	179	434
15	4930	Centrale thermique de Lucciana	Power generation	France	171	401
16	149951	SC CET ARAD SA — pe lignit	Power generation	Romania	170	410
17	138430	Arcelormittal Upstream sa (Coke Fonte)	Production of pig iron or steel	Belgium	166	363
18	11124	Rafinérie Litvínov	Mineral oil and gas refineries	Czech Republic	162	386
19	5166	Guardian Orosháza Kft.	Manufacture of glass	Hungary	162	381
20	143642	Euroglas GmbH	Manufacture of glass	Germany	160	381

Table 3.5 The 20 facilities with the highest estimated damage costs from emissions to air (excluding CO_2)

No	Number of facility in Table 3.1	E-PRTR facility ID	Facility name	Country	Emissions (tonnes)			Estimated damage cost per pollutant group (million EUR)			Aggregated damage cost (million EUR)	
					NO_x	SO_x	PM_{10}	Regional air pollutants VOLY low	Regional air pollutants VSL high	Heavy metals and organic micro-pollutants	VOLY low	VSL high
1	2	99010	'TETs Maritsa Iztok 2' EAD	Bulgaria	11 700	290 000	N.R.	1 108	3 015	N.R.	1 108	3 015
2	6	149935	Complexul Energetic Turceni	Romania	15 400	106 000	1 320	684	1 878	0.4	685	1 878
3	1	1298	PGE Elektrownia Bełchatów S.A.	Poland	42 900	50 700	1 810	557	1 525	1.9	559	1 527
4	12	14192	PPC S.A. SES Megalopolis A'	Greece	3 090	184 000	5 590	541	1 459	1.0	542	1 460
5	3	143123	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Germany	18 200	21 400	675	439	1 209	0.3	440	1 209
6	16	149936	Complexul Energetic Rovinari	Romania	11 800	63 500	2 400	439	1 204	0.3	439	1 204
7	5	13777	Drax Power Limited, Drax Power Ltd	United Kingdom	38 400	27 800	362	337	935	0.2	337	936
8	10	198	PGE Elektrownia Turów S.A.	Poland	11 800	40 600	1 400	329	906	N.R.	329	906
9	13	4951	Elektrownia 'Kozienice' S.A.	Poland	21 200	32 200	711	320	878	1.6	322	880
10		149940	Regia Autonoma Pentru Activitati Nucleare — Sucursala Romag Termo	Romania	2 580	49 800	777	290	798	0.1	290	798
11	19	155619	Longannet Power Station	United Kingdom	15 200	32 200	459	278	769	0.4	278	770
12		149932	Sucursala Electrocentrale Isalnita	Romania	3 520	44 800	1 210	273	750	N.R.	273	750
13		98893	Gorivna instalatsias nominalna toplinna moshtnost	Bulgaria	1 490	70 700	N.R.	264	719	N.R.	264	719
14		140394	ThyssenKrupp Steel Europe AG Werk Schwelgern	Germany	5 280	10 300	1 060	235	648	25.0	260	673
15		9701	Slovenské elektrárne a.s. — Elektrárne Nováky, závod	Slovakia	3 820	32 400	N.R.	255	703	0.2	255	703
16	14	144664	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Germany	8 590	14 000	95.3	245	675	1.9	247	677
17	4	140663	RWE Power AG Bergheim	Germany	15 400	6 420	440	246	676	0.4	246	676
18		99007	TETs 'Bobov dol'	Bulgaria	4 840	53 100	3 850	239	651	N.R.	239	651
19	17	12825	Elektrárny Prunéřov	Czech Republic	17 100	15 800	628	236	644	0.7	236	644
20		149956	SC Electrocentrale Deva SA	Romania	10 400	26 200	1 200	221	605	N.R.	221	605

Note: Shaded cells indicate those facilities also included in Table 3.1.

'N.R.' denotes 'not reported'.

If this analysis is extended to all E-PRTR facilities and not just to the list of those 20 facilities with the highest estimated aggregated damage costs then the ranking alters significantly (Table 3.4). When all facilities have their damage costs normalised by CO_2 emissions, the facilities that were previously included in the top 20 now appear a long way down the ranking. To illustrate, the top five facilities shown in Table 3.3 would appear in positions 24, 29, 32, 59, and 290 if Table 3.4 were extended to include all facilities.

It is also useful to consider the ranking of facilities when emissions of CO_2 are not included, because this will highlight the extent to which operators have reduced what might be termed the 'traditional' air pollutants. Table 3.5 shows the facilities having the highest estimated damage costs when CO_2 is not included.

Seven facilities that were not in the original list of the 20 facilities with the highest aggregated damage costs (Table 3.1) now appear in the new listing (these are the non-shaded entries in Table 3.5). The clearest difference between the tables is the reduction in facilities from Germany (down from eight to four) and the increase in facilities from Romania (up to five from two) and Bulgaria (from one to three). The presence of so many facilities from Bulgaria and Romania in the list is perhaps not surprising given that these countries are the newest entrants to the EU and hence may still have been in the process of fully implementing relevant legislation. At least for some facilities, action to further reduce emissions from these sites is understood to be under way, so it is possible that significant improvements will be seen in the data reported to E-PRTR in the future.

3.3 Aggregated damage costs

Total emissions of each pollutant from the E-PRTR are shown in Figure 3.4. The emissions of differing pollutants vary in scale by twelve orders of magnitude. Emissions are dominated by CO_2, followed by the regional pollutants and heavy metals. Reported emissions of organic micro-pollutants are so small (under 2 kg for dioxins) they are not visible on the graph. The ordering of pollutants by emission is roughly the reverse of the ordering by damage cost per tonne as shown in Figure 3.1. Thus, those pollutants that are most hazardous per unit emission tend to be emitted in the smallest quantities.

Figure 3.4 Aggregated annual emissions to air of selected pollutants from E-PRTR in 2009 (note the logarithmic scale on the Y-axis)

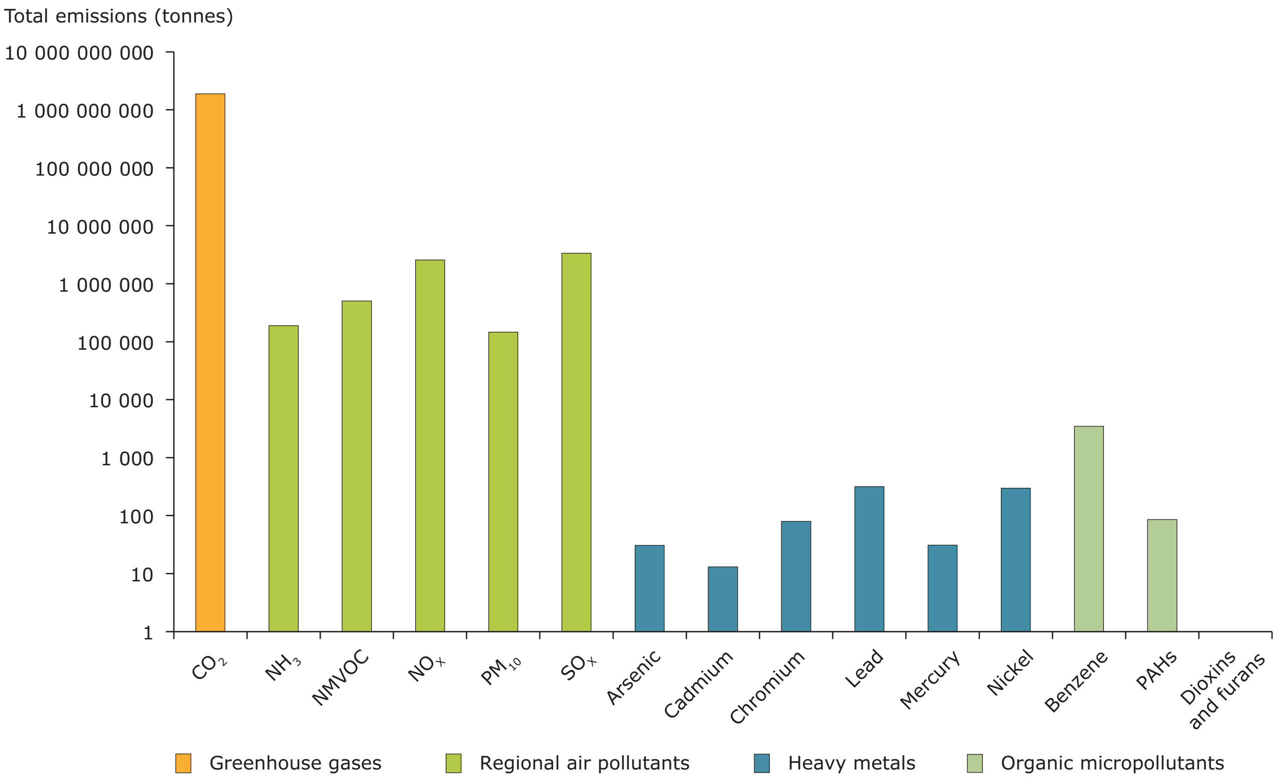
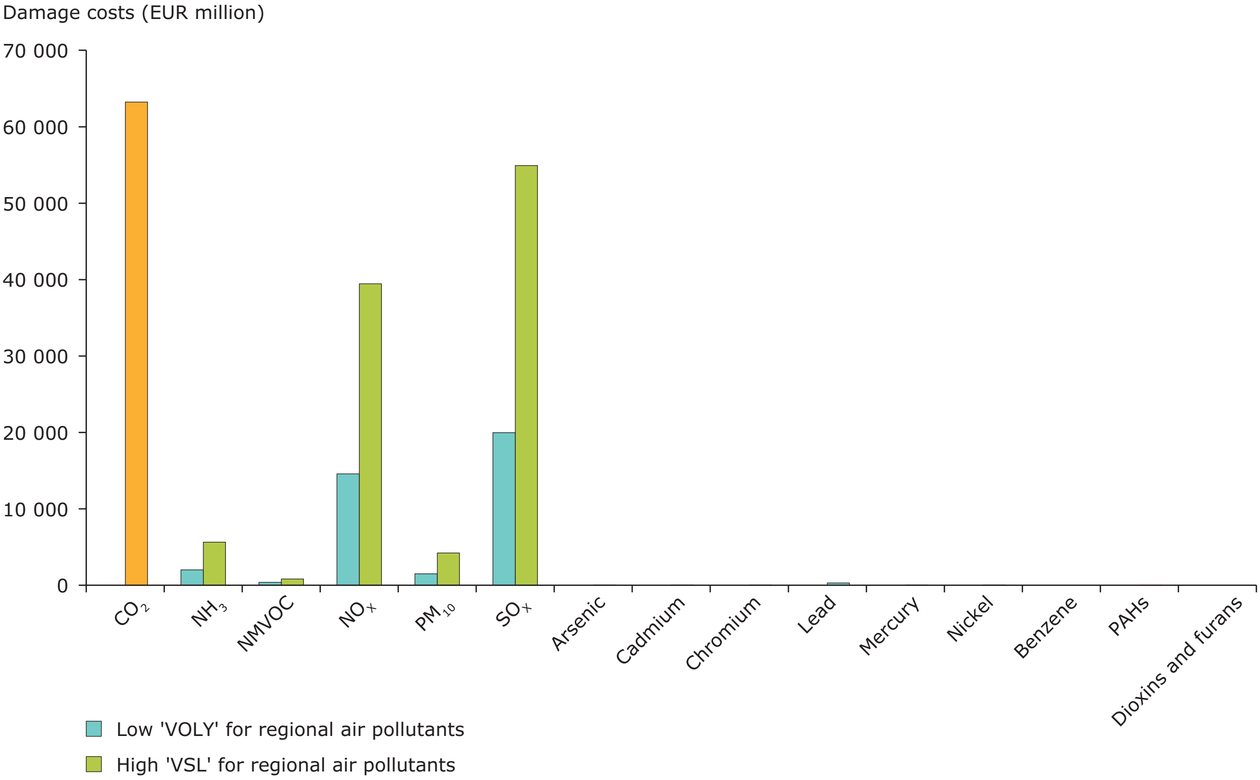


Figure 3.5 Aggregated damage costs by pollutant



Note: The blue bars for the regional pollutants represent the lower bound figures for the valuation of mortality calculated using the VOLY approach, green bars are for cases where the VSL approach has been applied to mortality valuation.

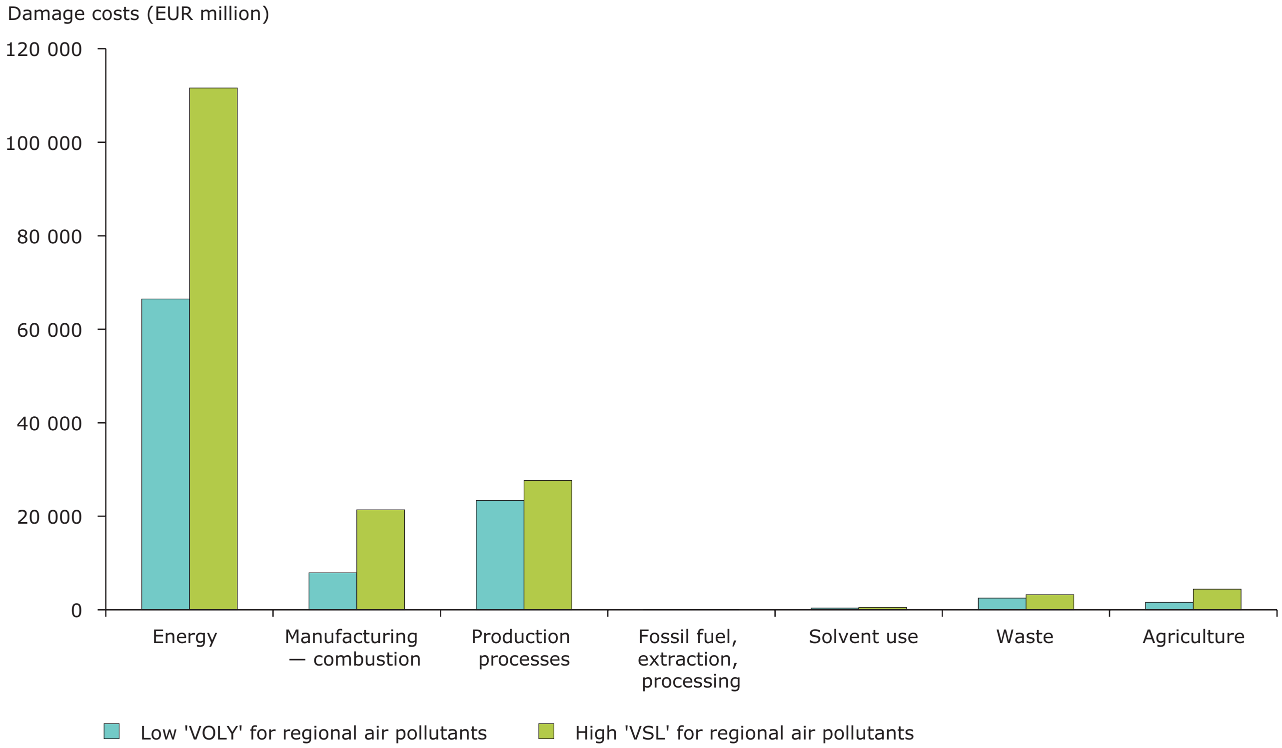
Table 3.6 Estimated damage costs aggregated by pollutant group (2005 prices)

Pollutant group	Aggregated damage cost (billion EUR)
CO_2	63
Regional air pollutants (NH_3, NO_x, PM_{10}, SO_2, NMVOCs)	38–105
Heavy metals (As, Cd, Cr, Hg, Ni, Pb)	0.35
Organic micro-pollutants (benzene, dioxins and furans, PAHs)	0.13

Multiplying the country-specific estimates of damage cost per tonne of pollutant, corrected where appropriate to account for differences between sectors, by the E-PRTR emissions generates the total damage cost estimates by pollutant presented in Figure 3.5 and Table 3.6. The order of pollutants by damage cost is CO_2, SO_2, NO_x, PM_{10}, NH_3 and NMVOC, followed by the heavy metals and then the organic micro-pollutants. Quantified damage costs from the metals and organics is small relative to the other pollutants.

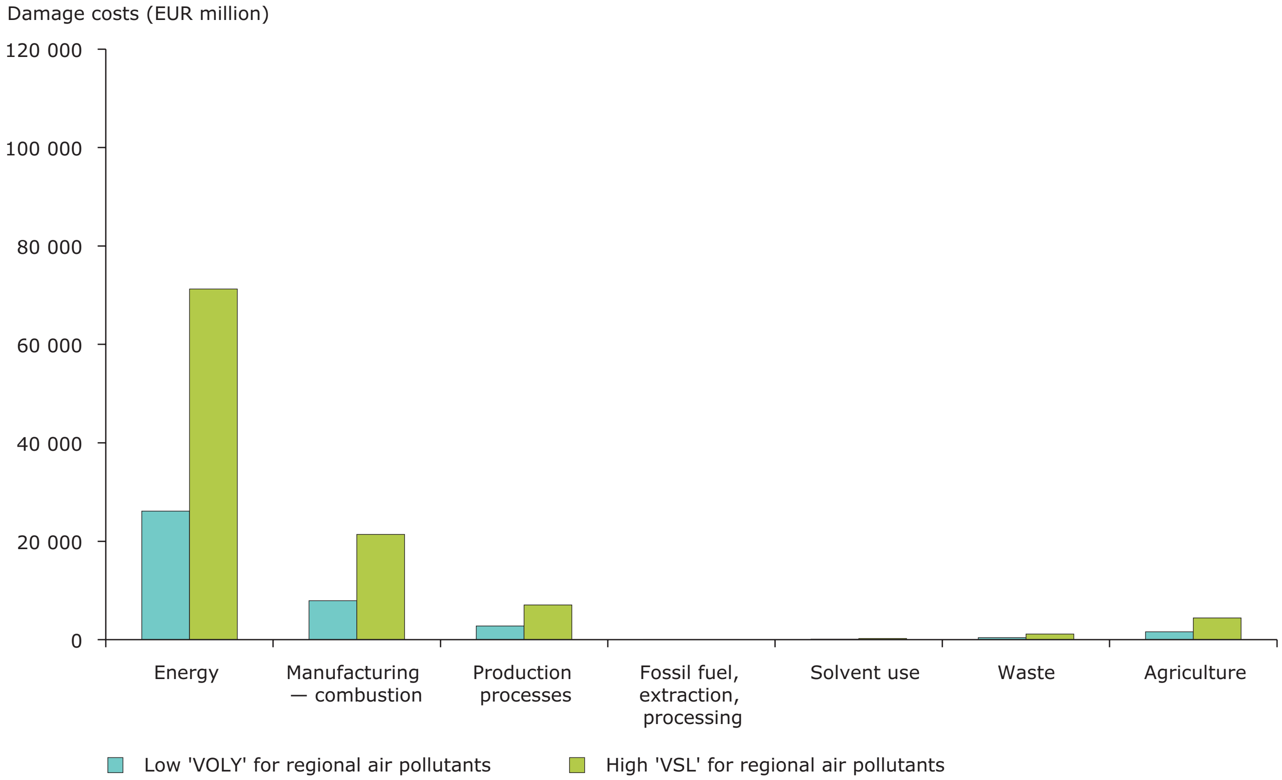
Figures 3.6 and 3.7 illustrate which sectors generate the largest damage costs (with and without the damage cost arising from CO_2 emissions). The low/high ranges reflect the variation in results from the alternative approaches to valuing mortality for the regional air pollutants (NH_3, NO_x, PM_{10}, SO_2 and NMVOCs) in line with the CAFE methodology. Other sources of uncertainty are not considered. The dominant sectors contributing the highest aggregated damage costs are energy and then manufacturing and production processes.

Figure 3.6 Damage costs aggregated by sector including CO_2



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional pollutants.

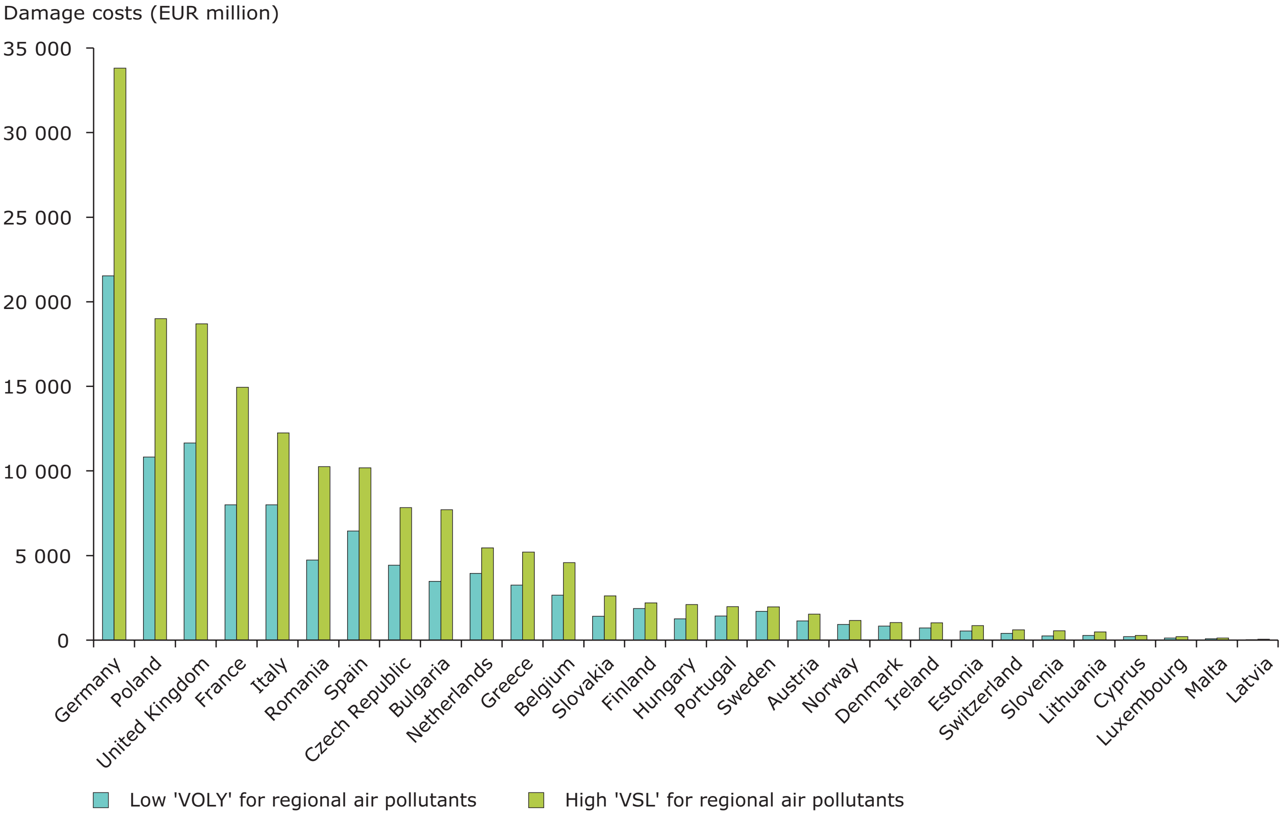
Figure 3.7 Damage costs aggregated by sector excluding CO_2



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional pollutants.

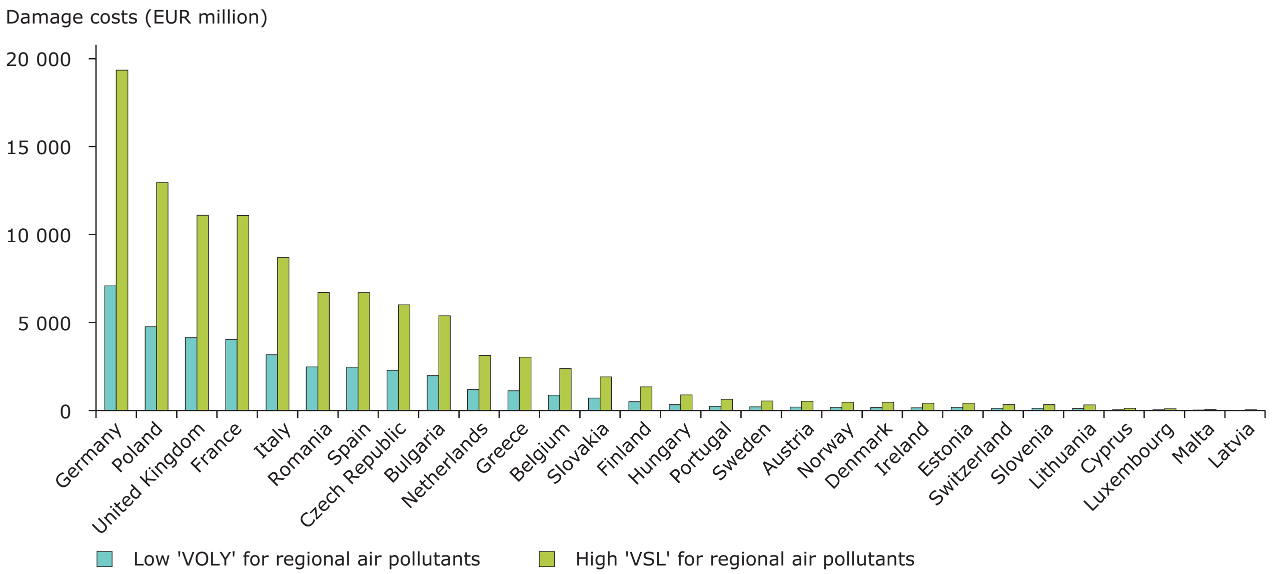
Results are aggregated by country (with and without CO_2) in Figures 3.8 and 3.9. The highest aggregate damage costs are, unsurprisingly, attributed to the larger countries and those with more polluting facilities.

Figure 3.8 Aggregated damage costs by country, including CO_2



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional pollutants.

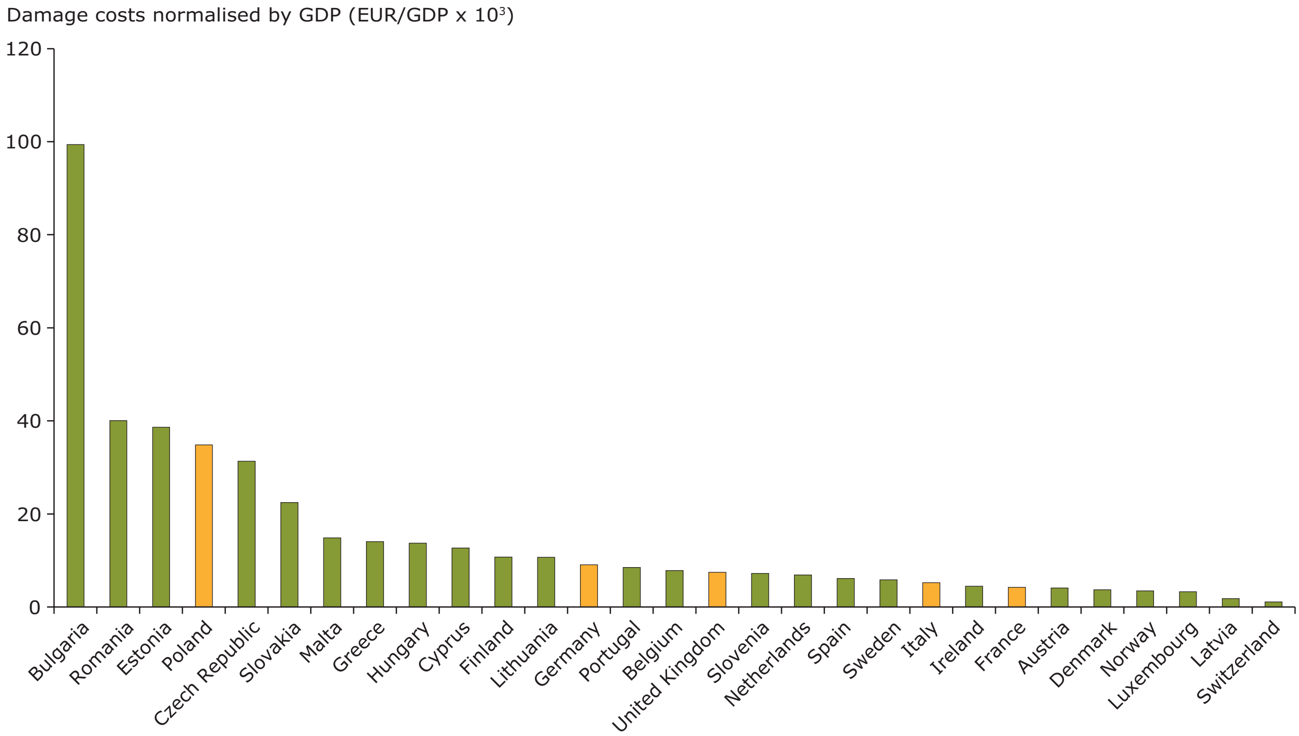
Figure 3.9 Aggregated damage costs by country, excluding CO_2



Note: The low-high range shows the differing results derived from the alternative approaches to mortality valuation for the regional pollutants.

An alternative way to rank countries is to normalise the estimated damage costs by introducing the concept of efficiency into the analysis, similar to the approach taken for individual facilities in Table 3.3. Normalising the damage costs by gross domestic product (GDP) to reflect the output of national economies results in significant changes in the ordering of countries. Certain countries previously listed as having the highest damage costs — Germany, the United Kingdom, France and Spain — drop significantly down the ranking, while Bulgaria, Romania, Estonia and the Czech Republic rise to the top (Figure 3.10).

Figure 3.10 Aggregate damage costs by country normalised against GDP



Note: The orange bars highlight the countries with the highest damage costs from Figure 3.8.

4 Discussion

The preceding chapters described the development and application of a simplified methodology to determine damage costs to human health and the environment arising from emissions to air that industrial facilities report to the E-PRTR. Various issues were identified that introduce potential uncertainties into the results and can therefore affect the robustness of analysis. These are explored further in this chapter, grouped under the following themes:

- suitability of the methodology employed;
- areas in which the analysis could be improved;
- ways in which the E-PRTR might be improved for this type of assessment; and
- interpretation of the results from this report.

4.1 Suitability of the methods used

4.1.1 Main regional air pollutants

The methods presented for assessing emissions of the major regional air pollutants (SO_2, NO_X, NMVOCs, NH_3 and fine particulate matter, ozone from emissions of NO_x and NMVOCs) have been developed over many years. They have been extensively discussed at the European level by researchers, European institutions, European and member state policymakers, NGOs and industry. For these pollutants the methods used are therefore reasonably mature, although important questions persist, notably in attributing effects to secondary inorganic particulate matter (ammonium sulphate and ammonium nitrate).

It is to be expected that different types of particulate matter will vary in their effect on health. Some previous studies (e.g. ExternE) have introduced some factors to differentiate between $PM_{2.5}$, PM_{10}, sulphate aerosols and nitrate aerosols. These factors constitute expert judgement within the ExternE team based on evidence of the likely effect of different pollutants. However, other expert groups (e.g. the Task Force on Health convened by WHO under the Convention on Long-Range Transboundary Air Pollution) have concluded that there is no empirical evidence on which to differentiate, so currently suggest that it should not be done.

The analysis in this report presumes consistent health impacts per unit of exposure in different parts of Europe. The information presented in Section 4.3 below shows a recent development in mortality assessment that challenges this view. If response functions for mortality were derived nationally it would cause the estimated damage costs to increase significantly in some countries and decrease in others.

Overall, however, the magnitude of quantified damage costs for the main regional air pollutants seems unlikely to be challenged in the near future, so the methods for these pollutants are deemed fit for purpose.

4.1.2 Heavy metals and organic micro-pollutants

There is greater uncertainty in the treatment of heavy metals and organic micro-pollutants. The effects of most of the metals, dioxins and furans is conveyed in terms of extra cases of cancer. It is possible that their true impact is greater than shown here because of their association with particulate matter and hence with other health impacts such as mortality and morbidity resulting from respiratory and circulatory disease. While this would be accounted for in the results for $PM_{2.5}$ and PM_{10} it would imply underestimation of the damage costs when focusing only on the metals.

Epidemiological research is continuing into the toxicological effects of heavy metals. Recent preliminary findings indicate damage costs may be larger in magnitude than those previously estimated under ExternE. This suggests that there may be significant increases in the unit damage costs estimates for these pollutants in the near future. Nevertheless, much of the impact pathway would be unchanged, for example the quantification of exposure via air and ingestion. It would also be surprising if a revision meant that the impacts from heavy metals and dioxins and furans would be substantial relative to those reported here for the regional pollutants and CO_2. As such, changes in methods may have little impact on the answers to the questions posed in this analysis.

4.1.3 Carbon dioxide

For CO_2 it has already been noted that the estimate of damage cost per tonne emitted is based on a different methodology (marginal abatement costs) to that used for the other pollutants and is thus subject to a number of questions. However, the value selected is considered to be in a reasonable range relative to other available estimates for greenhouse gases. Thus, while the figure could be changed, it would be unlikely to alter the conclusion that the damage costs of CO_2 emissions from E-PRTR facilities are likely to be very significant.

Nevertheless, as recommended in Chapter 2, it is clear that a wider debate is required on how better to estimate the economic impacts of greenhouse gas emissions on the environment and health.

4.1.4 Valuing mortality

In general, the most important issues with respect to valuation centre on valuing mortality, specifically the question of whether to employ the value of statistical life (VSL) or the value of a life year (VOLY).

The response functions for effects of acute exposure provide an estimated number of deaths, while those for chronic exposure provide (most robustly) an estimate of the number of life years lost. This may appear to make the choice of when to apply the VSL and when to apply the VOLY quite straightforward. Indeed, this would be in line with the OECD guidance on environmental cost benefit analysis (OECD, 2006). However, it is widely considered that the effects of acute exposures on mortality lead to a shorter loss of life per case than chronic exposures. Further to this, acute exposures seem likely to affect people who are already sick, possibly primarily as a result of exposure to air pollution, but more probably from smoking, diet, age and so on. Attribution of a full VSL to the acute cases is thus very questionable, and for these reasons, acute ozone deaths in CAFE were valued only using the VOLY.

Overall, therefore, it is considered that the methods used here are fit for purpose. They can certainly be improved but conclusions based on the current formulations should be reasonably robust.

4.1.5 Combining damage cost estimates for different pollutants

Combining the damage cost values for different pollutants to give an estimate of total damage from a facility, sector or country, may be seen as inappropriate in view of:

- the varying maturity of assessment methodologies for the different pollutants, bearing in mind that quantifying impacts of the major regional air pollutants (SO_2, NO_x, NH_3, PM and NMVOCs) has been debated much more thoroughly than the quantification of the other pollutants;
- the differences between the general methodologies, noting that particular caution is needed in including estimates of greenhouse gas damage costs, which are based on the cost of marginal abatement rather than damage costs;
- specific methodological questions, such as previous decisions (e.g. by the WHO Task Force on Health that advised CAFE) to quantify impacts of NO_x and SO_2 on health only in terms of their contribution to secondary inorganic aerosol levels.

There are therefore some arguments for keeping damage cost estimates for the different pollutants separate. However, this overlooks one of the main purposes of monetisation, which is to bring data together in a common metric that weights emissions according to the severity of their effects. While caution is advised in interpreting and using estimates that are aggregated across different pollutants, it is nevertheless considered that such estimates also provide additional and useful insights into the overall burdens generated by facilities, sectors, etc. Accordingly, the estimated damage costs presented in this report are in various instances presented both separately for the pollutant groups and aggregated.

4.2 Potential future improvements to the methods employed

Several potential refinements to the methods employed in this study might be implemented in the future based on continuing scientific work. For example, the dispersion modelling that underpins analysis of the regional pollutants could be improved. Similarly, the country-specific pollutant damage costs can be developed when new source-receptor matrices are generated by the EMEP chemical transport model. The matrices used for the present work date back to 2006 and the EMEP model has since been refined. This revision of the matrices might not, however, be done until 2012–2013 due to the demands of other work presently being undertaken by EMEP.

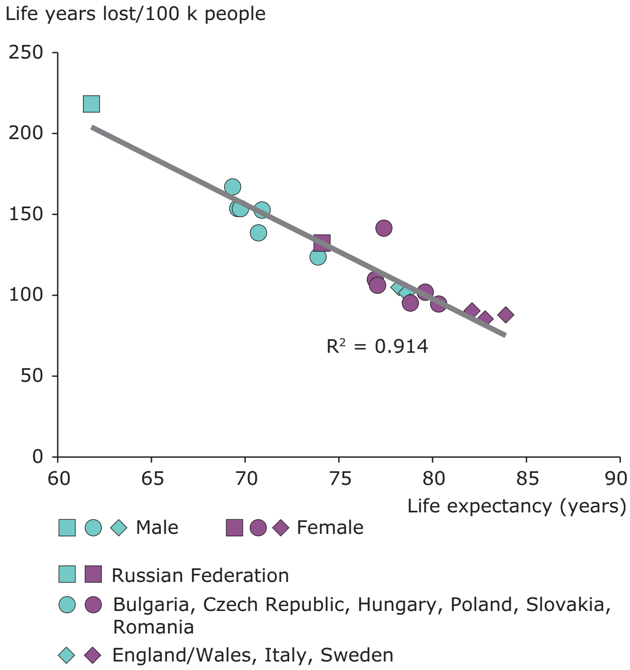
The response functions for quantifying the **impacts of the major regional pollutants** are under regular review. The European Commission is presently undertaking a review of the EU air quality legislation to be completed by 2013 and in this context will ask the Task Force on Health led by WHO-Europe under the LRTAP Convention (UNECE, 1979) to consider in detail modifications to the current set of functions.

Further to the analysis presented in this report, the Institute of Occupational Medicine in Edinburgh has performed additional life-table analysis to inform cost-benefit analysis such as that being used in the current revision to the Gothenburg Protocol under the LRTAP Convention (Miller et al., 2011). The study considered the sensitivity of national populations to a unit change in exposure to fine particulate matter. Initial analysis for Italy and Sweden suggested that there was little error associated with basing European analysis on results for the population of England and Wales. The England and Wales results were used in the mortality analysis for fine particulate matter in terms of loss of longevity presented in the CAFE work and also used in the present report.

However, subsequent analysis for Bulgaria, the Czech Republic, Hungary, Poland, Romania, Slovakia and the Russian Federation showed that the populations in those countries were more sensitive than those in the countries originally considered, perhaps due to differences in life expectancy (Figure 4.1). Results were particularly significant for the Russian Federation, reflecting especially the very limited life expectancy of Russian men (the top left data point in Figure 4.1).

These results were discussed at the May 2011 meeting of the WHO Task Force on Health, which concluded that they should be factored into analysis immediately. Unfortunately this has not been possible for the present report, which probably implies a bias toward underestimation of damage costs here.

Figure 4.1 Relationship between life expectancy and life years lost per 100 000 people from a one-year change in exposure to $PM_{2.5}$ of 1 µg.m^{-3}



Further methodological refinements that might be introduced during the next year or so concern:

- quantifying chronic effects of $PM_{2.5}$ exposure on mortality against cause-specific death rates rather than, as at present, total death rates;
- quantifying possible effects of chronic exposure to ozone on mortality, based on the work of Jerrett et al. (2009);
- revising the quantification of chronic bronchitis impacts linked to $PM_{2.5}$ exposure, based on results of the Swiss SAPALDIA study (Schindler et al., 2009).

The most important of these changes may concern chronic exposure to ozone and its effects on mortality. The other changes may not make a great deal of difference to analysis for the European population, whereas inclusion of chronic effects on mortality could greatly increase the overall significance of ozone impacts.

Quantifying the **impacts of regional air pollutants on ecosystems** may be possible in the medium term through studies using the 'ecosystem services' approach. Some advances have been made in this area recently through work by Jones et al. (2011) and Mills et al. (2011). A possible halfway step to this goal would be to use the pollution transfer matrices to assess the contribution of E-PRTR facilities to exceedance of critical loads and levels across Europe.

Quantifying the damage costs associated with **heavy metals** raises uncertainties because data on deposition suggest much higher emissions than are accounted for in available inventories (Fowler et al., 2006). This may in part be linked to instances where facilities included in the E-PRTR emit below the respective reporting thresholds for heavy metals or simply fail to report emissions of some pollutants.

For **greenhouse gases** it would be useful to have a wider European debate on the values used in analysing damage costs (e.g. whether to use damage costs or, as in this report, an estimate of marginal abatement costs). Some useful information should be forthcoming from the European Commission-funded ClimateCost project, which is due to report in late 2011. Until such information or agreement is available, a pragmatic approach, as implemented here, is to report damage costs both with and without including greenhouse gases.

One improvement for the **sectoral analysis** presented here would be to supplement the point-source data from the E-PRTR with information from national emission inventories that summarise total emissions from each sector. This would at least partially address concerns that not all facilities report all emissions and the lack of data from facilities that are not required to report to the E-PRTR. This extension of the analysis would be particularly useful for the agriculture sector, since it accounts for the vast majority of NH_3 emissions in Europe and most operators are unlikely to be included under the E-PRTR.

4.3 Changes to the E-PRTR to facilitate assessments

As highlighted in preceding sections, there are some ways to improve the E-PRTR register to facilitate its use in assessments like the present report. The following are considered to be the most important:

- **Providing information on the fuel consumption or productive output of individual facilities**. This would enable the efficiency of facilities to be calculated in terms of estimated damage costs per unit of production or fuel consumption. At present, such information is not reported to the E-PRTR so this type of analysis cannot be done. This reduces the value of the analysis as regulators, for example, cannot assess the merits of controlling a few large facilities over a larger number of smaller facilities. It also limits the usefulness of the register for members of the public, as a lack of information on facility capacity or production limits the potential for fair comparisons. There is some limited information publicly available at the European level which provides information on, for example, fuel combustion by certain large combustion plants in most, but not all, Member States. This report did not investigate using such data to augment the data available from the E-PRTR. This is a potential task that could be undertaken in the future.

  In this study CO_2 emissions were used as an indicator for power output from individual facilities (Tables 3.3 and 3.4) and GDP as an indicator of national production (Figure 3.10) to normalise damage costs against service provided. However, the deficiencies of these proxy outputs are recognised and it would be far better to base the normalisation on actual fuel consumption or productive output. Barrett and Holland (2008) normalised against facility capacity but this is also problematic as it implies that all facilities are operating at full capacity.

- **More complete reporting of emissions from individual facilities**. Review of the facilities with the highest estimated damage costs reveals significant variation in the completeness of reporting of heavy metals and other pollutants. The most notable single potential omission is undoubtedly the lack of PM_{10} emissions data for the Bulgarian plant ranked as having the second highest damage costs of all facilities. Omissions like this clearly bias any ranking of facilities by the damage costs that they generate against facilities whose operators have been more conscientious in reporting data.

- **More extended data checking**. Recognising the need to improve the quality of data reported to the E-PRTR register, the EEA has initiated an annual data review process in recent years, providing feedback to the competent authorities in each country responsible for compiling facility data (e.g. ETC/ACC, 2010). Nevertheless, it is considered that consideration be given to further checking by national regulators before data are reported to the E-PRTR, particularly to address completeness of data and to identify outlying values. Such checking is to some extent facilitated by the annual updating of the E-PRTR, which allows the identification of facilities whose emissions vary significantly between years.

- **Improved traceability of facilities**. It proved difficult to compare the results calculated for the present study with those from previous works (Holland, 2006; Barrett and Holland, 2008) on a facility-by-facility basis. Part of the problem relates to differences in the annual E-PRTR datasets received by the EEA, in which facilities may change ownership, name and/or national facility identification code. In addition, locational references can also change over time, from a village location to the nearest town or district for example.

While these suggestions are put forward for potentially improving E-PRTR, the register is nevertheless recognised as an extremely useful resource for researchers and members of the public interested in the transparency of environmental information.

4.4 Interpreting the results of this study

The E-PRTR already provides substantial useful information for a variety of users. For example, emissions data show how the major polluters in Europe contribute to the overall pollution burden, and changes in emissions from these facilities provide an indication of the effectiveness of legislation to reduce the pollutant burdens imposed on society by industry.

The progress in reducing emissions is apparent if the results generated here are compared with those of past studies by Holland (2006) and Barrett and Holland (2008) based on the E-PRTR's predecessor, the European Pollutant Emissions Register (EPER). This comparison reveals significant changes in the list of most polluting facilities, presumably as a result of either facility closure or modernisation (but perhaps also due to a change of facility name, as noted in Section 4.3). It is important to note that the report does not in any way assess whether the emissions of a facility are consistent with its legal requirements for operating.

The main insight provided by this report is the expression of pollution problems in terms of what really matters to people — the impacts and damage costs that pollution causes. The knowledge that a given quantity of pollution released to air from a particular location will cause a quantifiable increase in mortality and various kinds of morbidity (e.g. new incidence of chronic bronchitis, restrictions to normal activity, use of medication), along with the associated costs, helps convey the real nature of pollution problems in a way that a simple measure of emissions cannot. This is the reality even though the analysis is incomplete, especially with respect to quantification of ecosystem damage.

Quantifying effects in monetary terms provides information relevant to cost-benefit analysis of pollution controls. Information regarding the size of pollution damage can easily be coupled with ball-park estimates of the costs of abatement for a preliminary cost-benefit analysis (see Barrett and Holland, 2008). In this context, it is important that the benefits of industrial facilities (such as producing goods and products, and generating employment and tax revenues) are properly recognised, and not just the costs. These benefits are not addressed in this report.

It is also useful to recognise that pollution impacts vary depending on the site of release, as this may imply that different control strategies should be employed in different areas. In recommending differentiated control strategies, however, it is important to ensure that impact assessments take account of ecological effects.

The analysis also suggests which pollutants and sectors should be prioritised for future control. This is complicated by the lack of data in areas such as ecological impacts and emissions not reported to the E-PRTR. These issues can be factored in separately, however, for example using multi-criteria analysis if needed.

In summary, this report has presented a simplified methodology that allows for the estimation of damage costs caused by emissions of selected pollutants from industrial facilities included in the E-PRTR. It demonstrates that, compared to using emissions data alone, these methods provide additional insights and transparency into the costs of harm caused by air pollution. Such insights are particularly valuable in the context of current discussions in Europe on how best to move towards a resource-efficient and low-carbon economy. Moreover, the analysis can be further strengthened by integrating efficiency and productivity data for individual facilities into the analysis of damage costs.

References

AEA Technology, 1997, *Economic evaluation of air quality targets for CO and benzene*, report for the European Commission (http://ec.europa.eu/environment/enveco/air/pdf/benzene.pdf and http://ec.europa.eu/environment/enveco/air/pdf/benzene_annex.pdf) accessed 1 December 2010.

Baes, C. F., Sharp, R. D., Sjoreen, A. L. and Shor, R. W., 1984, *A review and analysis of parameters for assessing transport of environmentally released radionuclides through agriculture*, Oak Ridge National Laboratory, ORNL 5786. September 1984.

Barrett, M. and Holland, M., 2008, *The costs and health benefits of reducing emissions from power stations in Europe: Air Pollution and Climate Series 20* (http://www.airclim.org/reports/APC20_final.pdf) accessed 10 December 2010.

Bickel, P. and Friedrich, R. (eds), 2005, *ExternE: externalities of energy — methodology 2005 update* (http://www.externe.info/brussels/methup05a.pdf) accessed 12 December 2010.

Bosch, P., Coenen, P., Fridell, E., Astrom, S., Palmer, T. and Holland, M., Wagner, A., and Palmer, T., 2009, *Cost-benefit analysis to support the impact assessment accompanying the revision of Directive 1999/32/EC on the sulphur content of certain liquid fuels*, Report for European Commission DG Environment (http://ec.europa.eu/environment/air/transport/pdf/CBA_of_S.pdf) accessed 22 November 2010.

CIEMAT, 1999, *ExternE externalities of energy: volume X: national implementation* (http://www.externe.info/reportex/vol10.pdf) accessed 10 December 2010.

DECC, 2011, *Update short term traded carbon values for UK public policy appraisal*, Department of Energy and Climate Change, October 2011 (http://www.decc.gov.uk/assets/decc/11/cutting-emissions/carbon-valuation/3137-update-short-term-traded-carbon-values-uk.pdf) accessed 28 October 2011.

EEA, 2010, *The European Environment — State and Outlook 2010*, European Environment Agency (http://www.eea.europa.eu/soer) accessed 9 November 2011.

EEA, 2011, 'The European Pollutant Release and Transfer Register (E-PRTR) Dataset version 3.2 (17 October 2011)' (http://www.eea.europa.eu/data-and-maps/data/member-states-reporting-art-7-under-the-european-pollutant-release-and-transfer-register-e-prtr-regulation-4) accessed 1 November 2011.

EIPPCB, 2006, *BREF on economics and cross media effects*, European Integrated Pollution Prevention and Control Bureau, Seville (http://eippcb.jrc.es/reference/ecm.html) accessed 28 November 2010.

EMEP, 2005, Transboundary acidification, eutrophication and ground level ozone in Europe in 2003, European Monitoring and Evaluation Programme (EMEP) Report 1/2005, (http://www.emep.int/publ/reports/2005/status_report_1_2005_ch5-8_app.pdf), accessed 28 October 2011.

EMEP, 2008, Transboundary acidification, eutrophication and ground level ozone in Europe in 2006, European Monitoring and Evaluation Programme (EMEP) Report 1/2008, (http://www.emep.int/publ/reports/2008/status_report_1_2008.pdf), accessed 28 October 2011.

Entec, 2001, *Economic evaluation of air quality targets for heavy metals*, report for European Commission DG Environment (http://ec.europa.eu/environment/enveco/air/pdf/report_heavy_metals.pdf) accessed 1 December 2010.

EPA, 1994, *Estimating exposure to dioxin-like compounds – Volume: executive summary*, US Environmental Protection Agency, Office of Health and Environmental Assessment, EPA600-6-88-005Ca.

EPA, 1997, *Exposure Factors Handbook*, US Environmental Protection Agency, EPA-600-P-95-002Fa-c.

EPA, 2002, *Child-Specific Exposure Factors Handbook*, US Environmental Protection Agency, EPA-600-P-00-002B.

EPA, 2005, *Human health risk assessment protocol for hazardous waste combustion facilities*, US Environmental Protection Agency, Office of Solid Waste, EPA530-R-05-006.

E-PRTR, 2011, 'E-PRTR — The European Pollutant Release and Transfer Register' (http://prtr.ec.europa.eu) accessed 2 November 2011.

ETC/ACC, 2010, *E-PRTR Review Report 2010 covering the 2008 E-PRTR dataset*, European Topic Centre on Air and Climate Change report for the European Environment Agency (http://air-climate.eionet.europa.eu/docs/ETCACC_TP_2010_5_RevRep_2008_E-PRTRdata.pdf) accessed 2 December 2010.

ETSU/Metroeconomica, 1995, *ExternE: externalities of energy – volume 2: methodology* (http://www.externe.info/reportex/vol2.pdf) accessed 10 December 2010.

EU, 1978, Council Directive 78/176/EEC of 20 February 1978 on waste from the titanium dioxide industry, Official Journal L 054 , 25/02/1978 pp. 19–24 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31978L0176:en:HTML) accessed 2 November 2011.

EU, 1982, Council Directive 82/883/EEC of 3 December 1982 on procedures for the surveillance and monitoring of environments concerned by waste from the titanium dioxide industry, Official Journal L 378 , 31/12/1982 pp. 1–14 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31982L0883:en:HTML) accessed 2 November 2011.

EU, 1992, Council Directive 92/112/EEC of 15 December 1992 on procedures for harmonizing the programmes for the reduction and eventual elimination of pollution caused by waste from the titanium dioxide industry, Official Journal L 409, 31/12/1992 pp. 11–16 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31992L0112:en:HTML) accessed 2 November 2011.

EU, 1999, Council Directive 1999/32/EC of 26 April 1999 relating to a reduction in the sulphur content of certain liquid fuels and amending Directive 93/12/EEC, OJ L 121, 11.5.1999, p. 13–18 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:31999L0032:EN:NOT) accessed 27 July 2011.

EU, 2001a, Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants, OJ L 309, 27.11.2001, p. 1–21 (http://eur-lex.europa.eu/Notice.do?val=261603:cs&lang=en&list=496647:cs,261603:cs,&pos=2&page=1&nbl=2&pgs=10&hwords=2001/80/EC~) accessed 27 July 2011.

EU, 2001b, Directive 2001/81/EC of the European Parliament and of the Council of 23 October 2001 on national emission ceilings for certain atmospheric pollutants, OJ L 309, 27.11.2001 (http://eur-lex.europa.eu/Notice.do?val=261604:cs&lang=en&list=576968:cs,573314:cs,548466:cs,489472:cs,485090:cs,471128:cs,468193:cs,405222:cs,261604:cs,414663:cs,&pos=9&page=1&nbl=11&pgs=10&hwords=Directive%202001/81/EC~) accessed 27 July 2011.

EU, 2003, Directive 2003/17/EC of the European Parliament and of the Council of 3 March 2003 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels, OJ L 76, 22.3.2003, p. 10–19 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32003L0017:EN:NOT) accessed 27 July 2011.

EU, 2004a, Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air, OJ L 23, 26.1.2005 (http://eur-lex.europa.eu/Notice.do?val=393964:cs&lang=en&list=547852:cs,393964:cs,413804:cs,497555:cs,&pos=2&page=1&nbl=4&pgs=10&hwords=DIRECTIVE%202004/107/EC~) accessed 27 July 2011.

EU, 2004b, Decision 280/2004/EC of the European Parliament and of the Council of 11 February 2004 concerning a mechanism for monitoring Community greenhouse gas emissions and for implementing the Kyoto Protocol, Official Journal of the European Communities, L 49/1, 19.2.2004.

EU, 2006, Regulation (EC) No 166/2006 of the European Parliament and of the Council of 18 January 2006 concerning the establishment of a European pollutant Release and Transfer Register and amending Council Directives 91/689/EEA and 96/61/EC. Official Journal of the European Union, L33/1, 4.2.2006.

EU, 2008, Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe, OJ L 152, 11.6.2008 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:152:0001:0044:EN:PDF) accessed 27 July 2011.

EU, 2010, Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control), OJ L 334, 17.12.2010, p. 17–119 (http://eur-lex.europa.eu/Notice.do?val=553885:cs&lang=en&list=572494:cs,553885:cs,571912:cs,&po

s=2&page=1&nbl=3&pgs=10&hwords=Directive%20 2010/75/EU~) accessed 27 July 2011.

Fowler, D., McDonald, A. G., Crossley, A., Nemitz, E., Leaver, D., Cape, J. N., Smith, R. I., Anderson, D., Rowland, P., Ainsworth, G., Lawlor, A. J., Guyatt, H. and Harmens, H., 2006, *UK Heavy Metal Monitoring Network* (http://www.uk-pollutantdeposition.ceh.ac.uk/sites/uk-pollutantdeposition.ceh.ac.uk/files/UK_HeavyMetals_Final_report_2006_final_version.pdf) accessed 15 December 2010.

Holland, M., 2006, *Health impacts of emissions from large point sources (second edition),* Air Pollution and Climate Series 19 (http://www.airclim.org/reports/APC19SE.pdf) accessed 10 December 2010.

Holland, M. and King, K., 1998, *Economic evaluation of air quality targets for tropospheric ozone, Part C: economic benefit assessment*, report for the European Commission DG Environment (http://ec.europa.eu/environment/enveco/air/pdf/tropozone-c.pdf) accessed 1 December 2010.

Holland, M., Berry, J. and Forster, D., 1999, ExternE: externalities of energy – volume 7: methodology 1998 update (http://www.externe.info/reportex/vol7.pdf) accessed 10 December 2010.

Holland, M., Jones, H., Berdowski, J., Bleeker, A. and Visschedijk, A, 2001, *Economic evaluation of air quality targets for PAHs*, report for the European Commission DG Environment (http://ec.europa.eu/environment/enveco/air/pdf/pah_report.pdf) accessed 1 December 2010.

Holland, M., Hunt, A., Hurley, F., Navrud, S. and Watkiss, P., 2005a, *Development of methodology for the CBA of the Clean Air For Europe (CAFE) Programme, Volume 1: overview of methodology*, report for the European Commission DG Environment (http://cafe-cba.aeat.com/files/CAFE%20CBA%20Methodology%20Final%20Volume%201%20v4e.pdf) accessed 1 December 2010.

Holland, M., Hurley, F., Hunt, A., and Watkiss, P., 2005b, *Development of methodology for the CBA of the Clean Air For Europe (CAFE) Programme, Volume 3: uncertainty in the CAFE CBA: methods and first analysis*, report for the European Commission DG Environment (http://cafe-cba.aeat.com/files/cba_method_vol3.pdf) accessed 1 December 2010.

Holland, M., Watkiss, P., Pye, S., de Oliveira, A., and van Regemorter, D., 2005c, *Cost Benefit Analysis of policy option scenarios for the Clean Air For Europe Programme*, report for the European Commission DG Environment (http://www.cafe-cba.org/assets/thematic_strategy_scenario_v4.pdf) accessed 1 December 2010.

Holland, M., Pye, S., Watkiss, P., Droste-Francke, B. and Bickel, P., 2005d, *Cost per tonne emission of PM2.5, NH3, SO2, NOx and VOCs from each EU-25 Member State (except Cyprus) and surrounding seas*, report for the European Commission DG Environment (http://cafe-cba.aeat.com/files/CAFE%20CBA%20marginal%20damage%20March%202005%20final_vsc.doc) accessed 1 December 2010.

Holland, M., Hogg, D. and Ballinger, A., 2010, *Use of damage cost data for BAT decision making*, contract report for the Environment Agency for England and Wales.

Holland et al., in preparation, *Cost Benefit Analysis for the Revision of the National Emission Ceilings Directive: Policy Options for revisions to the Gothenburg Protocol to the UNECE Convention on Long-Range Transboundary Air Pollution*, for the European Commission DG Environment.

Hurley, F., Hunt, A., Cowie, H., Holland, Miller, B., Pye, S., and Watkiss, P., 2005, *Development of methodology for the CBA of the Clean Air For Europe (CAFE) Programme, Volume 2: health impact assessment*, report for the European Commission DG Environment (http://cafe-cba.aeat.com/files/CAFE%20CBA%20Methodology%20Final%20Volume%202%20v1h.pdf) accessed 1 December 2010.

IAEA, 1982, *Generic models and parameters for assessing the environmental transfer of radionuclide from routine releases*, Safety Series No.57, International Atomic Energy Agency, Vienna, Austria.

IAEA, 1994, *Handbook of parameters values for the prediction of radionuclide transfer in temperate environments*, Technical Series 364, International Atomic Energy Agency, Vienna, Austria.

IAEA, 2001, *Generic models for use in assessing the impacts of discharges of radioactive substances to the environment*, Safety Reports Series No.19, International Atomic Energy Agency, Vienna, Austria.

ICP Mapping and Modelling, 2004, *Manual on methodologies and criteria for modelling and mapping critical loads and levels and air pollution effects, risks and trends*, International Cooperative Programme on Modelling and Mapping of Critical Loads and Levels and Air Pollution Effects, Risks and Trends, (http://www.rivm.nl/en/themasites/icpmm/manual-and-downloads/manual-english/index.html), accessed 12 October 2011.

IPCC, 2007, *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007. Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. and Meyer, L.A., (eds), Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jerrett, M., Burnett, R., Pope, A. C., Ito, K. and Thurston, G., 2009, 'Long-term ozone exposure and mortality', *N Engl J Med* 360 (11) 1 085–1 095.

Jones, M. L. M., Provins, A., Harper-Simmonds, L., Holland, M., Mills, G., Hayes, F., Emmett, B. A., Hall, J., Sheppard, L. J., Smith, R., Sutton, M., Hicks, K., Ashmore, M., Haines-Young, R., in preparation, *Using the ecosystems services approach to value air quality*, report to Department for Environment Food and Rural Affairs (Defra).

Krupnick, Ostro, B. and Bull, K., 2005, *Peer review of the methodology of cost-benefit analysis of the Clean Air For Europe Programme* (http://www.cafe-cba.org/assets/cafe_peer_review.pdf) accessed 28 December 2010.

Lavric et al., 2010, *Assessment of the possible development of an EU-wide NO_X and SO_2 trading scheme for IPPC installations*, report for the European Commission DG Environment (http://circa.europa.eu/Public/irc/env/ippc_rev/library?l=/emissions_trading/final_report_first&vm=detailed&sb=Title) accessed 22 November 2010.

Mills, G., Hayes, F., Norris, D., Hall, J., Harmens, H., Coyle, M., Simpson, D., Cambridge, H., Cinderby, S., Abbott, J., Cooke, S., Murrells, T. and Posch, M., in preparation, *Quantifying the threat from ozone pollution to food security: UK and Europe*.

Miller, B., Hurley, F. and Shafrir, A., *Health Impact Assessment for the National Emissions Ceiling Directive (NECD) – Methodological Issues*, research report TM/11/03, Institute of Occupational Medicine, Edinburgh, United Kingdom.

OECD, 2006, *Cost-Benefit Analysis and the Environment Recent Developments*, Organisation for Economic Co-operation and Development, Paris, France.

Pye, S., Holland, M. and Watkiss, P., 2007, *Analysis of the costs and benefits of proposed revisions to the National Emission Ceilings Directive*, NEC CBA Report 2, CBA of TSAP and EP target optimisation model runs, report for the European Commission DG Environment (http://www.cafe-cba.org/assets/necdcba2.pdf) accessed 22 November 2010.

Rabl, A. and Spadaro, J. V., 2006, A dose-response function for health impacts of lead, ARMINES/Ecole des Mines de Paris, 60 Boulevard St-Michel, F-75272, Paris, France.

Schindler, C., Keidel, D., Gerbase, M. W., Zemp, E., Bettschart, R., Brändli, O., Brutsche, M. H., Burdet, L., Karrer, W., Knöpfli, B., Pons, M., Schwartz, J., Rapp, R., Liu, L. J. S., Bayer-Oglesby, L., Künzli, N., Ackermann-Liebrich, U. and Rochat, T., 2009, 'Improvements in PM10-exposure and reduced rates of respiratory symptoms in a cohort of Swiss adults (SAPALDIA-study)', *Am J Respir Crit Care Med*., 179, 579-87. Epub 2009 Jan 16.

Schoof, R. A., Yost, L. J., Eickhoff, J., Crecelius, E. A., Cragin, D. W., Meacher, D. M. and Menzel, D. B., 1999, 'A market basket survey of inorganic arsenic in food', *Food and Chemical Toxicology* 37:839–846.

Smith, K. R., Jerrett, M., Anderson, H., Burnett, R., Stone, V., Derwent, R., Atkinson, R., Cohen, A., Shnokoff, S., Krewski, D., Pope III, C. A., Thun, M. and Thurston, G., 2009, 'Public health benefits of strategies to reduce greenhouse-gas emissions: Health implications of short-lived greenhouses pollutants' *The Lancet*, 374, 2 091–2 103.

Spadaro, J. V. and Rabl, A., 2004, 'Pathway analysis for population-total health impacts of toxic metal emissions', *Risk Analysis*, 25(5).

Spadaro, J. V. and Rabl, A., 2008a, 'Global health impacts and costs due to mercury emissions', *Risk Analysis*, 28(3).

Spadaro, J. V. and Rabl, A., 2008b, 'Estimating the uncertainty of damage costs of pollution: a simple transparent method and typical results', *Environmental Impact Assessment Review*, 28:166–183.

Stewart, R., Lawrence, H., Leonard, A., Holland, M., van Hyfte, A., Algoet, A. and de Smet, L., 2007, *Analysis of the simplification of the titanium dioxide directives*, report for the European Commission DG Environment (http://ec.europa.eu/environment/waste/pdf/tio2_simplification_report_iss3.pdf) accessed 22 November 2010.

Thunis, P., Cuvelier, C., Roberts, P., White, L., Post, L., Tarrason, L., Tsyro, S., Stern, R., and

Kerschbaumer, A., Rouill, L., Bessagnet, B., Bergstrom, R., Schaap, M., Boersen, G. A. C. and Builtjes, P. J. H., 2008, *Eurodelta II, evaluation of a sectoral approach to integrated assessment modelling including the Mediterranean Sea* (http://aqm.jrc.it/eurodelta/publications/EDII_finalreport.pdf) accessed 8 November 2011.

UBA, 2008, *Economic valuation of environmental damage: methodological convention for estimates of environmental externalities*, Umweltbundesamt (http://www.umweltdaten.de/publikationen/fpdf-l/3482.pdf) accessed 12 December 2010.

UNECE, 1979, *Convention on Long-range Transboundary Air Pollution* (http://unece.org/env/lrtap), accessed 11 October 2011.

UNECE, 1999, Convention on Long-range Transboundary Air Pollution — Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (http://live.unece.org/env/lrtap/multi_h1.html) accessed 27 July 2011.

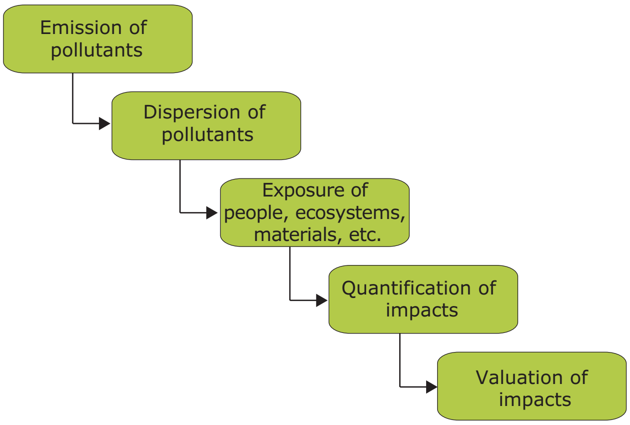
WHO, 1999, *Guidelines for air quality*, World Health Organization, Geneva, Switzerland.

WHO, 2004, *Health aspects of air pollution — Results from the WHO project 'Systematic review of health aspects of air pollution in Europe'* (http://www.euro.who.int/__data/assets/pdf_file/0003/74730/E83080.pdf) accessed 24 October 2011.

Annex 1 Determination of country-specific damage cost per tonne estimates for the major regional air pollutants

A1.1 Overview

This annex addresses the methods for quantifying damage costs for the major regional pollutants: NH_3, NO_x, PM_x, SO_2 and VOCs. Analysis follows the impact pathway methodology developed in the ExternE Project funded by European Commission's DG Research (ETSU, Metroeconomica, 1995; Holland et al., 1999; Bickel and Friedrich, 2005) with further refinement from the CAFE Programme (Holland et al., 2005a and 2005b; Hurley et al., 2005). The pathway described by the analysis is as follows:



The dispersion modelling tracks pollutants through the atmosphere and follows their chemical reactions, enabling quantification of effects linked to emissions, not simply to the atmospheric concentration of the pollutant in the chemical state in which it was released. An important consequence is that effects caused by secondary particulates are not assigned to $PM_{2.5}$ but to the primary pollutant from which they are formed (e.g. SO_2 for sulphate aerosol, NO_x for nitrate aerosol and NH_3 for ammonium aerosol). It also enables accounting for less obvious interactions between air pollutants, for example the effects of NMVOC emissions on inorganic particle concentrations, or the effects of NO_2 and NH_3 emissions on ground-level (tropospheric) ozone formation.

The price year used here is 2005, for consistency with, for example, the pollution control data used in the GAINS model of the International Institute for Applied Systems Analysis (IIASA).

A1.2 Impacts considered and omitted from the analysis

The impacts that have been quantified for this report are listed in Table A1.1. It is important not to forget those effects that remain unquantified as a result of limitations in the availability of data on response functions and / or valuation. These are listed in Table A1.2, which shows that a large number of effects have not been quantified.

To interpret the information presented in the two tables it is important to be aware that:

1. the effects that have been quantified are substantial;

2. several of the effects that have not been quantified here are likely to be negligible (e.g. direct effects of SO_2 and NO_X on crops) and would not lead to a significant increase in damage per tonne of emissions;

3. the value of certain ecosystem effects (not quantified in this report) may also be substantial.

In summary, while omitting any impact leads to a bias to underestimate damages and some of the omitted effects are undeniably important, the results generated here quantify a large fraction of total damages for most of the pollutants considered. The most serious omissions probably apply with respect to NMVOCs because of the failure to account for organic aerosols and, possibly, a failure to account for impacts associated with long-term (chronic) exposure to ozone, should they exist.

The effect of omitting impacts has to be seen in the context of the full range of uncertainties in the assessment. While it clearly biases towards underestimation, the full set of uncertainties, including also model assumptions and statistical uncertainties, may push the results either up or down. More information on these uncertainties is provided in the third volume of the CAFE CBA methodology (Holland et al., 2005c).

Table A1.1 Quantified impacts for the major regional pollutants

Burden	Effect
Human exposure to $PM_{2.5}$	Chronic effects on: Mortality Adults over 30 years Infants Morbidity Bronchitis Acute effects on: Morbidity Respiratory hospital admissions Cardiac hospital admissions Consultations with primary care physicians Restricted activity days Use of respiratory medication Symptom days
Human exposure to ozone	Acute effects on: Mortality Morbidity Respiratory hospital admissions Minor restricted activity days Use of respiratory medication Symptom days
Exposure of crops to ozone	Yield loss for: barley, cotton, fruit, grape, hops, millet, maize, oats, olive, potato, pulses, rapeseed, rice, rye, seed cotton, soybean, sugar beet, sunflower seed, tobacco, wheat
SO_2 effects on utilitarian buildings	Degradation of stone and metalwork, particularly zinc, galvanised steel

Table A1.2 Effects omitted from the analysis of major regional pollutants

Effect	Comments
Health	
Ozone chronic – mortality chronic – morbidity	No information on possible chronic effects, suspected but not proven
Direct effects of SO_2 , NO_x, NMVOCs	
Effects of NMVOCs through the formation of secondary organic particulate matter	Not currently included in the EMEP model
Social impacts	Limited data availability
Altruistic effects	Reliable valuation data unavailable
Agricultural production	
Direct effects of SO_2 and NO_x	Negligible according to past work
N deposition as crop fertiliser	Negligible according to past work
Visible damage to marketed produce	Locally important for some crops
Interactions between pollutants, with pests and pathogens, climate etc.	Exposure-response data unavailable
Acidification/liming	Negligible according to past work
Materials	
Effects on cultural assets, steel in re-inforced concrete	Lack of information on the asset stocks at risk and valuation data
PM and building soiling	
Effects of O_3 on paint, rubber	
Ecosystems	
Effects on biodiversity, forest production, etc. from excess O_3 exposure, acidification and nitrogen deposition	Valuation of ecological impacts is currently considered too uncertain
Visibility	
Change in visual range	Impact of little concern in Europe.
Drinking water supply and quality	
	Limited data availability

A1.3 Other uncertainties considered

In addition to the uncertainty arising from omitting a number of impacts from the analysis, the earlier analysis by Holland et al. (2005c) specifically addressed some other key uncertainties and sensitivities:

- valuation of mortality using the value of statistical life (VSL) and value of a life year (VOLY) approaches;
- quantifying ozone effects on health with and without a 'cut-point' (effectively, the assumption of a threshold at 35 ppb).
- separating health impacts into a 'core' set of functions that are determined to be most robust and a 'sensitivity' set of functions that are less robust.

A conclusion drawn from the earlier work was that the uncertainty in mortality valuation was dominant, and so this is the main quantified uncertainty carried into the present study.

An important issue that has not been addressed relates to uncertainty in apportioning impacts to each pollutant. This is most problematic for quantifying the impacts of fine particulate matter, which are typically described by epidemiological studies in terms of PM_{10} or $PM_{2.5}$ rather than the constituent species of particulate matter (e.g. sulphate aerosol, combustion particulate matter, natural material). The review of health aspects of air pollution in Europe performed by WHO (2004), did not attempt to differentiate between particulate matter.

A1.4 Development of source-receptor relationships

Source-receptor relationships define the link between the site of emission and the site of impact. These have been developed using data provided from the EMEP chemical transport model ([3]).

> 'Source-receptor (SR) matrices give the change in various pollution levels in each receptor country (or grid square) resulting from a change in anthropogenic emissions from each individual emitter. Such matrices are generated by reducing emissions for each emitter of one or more precursors by a given percentage (15 % in this case), running the EMEP model with these reduced emissions, and comparing the resulting output fields with the base simulation, i.e. a simulation without any emission reduction. The reason for this procedure is to keep the chemical conditions as close to the original conditions as possible.'
>
> **Source:** EMEP, 2005.

These data cover a variety of pollutants, the primary species emitted and their reaction products. For each EMEP model run the analysis adjusts by 15 % the emissions of one pollutant in one country for one baseline year. This is repeated until all combinations of pollutants, countries and baseline year have been modelled. For the purpose of the present analysis, the change in pollutant concentration or deposition is then divided by the quantity of pollutant adjusted in each model run, to derive a change per tonne of emission.

The steps undertaken for the present study were as follows:

1. Each 15 % reduction file was subtracted from the baseline to provide the difference in concentration per grid cell by substance, reduced pollutant and emitting country;
2. The concentration in each grid cell was multiplied by the population (population by grid cells taken from EMEP data) in that grid cell to generate a population-weighted average change in concentration.

([3]) http://www.emep.int/index_model.html.

3. The change in concentration in each grid cell was divided by the total 2010 (or 2020) emissions for each country to generate the change in concentration per tonne emission of each of the five emitted pollutants (SO_2, NO_x, NMVOCs, NH_3 and $PM_{2.5}$). The total 2010 and 2020 emissions where provided by EMEP.

4. Thee population-weighted values were multiplied by the health concentration-response functions and the values associated with each type of health impact according to the CAFE methodology;

5. These country-specific damage costs were then multiplied by the E-PRTR facility emissions data to provide the estimated damage costs from each E-PRTR facility.

An initial option investigated was using the latest EMEP source-receptor (SR) matrices available at the time of this study (which were based on the meteorological situation in 2006). Previous SR runs are generally based on five consecutive metrological years with the average taken for the matrices. The EMEP 2008 status report (EMEP, 2008) describes 2006 as a particularly warm year with the highest temperatures for the spring months (April, May) ever recorded. Hence the wider applicability of the source receptor data for that year is not good, due to the strong correlation between meteorological conditions and the distribution of pollutants as described in the 2005 EMEP report. Hence, this study used the earlier EMEP runs generated for the revision of the National Emission Ceilings Directive and the Gothenburg Protocol which were based on five meteorological years selected in terms of their climatological representation over the last 30 years. It should be noted that these data do not reflect recent improvements to the EMEP model. Due to the time frame of this study not all five meteorological years were analysed. The year 1998 was chosen because it is considered reasonably representative of all five years run within the EMEP model.

When generalising such results there may be problems from non-linearity of some of the atmospheric processes, most notably those dealing with ozone and hence linked to emissions of NO_X and NMVOCs. However, these are not considered too problematic here for several reasons. Most importantly, ozone effects generate only a small amount of the overall pollution damage, with effects of fine particulate matter being far more significant. Recent analysis for the Gothenburg Protocol suggests that over 95 % of health damage from regional pollutants is attributable to particulate matter. It may be argued that the role of ozone is being underestimated, perhaps through the omission of some types of effect, but ozone-related damage would need to increase very markedly for this to be a problem. An indication of the importance of these non-linearities can be gained from comparing the results in Section A1.7 for 2010 and 2020, as the difference between the years is entirely attributable to differences in the emission scenarios used.

A1.5 Quantification of health damages

The data used for quantifying health damages, based on information from the UN health statistics and data, functions and valuations presented in Volume 2 of the CAFE-CBA methodology report (Hurley et al., 2005), are given in Table A1.3 for effects of exposure to $PM_{2.5}$ and Table A1.4 for effects of exposure to ozone. The values used for VOLY and VSL are consistent with those used in the earlier CAFE programme. It should be noted that:

- chronic mortality estimates for $PM_{2.5}$ based on VSL/VOLY or median/mean estimates are not additive but are used as alternatives in sensitivity analysis;
- similarly, for the VOLY mean and median valuations listed for ozone;
- several effects listed in the CAFE-CBA methodology report volume 2 (Hurley et al., 2005) have not been included in the quantification as further validation of incidence data is required, specifically:
  - upper-bound estimates for chronic bronchitis, recommended for inclusion in the sensitivity functions for $PM_{2.5}$;
  - respiratory medication use and lower respiratory symptoms among children, recommended for inclusion in the core functions for ozone;
  - consultations for allergic rhinitis in adults and children, recommended for inclusion in the sensitivity functions for ozone;
- valuation of ozone mortality impacts using the VOLY approach assumes an average loss of life expectancy amongst those affected of one year;
- the 'pollution factors' and 'population factors' convert from units (etc.) defined in the

CAFE-CBA methodology report volume 2 (Hurley et al., 2005) to units that match the population-weighted pollution metrics that form the basis of the quantification;

- population factors are specific to 2010;
- valuation data refer to the year 2000.

Concerning the parameters in Table A1.3 and Table A1.4, note that in any column a figure of 1 is a default value, given that quantification simply multiplies all of the variables shown together:

- Population factor 1: This factor accounts for most functions applying to only part of the population. For example, the chronic mortality function (deaths) is applicable only to those aged over 30, who account for 62.8 % of the population in the modelled domain. While the table provides European average figures, the modelling undertaken to generate the results that follow used national data.
- Population factor 2: This factor accounts for some functions being expressed per thousand or per hundred thousand of population.

Incidence rate, response functions and valuation data are all given by Hurley et al. (2005).

For ozone, effects are typically quantified against the metric SOMO35 for European analysis (sum of mean ozone over 35 parts per billion).

A1.6 Quantification of ozone crop damage

The analysis of crop damage included here is based on the use of AOT40 relationships, combined with EMEP estimates of change in AOT40 on a 50 x 50 km grid. The functions and pollution data have been adjusted as follows:

- The AOT40 outputs from EMEP are for the period May–July. These have been adjusted by country-specific factors derived from earlier EMEP model runs to better represent the growing season for each country.
- The EMEP data are generated for a height of three metres. This has been adjusted to canopy height for each crop based on default relationships in the ICP Mapping and Modelling Manual (ICP Modelling and Mapping, 2004).

Functions and other data are shown in Table A1.5. Valuation data are based on world market prices reported by the United Nations Food and Agriculture Organization. The height factor accounts for variation in ozone concentration with height and is based on default estimates in ICP Mapping and Modelling Manual (2004).

Table A1.3 Incidence data, response functions and valuation data for quantification of health damages linked to PM exposure for 2010 (2005 prices)

Effect	Population factor 1	Population factor 2	Incidence rate	Response functions	Valuation (EUR)
Core functions					
Chronic mortality (deaths, VSL valuation)	0.628	1	1.61 %	0.60 %	2 080 000
Chronic mortality (life years lost, VOLY valuation)	1	1.00E-05	1	65.1	54 000
Infant mortality (1–12 months)	0.009	1	0.19 %	0.40 %	1 530 000
Chronic bronchitis, population aged over 27 years	0.7	1	0.378 %	0.70 %	208 000
Respiratory hospital admissions, all ages	1	1.00E-05	617	0.114 %	2 364
Cardiac hospital admissions, all ages	1	1.00E-05	723	0.06 %	2 364
Restricted activity days (RADs) working age population	0.672	1	19	0.475 %	97
Respiratory medication use by adults	0.817	0.001	4.50 %	90.8	1
Respiratory medication use by children	0.112	0.001	20 %	18.0	1
Lower respiratory syndromes (LRS), including cough, among adults with chronic symptoms	0.817	1	0.3	0.130	42
LRS (including cough) among children	0.112	1	1	0.185	42

Note: ERF units: impact per 10 ug.m^{-3} 8 hour daily average ozone. Response function expressed as change in incidence (rate, if as %) per µg.m^{-3} $PM_{2.5}$.

Table A1.4 Incidence data, response functions and valuation data for quantification of health damages linked to ozone exposure for 2010 (2005 prices)

Effect	Population factor 1	Population factor 2	Incidence rate	Response functions	Valuation
Core functions					
Acute mortality (life years lost, VOLY median valuation)	1	1	1.09 %	0.30 %	54 000
Acute mortality (life years lost, VOLY mean valuation)	1	1	1.09 %	0.30 %	125 000
Respiratory hospital admissions, ages over 65	1	1.00E-05	617	0.30 %	2 364
Minor restricted activity days, ages 18–64	0.64	1	7.8	1.48 %	42
Respiratory medication use by adults	0.817	0.001	4.50 %	730	1

Note: Response function units: impact per 10 ug.m^{-3} 8 hour daily average ozone.

Table A1.5 Functions and associated factors for quantification of ozone damage to crop production

Crop	Value (EUR)	Function	Height (m)	Height factor
Barley	120	0	1	0.88
Fruit	680	0.001	2	0.93
Grapes	360	0.003	1	0.88
Hops	4 100	0.009	4	0.96
Maize	100	0.004	2	0.93
Millet	90	0.004	1	0.88
Oats	110	0	1	0.88
Olives	530	0	2	0.93
Potatoes	250	0.006	1	0.88
Pulses	320	0.017	1	0.88
Rapeseed	240	0.006	1	0.88
Rice	280	0.004	1	0.88
Rye	80	0	1	0.88
Seed cotton	1 350	0.016	1	0.88
Soybeans	230	0.012	1	0.88
Sugar beets	60	0.006	0.5	0.81
Sunflower seed	240	0.012	2	0.93
Tobacco leaves	4 000	0.005	0.5	0.81
Wheat	120	0.017	1	0.88

Note: The function shows proportional change in yield per ppm.hour.

A1.7 Results

The tables below present the estimated damage of pollution, expressed as euros/tonne of emissions of NH_3, NO_x, $PM_{2.5}$, PM_{10}, SO_2 and NMVOCs, for countries throughout Europe. The baseline years for pollution climate are 2010 (used in this study) and 2020.

For information, country-specific damage costs were determined for both 2010 and 2020. This is because a further source of variation arises for the regional pollutants from modelled results for different years. The EMEP data used in this study provide information for scenarios for both 2010 and 2020. Emissions of SO_2, NO_x and NMVOCs (and to a lesser extent for PM and NH_3) are expected to decline significantly over this period as a result of European legislation that has yet to have its full effect. A good example concerns legislation on vehicle emissions, which will not be fully effective until the current vehicle fleet is fully replaced.

The change in the overall pollution load of the atmosphere will in the future affect the chemical reactions between pollutants. This, in turn, affects the formation of secondary aerosols and ozone, and hence calculated levels of damage. The effect appears particularly marked for ammonia and NMVOCs (Figure A1.1). It is possible that the true effect will not be so pronounced, particularly for NMVOCs, as it could be an artefact of model calibration at the time that model runs were performed, particularly for 2020. The results do, however, demonstrate the need to take the overall pollution climate into account and not simply assume that damage/tonne emission will be constant over time.

Figure A1.1 European average damage costs per tonne of emission in 2010 and 2020 normalised against damage in 2010 for ammonia, NO_x, PM_{10}, SO_2 and NMVOCs

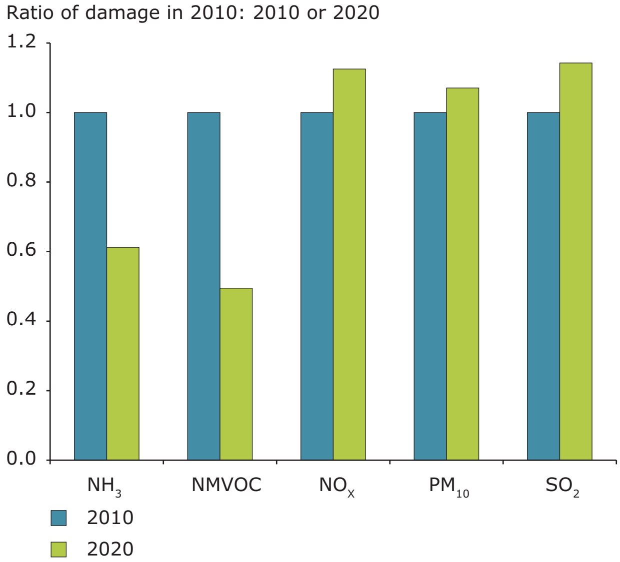


Table A1.6 Damage (EUR) per tonne emission estimates for NH_3 in 2010 and 2020 (2005 prices)

Country code	Country	NH_3 2010		NH_3 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	3 496	9 790	3 496	9 790
AT	Austria	15 269	42 746	9 064	25 376
BA	Bosnia and Herzegovina	14 989	41 964	8 543	23 918
BE	Belgium	27 218	76 193	18 596	52 059
BG	Bulgaria	6 382	17 869	4 060	11 366
BY	Belarus	9 187	25 718	5 428	15 193
CH	Switzerland	10 519	29 449	6 582	18 429
CY	Cyprus	1 335	3 742	741	2 080
CZ	Czech Republic	19 786	55 387	11 879	33 256
DE	Germany	20 541	57 504	13 082	36 625
DK	Denmark	7 793	21 819	3 937	11 023
EE	Estonia	6 791	19 014	4 366	12 222
EL	Greece	5 072	14 205	2 789	7 815
ES	Spain	5 297	14 830	1 970	5 518
FI	Finland	4 513	12 636	3 233	9 052
FR	France	10 581	29 620	6 608	18 501
HR	Croatia	17 091	47 847	10 168	28 466
HU	Hungary	16 727	46 824	10 217	28 602
IE	Ireland	2 354	6 593	1 327	3 715
IT	Italy	13 129	36 759	7 239	20 273
LT	Lithuania	5 761	16 128	2 971	8 317
LU	Luxembourg	23 247	65 078	15 330	42 916
LV	Latvia	5 721	16 017	3 346	9 367
MD	Moldova	7 041	19 711	4 777	13 374
MK	the former Yugoslav Republic of Macedonia	7 023	19 663	4 151	11 623
MT	Malta	7 857	22 013	3 056	8 576
NL	Netherlands	19 765	55 329	13 872	38 835
NO	Norway	1 905	5 345	1 045	2 936
PL	Poland	12 945	36 238	7 418	20 767
PT	Portugal	4 675	13 089	1 635	4 576
RO	Romania	7 512	21 029	4 689	13 127
SE	Sweden	6 338	17 747	3 385	9 478
SI	Slovenia	17 421	48 770	10 428	29 194
SK	Slovakia	18 368	51 419	10 761	30 124
TR	Turkey	4 583	12 835	3 319	9 296
UA	Ukraine	9 439	26 423	6 613	18 512
UK	United Kingdom	15 159	42 436	10 457	29 277

Table A1.7 Damage (EUR) per tonne emission estimates for NO_x in 2010 and 2020 (2005 prices)

Country code	Country	NO_x 2010		NO_x 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	3 546	8 945	3 416	8 437
AT	Austria	12 046	32 709	13 306	36 019
BA	Bosnia and Herzegovina	6 465	16 997	7 099	18 611
BE	Belgium	8 332	23 589	11 561	32 388
BG	Bulgaria	5 768	15 127	5 843	15 254
BY	Belarus	5 316	14 247	6 515	17 537
CH	Switzerland	18 795	51 580	18 279	49 837
CY	Cyprus	647	1 610	737	1 804
CZ	Czech Republic	8 645	23 377	10 758	29 018
DE	Germany	13 924	38 145	15 209	41 426
DK	Denmark	3 812	10 324	4 159	11 171
EE	Estonia	1 901	4 934	2 600	6 839
EL	Greece	1 648	3 793	1 783	4 053
ES	Spain	3 346	8 489	2 551	6 054
FI	Finland	1 430	3 726	2 005	5 303
FR	France	10 343	27 549	10 291	27 098
HR	Croatia	8 767	23 409	9 252	24 549
HU	Hungary	11 480	30 957	14 287	38 540
IE	Ireland	3 997	10 565	3 574	9 250
IT	Italy	8 394	22 723	8 376	22 399
LT	Lithuania	4 574	12 114	5 357	14 254
LU	Luxembourg	12 203	33 417	14 151	38 501
LV	Latvia	3 022	7 865	3 762	9 878
MD	Moldova	7 245	19 225	7 945	21 079
MK	the former Yugoslav Republic of Macedonia	3 557	9 061	3 722	9 389
MT	Malta	572	1 234	999	2 258
NL	Netherlands	7 752	22 155	9 732	27 583
NO	Norway	1 990	4 997	1 985	4 922
PL	Poland	6 618	17 890	9 450	25 607
PT	Portugal	1 352	3 419	1 247	2 989
RO	Romania	9 004	24 107	9 320	24 869
SE	Sweden	2 306	5 955	2 688	6 960
SI	Slovenia	10 028	27 030	11 105	29 765
SK	Slovakia	10 197	27 402	12 937	34 857
TR	Turkey	1 918	4 485	2 135	5 000
UA	Ukraine	5 621	14 979	6 637	17 745
UK	United Kingdom	5 181	14 520	5 999	16 663

Table A1.8 Damage (EUR) per tonne emission estimates for $PM_{2.5}$ in 2010 and 2020 (2005 prices)

Country code	Country	Primary $PM_{2.5}$ 2010		Primary $PM_{2.5}$ 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	19 809	55 447	20 892	58 479
AT	Austria	29 737	83 236	30 902	86 499
BA	Bosnia and Herzegovina	17 809	49 851	19 298	54 018
BE	Belgium	43 179	120 862	50 623	141 700
BG	Bulgaria	19 270	53 938	18 898	52 899
BY	Belarus	11 425	31 979	12 811	35 859
CH	Switzerland	37 057	103 726	39 825	111 473
CY	Cyprus	12 926	36 182	10 777	30 167
CZ	Czech Republic	20 846	58 350	22 494	62 962
DE	Germany	44 612	124 873	50 957	142 635
DK	Denmark	10 925	30 581	13 140	36 781
EE	Estonia	7 129	19 954	7 959	22 278
EL	Greece	18 214	50 982	20 551	57 524
ES	Spain	19 391	54 277	20 170	56 459
FI	Finland	7 134	19 968	6 862	19 207
FR	France	30 388	85 058	32 330	90 495
HR	Croatia	26 839	75 125	28 079	78 596
HU	Hungary	29 372	82 216	29 199	81 731
IE	Ireland	15 230	42 629	16 229	45 426
IT	Italy	35 604	99 661	34 697	97 122
LT	Lithuania	9 706	27 168	8 793	24 611
LU	Luxembourg	32 179	90 071	35 212	98 562
LV	Latvia	9 689	27 122	9 559	26 757
MD	Moldova	21 708	60 763	21 529	60 262
MK	the former Yugoslav Republic of Macedonia	11 765	32 933	13 123	36 732
MT	Malta	15 828	44 303	15 238	42 652
NL	Netherlands	39 864	111 583	45 991	128 733
NO	Norway	7 964	22 291	8 290	23 205
PL	Poland	20 446	57 230	22 268	62 332
PT	Portugal	23 972	67 102	23 574	65 986
RO	Romania	20 864	58 399	18 605	52 077
SE	Sweden	11 208	31 371	11 383	31 863
SI	Slovenia	21 852	61 166	25 250	70 678
SK	Slovakia	20 587	57 625	22 853	63 968
TR	Turkey	19 113	53 499	21 454	60 051
UA	Ukraine	20 974	58 708	22 346	62 549
UK	United Kingdom	24 632	68 948	32 764	91 710

Table A1.9 Damage (EUR) per tonne emission estimates for PM_{10} in 2010 and 2020 (2005 prices)

Country code	Country	Primary PM_{10} 2010		Primary PM_{10} 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	12 863	36 005	13 566	37 973
AT	Austria	19 310	54 050	20 066	56 168
BA	Bosnia and Herzegovina	11 565	32 371	12 531	35 076
BE	Belgium	28 038	78 482	32 872	92 013
BG	Bulgaria	12 513	35 025	12 272	34 350
BY	Belarus	7 419	20 766	8 319	23 285
CH	Switzerland	24 063	67 354	25 860	72 385
CY	Cyprus	8 394	23 495	6 998	19 589
CZ	Czech Republic	13 536	37 890	14 606	40 885
DE	Germany	28 969	81 086	33 089	92 620
DK	Denmark	7 094	19 858	8 533	23 884
EE	Estonia	4 629	12 957	5 168	14 466
EL	Greece	11 827	33 105	13 345	37 353
ES	Spain	12 591	35 245	13 098	36 662
FI	Finland	4 632	12 966	4 456	12 472
FR	France	19 732	55 233	20 994	58 763
HR	Croatia	17 428	48 783	18 233	51 037
HU	Hungary	19 073	53 387	18 960	53 072
IE	Ireland	9 889	27 681	10 538	29 498
IT	Italy	23 120	64 715	22 531	63 066
LT	Lithuania	6 303	17 642	5 709	15 981
LU	Luxembourg	20 895	58 488	22 865	64 001
LV	Latvia	6 292	17 612	6 207	17 374
MD	Moldova	14 096	39 457	13 980	39 131
MK	the former Yugoslav Republic of Macedonia	7 640	21 385	8 521	23 852
MT	Malta	10 278	28 768	9 895	27 696
NL	Netherlands	25 885	72 456	29 864	83 593
NO	Norway	5 171	14 475	5 383	15 068
PL	Poland	13 277	37 163	14 460	40 475
PT	Portugal	15 567	43 572	15 308	42 848
RO	Romania	13 548	37 922	12 081	33 816
SE	Sweden	7 278	20 371	7 392	20 690
SI	Slovenia	14 190	39 718	16 396	45 895
SK	Slovakia	13 368	37 419	14 840	41 538
TR	Turkey	12 411	34 740	13 931	38 994
UA	Ukraine	13 619	38 122	14 511	40 616
UK	United Kingdom	15 995	44 772	21 275	59 552

Table A1.10 Damage (EUR) per tonne emission estimates for SO_2 in 2010 and 2020 (2005 prices)

Country code	Country	SO_2 2010		SO_2 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	4 252	11 757	4 505	12 476
AT	Austria	9 819	26 791	11 212	30 752
BA	Bosnia and Herzegovina	5 107	14 119	5 475	15 165
BE	Belgium	11 082	30 379	14 041	38 704
BG	Bulgaria	4 183	11 405	4 396	12 008
BY	Belarus	6 031	16 673	6 838	18 953
CH	Switzerland	13 534	37 449	14 867	41 253
CY	Cyprus	1 402	3 876	1 564	4 335
CZ	Czech Republic	8 456	23 281	10 245	28 355
DE	Germany	12 306	33 973	14 666	40 639
DK	Denmark	4 703	12 923	5 601	15 473
EE	Estonia	4 235	11 775	4 680	13 045
EL	Greece	3 149	8 476	3 571	9 663
ES	Spain	5 314	14 602	5 586	15 393
FI	Finland	2 942	8 176	3 229	8 995
FR	France	9 624	26 359	11 105	30 550
HR	Croatia	7 188	19 881	7 832	21 721
HU	Hungary	8 161	22 608	9 633	26 775
IE	Ireland	5 797	16 067	6 107	16 958
IT	Italy	7 994	21 986	8 304	22 901
LT	Lithuania	4 979	13 833	5 823	16 221
LU	Luxembourg	9 962	27 405	11 783	32 543
LV	Latvia	4 445	12 359	5 040	14 049
MD	Moldova	6 217	17 182	6 541	18 103
MK	the former Yugoslav Republic of Macedonia	3 250	8 984	3 532	9 782
MT	Malta	2 846	7 873	2 846	7 873
NL	Netherlands	12 821	35 320	15 365	42 482
NO	Norway	2 390	6 654	2 661	7 427
PL	Poland	7 330	20 239	8 928	24 754
PT	Portugal	3 582	9 794	4 177	11 476
RO	Romania	6 151	16 950	6 780	18 731
SE	Sweden	3 117	8 622	3 560	9 880
SI	Slovenia	8 132	22 481	8 830	24 491
SK	Slovakia	7 961	22 048	9 207	25 585
TR	Turkey	3 064	8 465	3 398	9 405
UA	Ukraine	6 759	18 678	7 531	20 857
UK	United Kingdom	7 814	21 530	10 309	28 571

Table A1.11 Damage (EUR) per tonne emission estimates for NMVOCs in 2010 and 2020 (2005 prices)

Country code	Country	NMVOC 2010		NMVOC 2020	
		Low VOLY	High VSL	Low VOLY	High VSL
AL	Albania	132	221	14	– 84
AT	Austria	790	1,835	312	556
BA	Bosnia and Herzegovina	120	25	– 53	– 424
BE	Belgium	1 926	4,336	1 133	2 176
BG	Bulgaria	– 128	– 505	– 162	– 576
BY	Belarus	375	827	77	45
CH	Switzerland	814	1 623	371	455
CY	Cyprus	– 47	– 163	– 59	– 184
CZ	Czech Republic	485	930	143	66
DE	Germany	1 248	2 713	705	1 301
DK	Denmark	715	1 463	342	485
EE	Estonia	208	435	39	– 10
EL	Greece	60	15	14	– 89
ES	Spain	294	542	133	132
FI	Finland	246	546	77	97
FR	France	995	2 218	461	803
HR	Croatia	368	642	52	– 186
HU	Hungary	262	467	51	– 58
IE	Ireland	625	1 372	281	464
IT	Italy	625	1 279	196	160
LT	Lithuania	440	1 062	96	143
LU	Luxembourg	1 781	4 007	1 070	2 109
LV	Latvia	370	836	74	57
MD	Moldova	433	1 014	170	305
MK	the former Yugoslav Republic of Macedonia	189	372	48	5
MT	Malta	274	419	42	– 168
NL	Netherlands	1 393	2 969	897	1 597
NO	Norway	278	544	108	107
PL	Poland	565	1,271	220	363
PT	Portugal	322	662	159	241
RO	Romania	157	250	32	– 72
SE	Sweden	371	807	155	233
SI	Slovenia	503	996	63	– 165
SK	Slovakia	286	521	75	– 11
TR	Turkey	8	– 118	– 39	– 234
UA	Ukraine	525	1 227	271	545
UK	United Kingdom	979	2 089	510	840

Annex 2
Determination of country-specific damage cost per tonne estimates for heavy metals and organic micro-pollutants

A2.1 Objective

The RiskPoll model was used to predict the health impacts and damage costs due to air emissions of the heavy metals arsenic, cadmium, chromium, lead, mercury and nickel and the organic compounds 1,3 butadiene, benzene, diesel particulates, dioxins/furans, formaldehyde and polycyclic aromatic hydrocarbon.

There are alternatives to using RiskPoll, for example the approach and results of the ESPREME project ([4]). Further debate on the differences in methodology between estimates for heavy metal damages is to be welcomed as the models have not been subject to the same degree of scrutiny as the analysis of the regional pollutants. The modelling of exposure to metals is far more complex, however, requiring a focus on ingestion (in particular), as well as inhalation. Further issues arise, for example the probability of surviving cancers caused by different pollutants.

A2.2 Atmospheric dispersion

Air concentrations are calculated using the Uniform World Model (UWM) methodology, described in Spadaro and Rabl (2004). A key parameter of the analysis is the bulk or total pollutant deposition velocity, which includes air removal by dry and wet mechanisms. Continental estimates of deposition velocities for Europe are 0.34 cm/s for arsenic and lead, and 0.57 cm/s for all the other pollutants, except mercury. Country-specific deposition velocities can vary a lot about mean regional estimates. In Europe, for example, the deposition velocity for arsenic ranges from 0.26 to 0.54 cm/s, while for dioxins/furans, the range is 0.43–0.89 cm/s. In both cases, the coefficient of variation is approximately 20 %.

The deposition velocity for mercury is much smaller than for other chemical species, at around 0.023 cm/s, owing to its long atmospheric residence time (one to two years). Mercury is a global pollutant. Global and regional estimates of the impact and damage cost of mercury air emissions (due to ingestion of methyl-mercury in contaminated fish products) have been carried out by Spadaro and Rabl (2008a).

Table A2.1 Country-specific depletion velocities (cm/s) for arsenic and lead (for all other pollutants multiply by 5/3)

Austria	0.35
Balkans	0.29
Belgium	0.40
Bulgaria	0.29
Cyprus	0.26
Czech Republic	0.36
Denmark	0.52
Estonia	0.37
Finland	0.37
France	0.27
Germany	0.31
Greece	0.29
Hungary	0.34
Ireland	0.36
Italy	0.42
Latvia	0.37
Lithuania	0.37
Luxembourg	0.40
Malta	0.27
Netherlands	0.40
Norway	0.54
Poland	0.34
Portugal	0.32
Romania	0.34
Slovakia	0.35
Slovenia	0.34
Spain	0.30
Sweden	0.52
Switzerland	0.36
United Kingdom	0.36

([4]) http://espreme.ier.uni-stuttgart.de/.

A2.3 Pollutant transport and environmental fate analysis in soil and water

Environmental concentrations are calculated using the methodology developed by the USEPA for assessing multimedia transport in soil and freshwater bodies (EPA, 2005). For the seawater compartment, the pollutant mass is computed assuming a first order process. Namely, the rate of change of mass in the compartment is equal to net change in the mass inflow and outflow. The outflow mass identifies the sink (pollutant settling to the bottom of the ocean), while the inflow mass is the source (mass flow into the ocean from freshwater bodies).

Environmental fate analysis comprises various stages:

- first, pollutant emissions to air;
- second, atmospheric dispersion and removal by deposition onto land and water surfaces or by chemical transformation;
- third, environmental accumulation, transport and estimation of concentrations in soil and water compartments;
- fourth, uptake by plants and animals;
- finally, passage through the human body on the way to its ultimate environmental disposal, which may involve, for example, soil fixation (the pollutant is trapped well below the surface layer in soils, making it no longer bio-available) or settling on water bed sediment.

At present, RiskPoll does not deal with discharges to water and soil, although the same methodology developed for air emissions may be extended to analyse these cases as well.

There are several routes of potential exposure to a pollutant, including inhalation, consumption of contaminated tap water, agricultural crops and animal products, such as fish, meat, milk, fruits and vegetables, and grains and cereals. All these pathways are addressed in RiskPoll. The inhalation dose depends very much on local conditions, especially the deposition velocity and the size of the population at risk. It contributes at most a few per cent of the total intake dose but this does not imply that associated health impacts are negligible. The ingestion dose, on the other hand, is much less sensitive to local conditions because of food trade between different countries and regions. The ingestion dose is much more uniform than the inhalation dose (see Table A2.2).

Other avenues of exposure that are not addressed in RiskPoll include groundwater contamination,

Table A2.2 Ingestion dose by compound property

Compound property	As	Cd	Cr	Ni	Pb
Soil-water partition factor (m^3/kg_{Soil})	0.029	0.075	0.019	0.065	0.9
Suspended sediment-water partition factor (m^3/kg_{Sed})	25	2	50	100	200
Plant-soil bio-concentration (root uptake, kg_{Soil}/kg_{DW})					
Fruits and green vegetables	6.33E-03	1.25E-01	4.88E-03	9.31E-03	1.40E-02
Root vegetables	8.00E-03	6.40E-02	4.50E-03	8.00E-03	9.00E-03
Grains and cereals	4.00E-03	6.20E-02	4.50E-03	6.00E-03	9.00E-03
Animal feed	3.60E-02	3.64E-01	7.50E-03	3.20E-02	4.50E-02
Animal feed to cattle meat biotransfer factor (day/kg)	2.00E-03	1.20E-04	5.50E-03	6.00E-03	3.00E-04
Animal feed to cattle milk biotransfer factor (day/L)	6.00E-05	6.50E-06	1.50E-03	1.00E-03	2.50E-04
Freshwater fish bioaccumulation factor (L/kg_{Fish})	300	200	200	100	300
Seawater fish bioaccumulation factor (L/kg_{Fish})	1 000	1 000	200	1 000	200
Shellfish bioaccumulation factor (L/kg_{Fish})	2 000	20 000	800	2000	1 000

Sources (compound properties, human risk factors, and other useful information):
Human Health Risk Assessment Protocol (http://www.epa.gov/osw/hazard/tsd/td/combust/riskvol.htm#volume2).
Risk Assessment Information System (http://rais.ornl.gov/cgi-bin/tox/TOX_select?select=chem).
Integrated Risk Information System (http://cfpub.epa.gov/ncea/iris/index.cfm).
Adaptive Risk Assessment Modeling System (http://el.erdc.usace.army.mil/arams).
International Toxicity Estimates for Risk (http://www.tera.org/ITER/).
Baes et al., 1984; IAEA, 1982, 1994 and 2001.

dermal contact and soil ingestion. Of these pathways, groundwater contamination could be of concern, but the remaining two items are usually negligible. Finally, it should be noted that the ingestion dose computed in RiskPoll represents a conservative estimate because no adjustment has been made to account for losses or reductions from food preparation and implementation of remedial strategies, other than specifying an efficiency of filtration for tap water consumption.

Table A2.3 Human and cattle dietary intake rates and population densities

Food consumption rates for European population (annual intake)			
	General population	**Infants (~ 1 % of population)**	
Drinking water (tap)	600	120	L
Fruits and above ground vegetables	88	86.3	kg_{FW}
Root vegetables	76	17.3	kg_{FW}
Grains and cereals	60	34.0	kg_{FW}
Beef meat	56	12.5	kg_{FW}
Fresh milk and other dairy products	101	275	L
Freshwater fish	3.6	0.32	kg_{FW}
Saltwater fish	6.0	0.55	kg_{FW}
Shellfish	1.8	0.21	kg_{FW}

Food consumption rates for beef and dairy cattle (daily intake)			
	Beef cattle	**Dairy cattle**	
Water intake	40	75	L
Forage	8.8	13.2	kg_{DW}
Silage	2.5	4.1	kg_{DW}
Grains	0.47	3	kg_{DW}
Soil ingestion	0.5	0.4	kg_{Soil}

Note: L = liters, kg_{FW} = kg of fresh weight, kg_{DW} = kg of dry weight, kg_{Soil} = kg of soil.

Sources: DAFNEsoft package (http://www.nut.uoa.gr/dafnesoftweb/), EPA (2002 and 2005), IAEA (1994).

Population density estimates for an unknown source location in Europe

The continental population density is 80 persons/km², population averaged uniformly over land and water surface areas. This value is used for estimating the population total (collective) ingested dose, namely the total pollutant intake through diet. For the collective inhalation dose calculations, the regional population density is 112 persons/km². The exposed population is normalised by a surface area with a radius of 1 000 km, centred at the hypothetical source location. This value is a weighted average of country-specific population density estimates (see below).

Country-specific population density estimates for an unknown source location in that country

Regional population density (persons/km²) varies by country of emission

Austria	110	Germany	152	Norway	43
Balkans	73	Greece	55	Poland	97
Belgium	214	Hungary	106	Portugal	62
Bulgaria	53	Ireland	59	Romania	73
Cyprus	56	Italy	150	Slovakia	106
Czech Republic	116	Latvia	40	Slovenia	110
Denmark	83	Lithuania	52	Spain	55
Estonia	33	Luxembourg	138	Sweden	75
Finland	36	Malta	33	Switzerland	139
France	105	Netherlands	228	United Kingdom	122

A2.4 Impacts on human health

Pollutants that are carcinogenic via inhalation only include cadmium, chromium (valence state VI, which comprises roughly 20 % of chromium air emissions), nickel, 1,3 butadiene, diesel particulate matter, and formaldehyde. Inorganic arsenic, benzene, polycyclic aromatic hydrocarbon (PAH) compounds, such as benzo-a-pyrene (BaP), and dioxins/furans also act via the ingestion pathway. These pollutants are known human carcinogens. Oral exposure is particularly important for PAHs and dioxins/furans, contributing more than 98 % of the total impact on human health. Generally, oral exposure to inorganic arsenic accounts for about two thirds of the total damage cost. About 80 % of total arsenic in air is assumed to be inorganic, 50 % in tap water, 50 % in fruits and vegetables, and 25 % in grains (Schoof et al., 1999; see also Health Canada (http://www.hc-sc.gc.ca/ewh-semt/pubs/contaminants/psl1-lsp1/index-eng.php)).

Lead and mercury (acting via methyl-mercury, MeHg, chemical transformation) are neurotoxins, which contribute to IQ loss in children, among other health impacts.

Inhalation unit risk factors [URF, lifetime excess cancer risk per μg/m^3]

- 4.3E-3 for (inorganic) As, 1.8E-3 for Cd, 1.2E-2 for Cr-VI, 2.4E-4 for Ni, 3E-5 for 1,3 butadiene, 4.14E-6 for benzene, 3.37E-5 for diesel particulate matter, and 1.3E-5 for formaldehyde.

Oral slope factors [SF, lifetime excess cancer risk per μg/(kgbw-day)]

- 1.5E-3 for (inorganic) As, 7.3E-3 for BaP, and 200 for dioxins/furans.

Dose response functions [DRF, Infant IQ loss per μg/day]

- 00.0416 for Pb and 0.036 for MeHg.

  Dose response relationships vary linearly with dose and do not have a 'no-effect' threshold value (i.e. impact is always positive for any intake dose).

Dose response functions [DRF, annual impact per person per μg/m^3]

- **DRF = URF/70 or DRF = SF/70 x ICf**, assuming a lifetime exposure of 70 years. The parameter ICf is the intake to concentration factor; its value depends on the share of adult males and females and children in the exposed population (i.e. receptors), and on the mean breathing rates and body weights (kgbw) appropriate for each group of individuals. For Europe, ICf = 0.21 m3 per (kgbw-day). The population weighted mean breathing rate and mean body weight estimates are 12.6 m3/day and 64.3 kg, respectively. The mean breathing rate for an infant is 5.65 m3/day.

Sources: EPA (1994, 1997 and 2002), Rabl and Spadaro (2006), Spadaro and Rabl (2008a), WHO (1999), IRIS (Integrated Risk Information System) database (http://cfpub.epa.gov/ncea/iris/index.cfm), NEEDS (http://www.needs-project.org/) and MethodEX (http://www.methodex.org/) projects of the European Commission.

A2.5 Monetary valuation

Damage costs are calculated by multiplying the physical impacts (cancer cases or IQ points lost) by the appropriate unit cost (euros per incident). The default unit costs in RiskPoll are as follows (2005 euros): EUR 2 000 000 for a fatal cancer, EUR 500 000 for a non-fatal cancer incident and EUR 9 300 for the loss of an IQ point. The cancer unit cost includes medical expenses (cost of illness), wage and productivity losses, and the willingness to pay to avoid the pain and suffering inflicted by the disease (welfare loss). Non-fatal cancers refer to incidents where the survival probability is greater than five years from the time of diagnosis. It is assumed that between 10 % and 20 % of cancer cases are non-fatal. The share is even greater for dioxins/furans, where up to 50 % of cancer cases are non-fatal. The unit cost of non-fatal cancers does not include welfare loss. The unit cost of an IQ point includes expenses associated with remedial learning and loss in potential lifetime earnings (Spadaro and Rabl, 2008a).

Costs are discounted at 3 % but without consideration given to increases in willingness to pay with economic growth in future years.

Table A2.4 Country-specific marginal damage costs for heavy metals, EUR/$kg_{emission}$ (based on RiskPoll, Ver. 2.0)

	Arsenic		Cadmium		Chromium		Nickel	
	Marginal damage cost	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*
Austria	345	*33–528*	27.5	*5–45*	36.7	*7–60*	3.7	*0.7–6.0*
Balkans	326	*31–499*	21.7	*4–36*	28.9	*5–47*	2.9	*0.5–4.7*
Belgium	407	*39–623*	47.0	*9–77*	62.6	*11–103*	6.3	*1.1–10.3*
Bulgaria	307	*29–470*	15.7	*3–26*	21.0	*4–34*	2.1	*0.4–3.4*
Cyprus	318	*30–487*	19.1	*3–31*	25.5	*5–42*	2.5	*0.5–4.2*
Czech Republic	347	*33–531*	28.2	*5–46*	37.6	*7–62*	3.8	*0.7–6.2*
Denmark	302	*29–462*	14.0	*3–23*	18.6	*3–31*	1.9	*0.3–3.1*
Estonia	282	*27–432*	7.8	*1–13*	10.4	*2–17*	1.0	*0.2–1.7*
Finland	284	*27–435*	8.5	*2–14*	11.3	*2–19*	1.1	*0.2–1.9*
France	365	*35–558*	31.0	*6–56*	45.4	*8–74*	4.5	*0.8–7.4*
Germany	393	*38–601*	42.4	*8–70*	56.6	*10–93*	5.7	*1.0–9.3*
Greece	309	*30–473*	16.2	*3–27*	21.7	*4–36*	2.2	*0.4–3.6*
Hungary	344	*33–526*	27.1	*5–44*	36.1	*7–59*	3.6	*0.7–5.9*
Ireland	303	*29–464*	14.3	*3–24*	19.1	*3–31*	1.9	*0.3–3.1*
Italy	355	*34–543*	30.7	*6–50*	40.9	*7–67*	4.1	*0.7–6.7*
Latvia	287	*27–439*	9.4	*2–15*	12.5	*2–20*	1.2	*0.2–2.0*
Lithuania	296	*28–453*	12.1	*2–20*	16.1	*3–26*	1.6	*0.3–2.6*
Luxembourg	353	*34–543*	30.2	*6–50*	40.2	*7–66*	4.0	*0.7–6.6*
Malta	292	*28–453*	10.8	*2–18*	14.4	*3–24*	1.4	*0.3–2.4*
Netherlands	417	*40–638*	50.0	*9–82*	66.7	*12–109*	6.7	*1.2–10.9*
Norway	279	*27–428*	6.9	*1–11*	9.2	*2–15*	0.9	*0.2–1.5*
Poland	335	*32–513*	24.5	*4–40*	32.6	*6–54*	3.3	*0.6–5.4*
Portugal	310	*30–475*	16.5	*3–27*	22.1	*4–36*	2.2	*0.4–3.6*
Romania	317	*30–485*	18.6	*3–31*	24.9	*5–41*	2.5	*0.5–4.1*
Slovakia	342	*33–523*	26.5	*5–43*	35.3	*6–58*	3.5	*0.6–5.8*
Slovenia	347	*33–531*	28.2	*5–46*	37.5	*7–62*	3.8	*0.7–6.2*
Spain	308	*29–471*	15.8	*3–26*	21.1	*4–35*	2.1	*0.4–3.5*
Sweden	297	*28–455*	12.6	*2–21*	16.8	*3–27*	1.7	*0.3–2.7*
Switzerland	364	*35–557*	33.4	*6–55*	44.6	*8–73*	4.5	*0.8–7.3*
United Kingdom	352	*34–539*	29.8	*5–49*	39.7	*7–65*	4.0	*0.7–6.5*

Notes: Cost estimates (mean values) apply to air emissions, and include intake by inhalation and ingestion pathways. Generally, the ingestion dose tends to be uniform because of food transport between countries. Only carcinogenic impacts have been evaluated. The damage cost range assumes a lognormal distribution (Spadaro and Rabl, 2008b), with a geometric standard deviation of four for arsenic and three for the other heavy metals (presently, considered toxic only via the inhalation route).

Only inorganic arsenic and chromium in valence state VI are considered carcinogenic. About 80 % of total arsenic in air is assumed to be inorganic, 50 % in tap water, 50 % in fruits and vegetables, and 25 % in grains. Typically, 20 % of chromium air emissions occur as chromium VI.

Table A2.5 European marginal damage costs for heavy metal emissions to air (based on RiskPoll, Ver. 2.0)

	Intake fraction (ppm)	Health impact endpoint	Marginal damage cost (EUR/$kg_{emission}$)	*68 % confidence interval (EUR/$kg_{emission}$)*
Arsenic	890 (as arsenic) 160 (as inorganic As)	Cancer	**349**	*30–530*
Cadmium	2270	Cancer	**29**	*5.2–47*
Chromium	150	cancer	**38**	*7.0–63*
Lead	440 (entire population) 1.1 (infants only)	IQ loss	**965**	*90–1 480*
Mercury	870 (as mg Hg in methyl-Hg per kg Hg emission)	IQ loss	**910** (European estimate) **2 860** (global estimate)	*80–1 360* *240–4 290*
Nickel	550	Cancer	**3.8**	*0.7–6.3*

Notes: The intake fraction is the amount of pollutant intake by the exposed population per unit emission rate. 'ppm' stands for 'parts per million', or equivalently, pollutant intake in mg per kg emission to air. Intake from inhalation is less than 1 % of the total.

Inorganic arsenic and chromium VI (about 20 % of chromium emissions) are carcinogenic. The share of inorganic arsenic varies by food product. About 80 % of total arsenic in air and 50 % in tap water is assumed to be inorganic. For lead computations, the infant intake fraction is the appropriate dose for estimating the IQ loss.

Mercury is a global pollutant, with a one- to two-year atmospheric residence time. The cost estimate for Europe corresponds to the impact (IQ loss) suffered by European citizens only. By contrast, the global assessment value applies to the worldwide population. The intake fraction is the mass of mercury (in mg) passing through the human body in the chemical form of methyl-mercury per unit air emission of mercury in kg.

Cost estimates (mean values) include intake by inhalation and ingestion pathways, and apply to a source of unknown location and characteristics (e.g., source stack height). Uncertainty intervals are based on a geometric standard deviation of 3 for cadmium, chromium and nickel, 4 for arsenic and lead, and 4.2 for mercury (Spadaro and Rabl, 2008a and 2008b).

Table A2.6a Country-specific marginal damage costs for organics, EUR/kg$_{emission}$ (based on RiskPoll, Ver. 2.0)

	1, 3 Butadiene		Benzene		PAH (as BaP equivalent)	
	Marginal damage cost	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*
Austria	0.49	*0.09–0.81*	0.075	*0.014–0.12*	1 279	*122–1 957*
Balkans	0.38	*0.07–0.62*	0.059	*0.011–0.10*	1 273	*122–1 948*
Belgium	0.82	*0.15–1.34*	0.120	*0.022–0.20*	1 296	*124–1 982*
Bulgaria	0.27	*0.05–0.45*	0.045	*0.008–0.07*	1 268	*121–1 940*
Cyprus	0.33	*0.06–0.54*	0.053	*0.010–0.09*	1 271	*122–1 945*
Czech Republic	0.49	*0.09–0.80*	0.074	*0.014–0.12*	1 279	*122–1 957*
Denmark	0.24	*0.04–0.40*	0.040	*0.007–0.07*	1 266	*121–1 938*
Estonia	0.14	*0.02–0.22*	0.026	*0.005–0.04*	1 261	*121–1 929*
Finland	0.15	*0.03–0.24*	0.027	*0.005–0.04*	1 261	*121–1 930*
France	0.59	*0.11–0.97*	0.088	*0.016–0.15*	1 284	*123–1 965*
Germany	0.74	*0.13–1.21*	0.109	*0.020–0.18*	1 292	*124–1 976*
Greece	0.28	*0.05–0.46*	0.046	*0.008–0.08*	1 268	*121–1 941*
Hungary	0.47	*0.09–0.77*	0.072	*0.013–0.12*	1 278	*122–1 955*
Ireland	0.25	*0.05–0.41*	0.041	*0.008–0.08*	1 267	*121–1 938*
Italy	0.53	*0.10–0.87*	0.081	*0.015–0.13*	1 281	*123–1 960*
Latvia	0.16	*0.03–0.27*	0.029	*0.005–0.05*	1 262	*121–1 931*
Lithuania	0.21	*0.04–0.34*	0.036	*0.007–0.06*	1 265	*121–1 935*
Luxembourg	0.52	*0.10–0.86*	0.079	*0.014–0.13*	1 281	*122–1 960*
Malta	0.19	*0.03–0.31*	0.033	*0.006–0.05*	1 263	*121–1 933*
Netherlands	0.87	*0.16–1.43*	0.127	*0.023–0.21*	1 298	*124–1 987*
Norway	0.12	*0.02–0.20*	0.024	*0.004–0.04*	1 260	*121–1 928*
Poland	0.42	*0.08–0.70*	0.066	*0.012–0.11*	1 276	*121–1 952*
Portugal	0.29	*0.05–0.47*	0.047	*0.008–0.08*	1 269	*121–1 941*
Romania	0.32	*0.06–0.53*	0.052	*0.009–0.08*	1 270	*121–1 944*
Slovakia	0.46	*0.08–0.75*	0.070	*0.013–0.12*	1 277	*122–1 955*
Slovenia	0.49	*0.09–0.80*	0.074	*0.014–0.12*	1 279	*122–1 957*
Spain	0.27	*0.05–0.45*	0.045	*0.008–0.07*	1 268	*121–1 940*
Sweden	0.22	*0.04–0.36*	0.037	*0.007–0.06*	1 265	*121–1 936*
Switzerland	0.63	*0.11–1.03*	0.094	*0.017–0.15*	1 286	*123–1 968*
United Kingdom	0.52	*0.09–0.85*	0.078	*0.014–0.13*	1 280	*122–1 959*

Notes: Cost estimates (mean values) apply to air emissions, and include intake by inhalation and ingestion pathways. Generally, the ingestion dose tends to be uniform because of food transport between countries (for PAH, inhalation accounts for 2 % of total intake dose). Only carcinogenic impacts have been evaluated. The damage cost range assumes a lognormal distribution (Spadaro and Rabl, 2008b), with a geometric standard deviation of 3 for 1, 3 butadiene and benzene (presently, considered toxic only via the inhalation route), and 4 for the polycyclic aromatic hydrocarbons (PAH).

BaP = Benzo-a-pyrene.

Table A2.6b Country-specific marginal damage costs for organics (RiskPoll, Ver. 2.0)

	Diesel particulate matter EUR/kg$_{emission}$		Formaldehyde EUR/kg$_{emission}$		Dioxins/furans million EUR/kg$_{emission}$ (PCDD and PCDF)	
	Marginal damage cost	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*	**Marginal damage cost**	*68 % confidence interval*
Austria	0.56	*0.10–0.91*	0.21	*0.04–0.35*	27.0	*1.5–37.0*
Balkans	0.42	*0.08–0.69*	0.16	*0.03–0.27*	26.9	*1.5–36.8*
Belgium	0.92	*0.17–1.5*	0.35	*0.06–0.58*	27.3	*1.5–37.4*
Bulgaria	0.31	*0.06–0.50*	0.12	*0.02–0.19*	26.8	*1.5–36.7*
Cyprus	0.37	*0.07–0.61*	0.14	*0.03–0.24*	26.9	*1.5–36.8*
Czech Republic	0.55	*0.10–0.90*	0.21	*0.04–0.35*	27.0	*1.5–37.0*
Denmark	0.27	*0.05–0.45*	0.11	*0.02–0.17*	26.8	*1.5–36.7*
Estonia	0.15	*0.03–0.25*	0.06	*0.01–0.10*	26.7	*1.5–36.5*
Finland	0.17	*0.03–0.27*	0.06	*0.01–0.10*	26.7	*1.5–36.5*
France	0.66	*0.12–1.1*	0.26	*0.05–0.42*	27.1	*1.5–37.1*
Germany	0..83	*0.15–1.4*	0.32	*0.06–0.52*	27.2	*1.5–37.3*
Greece	0.32	*0.06–0.52*	0.12	*0.02–0.20*	26.8	*1.5–36.7*
Hungary	0.53	*0.10–0.87*	0.20	*0.04–0.33*	27.0	*1.5–37.0*
Ireland	0.28	*0.05–0.46*	0.11	*0.02–0.18*	26.8	*1.5–36.7*
Italy	0.60	*0.11–0.98*	0.23	*0.04–0.38*	27.0	*1.5–37.0*
Latvia	0.18	*0.03–0.30*	0.07	*0.01–0.12*	26.7	*1.5–36.6*
Lithuania	0.24	*0.04–0.39*	0.09	*0.02–0.15*	26.7	*1.5–36.6*
Luxembourg	0.59	*0.11–0.97*	0.23	*0.04–0.37*	27.0	*1.5–37.0*
Malta	0.21	*0.04–0.35*	0.08	*0.01–0.13*	26.7	*1.5–36.6*
Netherlands	0.98	*0.18–1.6*	0.38	*0.07–0.62*	27.4	*1.5–37.5*
Norway	0.14	*0.02–0.22*	0.05	*0.01–0.09*	26.7	*1.5–36.5*
Poland	0.48	*0.09–0.78*	0.18	*0.03–0.30*	26.9	*1.5–36.9*
Portugal	0.32	*0.06–0.53*	0.12	*0.02–0.20*	26.8	*1.5–36.7*
Romania	0.36	*0.07–0.60*	0.14	*0.03–0.23*	26.9	*1.5–36.8*
Slovakia	0.52	*0.09–0.85*	0.20	*0.04–0.33*	27.0	*1.5–36.9*
Slovenia	0.55	*0.10–0.90*	0.21	*0.04–0.35*	27.0	*1.5–37.0*
Spain	0.31	*0.06–0.51*	0.12	*0.02–0.20*	26.8	*1.5–36.7*
Sweden	0.25	*0.04–0.40*	0.09	*0.02–0.16*	26.8	*1.5–36.6*
Switzerland	0.71	*0.13–1.2*	0.27	*0.05–0.45*	27.1	*1.5–37.2*
United Kingdom	0.58	*0.11–0.95*	0.22	*0.04–0.37*	27.0	*1.5–37.0*

Notes: Cost estimates (mean values) apply to air emissions, and include intake by inhalation and ingestion pathways. Only carcinogenic impacts have been evaluated. The damage cost range assumes a lognormal distribution, with a geometric standard deviation of 3 for diesel particulates and formaldehyde (presently, considered toxic only via inhalation), and 5 for the polychlorinated dibenzo-dioxins (PCDD) and dibenzo-furans (PCDF). For dioxins/furans, the inhalation exposure accounts for less than 2 % of the total intake dose. Generally, the ingestion dose tends to be uniform because of food transport between countries. Although the marginal damage cost for dioxins/furans is very high, the air emission rate is many orders of magnitude smaller than source emissions of the classical pollutants (e.g., primary particulate matter and secondary aerosols) and the heavy metals (total cost = marginal cost * emission rate).

Table A2.7 European marginal damage costs for organic emissions to air (RiskPoll, Ver. 2.0)

	Intake fraction (ppm)	**Health impact endpoint**	**Marginal damage cost ($EUR/kg_{emission}$)**	*68 % confidence interval ($EUR/kg_{emission}$)*
1,3 butadiene	2.9	Cancer	0.50	*0.09–0.82*
Benzene	3.2	Cancer	0.076	*0.014–0.12*
PAH (BaP equivalent)	140	Cancer	1279	*120–1,960*
Diesel particulates	2.9	Cancer	0.56	*0.10–0.92*
Formaldehyde	2.9	Cancer	0.22	*0.04–0.36*
Dioxins and furans	160	Cancer	27 million EUR/kg	*1.5–37 million EUR/kg*

Notes: The intake fraction is the amount of pollutant intake by the exposed population per unit emission rate. 'ppm' stands for 'parts per million', or equivalently, pollutant intake in mg per kg emission to air. Intake from inhalation is less than 2 % of total (applies only to PAH and dioxins/furans).

Cost estimates (mean values) include intake by inhalation and ingestion pathways, and apply to a source of unknown location and characteristics (e.g., source stack height). Uncertainty ranges are based on a geometric standard deviation of 3 for 1,3 butadiene, benzene, diesel particulate matter and formaldehyde, 4 for PAH, and 5 for dioxins/furans.

Annex 3
Sectoral adjustment

The methods used in this study recognise that the dispersion of emissions from point sources partly depends on characteristics specific to the emitting sector, such as stack height and flue gas temperature. Use of national average estimates of damage per tonne will introduce some error into the analysis if it ignores this issue. This Annex describes the methods used to adjust damage estimates for the regional pollutants by sector using the results of the Eurodelta II study (Thunis et al., 2008). This first requires conversion of E-PRTR sectors to the Selected Nomenclature for sources of Air Pollution (SNAP) sectors used in Eurodelta II.

A3.1 E-PRTR to SNAP Conversion

Activities reported under the E-PRTR Regulation (EU, 2006) are grouped into nine categories:

1. energy;
2. production and processing of metals;
3. mineral industry;
4. chemical industry;
5. waste and waste water management;
6. paper and wood production and processing;
7. intensive livestock production and aquaculture;
8. animal and vegetable products from the food and beverage sector;
9. other activities.

Sector-specific correction factors developed under the Eurodelta II study (see Section 2.3) are applied to account for the differences in pollutant dispersion between specific sectors, as well as the all-sector averages computed through the available EMEP source-receptor matrices.

The emissions data analysed in the Eurodelta II study were reported in a different reporting format to the one used under E-PRTR. In order to apply correction factors the facility/operator emissions need to be converted from E-PRTR to SNAP format. E-PRTR categories, however, are more aggregated than SNAP. For example, E-PRTR code 1C 'Thermal power stations and other combustion installations' covers:

- power stations (SNAP1);
- commercial/public sector plants (SNAP2);
- industrial facilities (SNAP3).

Operators need to report their emissions under E-PRTR at facility level. While facilities can report multiple activities they must indicate their main activity. To illustrate, the reported emissions of NMVOC from Audi's facility at Ingolstadt were considered. This facility carries out three different activities (combustion, solvent use, waste disposal). The primary activity at the Audi factory was fixed as 'combustion' (E-PRTR 1.1). However, it is probable that the NMVOC emissions are actually released from solvent use (i.e. painting of cars). Hence based on the main activity, all of the NMVOC emission would be assigned to SNAP 3 (Industrial combustion) rather than to SNAP 6 (Solvent and other product use).

In total the E-PRTR database lists approximately 10 000 facilities for the reporting year 2009. It was not within the scope of this study to go through each facility and assign the SNAP code based on the different activities reported. Hence it is assumed that the majority of emissions by facility are indeed associated with its main activity.

As an example, a previous analysis undertaken using E-PRTR data for the year 2008 checked the default main activity SNAP allocation for each UK facility against the overall facility emissions (Table A3.1), to establish whether the main activity captures the majority of emission for each site. It found that 32 % of emissions allocated to SNAP 4 would be better placed under the SNAP 1 or 5 because the main activity is not the most representative activity for these facilities. For example, UK Coal PLC's main activity is 'Underground mining and related operations' which is allocated to SNAP 4. However consultation with UK experts showed that the main activity at that facility is combustion which would be allocated to SNAP 1. The opposite case may occur for other sites where emissions are allocated to SNAP 1 but the actual site activity would be allocated to SNAP 4.

It is acknowledged that the assignment of SNAP sectors by main activity introduces an additional element of uncertainty. Due to the large number of sites under E-PRTR it is not possible to conduct a review of each facility. Nevertheless, it is believed that the overall sum for each SNAP code gives a representative estimate.

A3.2 Eurodelta II correction factors

The key results from the Eurodelta II report are presented in the following three tables. They show the ratio of 'sector efficiency' to 'all sectors efficiency' with respect to exposure of the European population to fine particulate matter (health impacts of emissions of SO_2 and NO_x are estimated in terms of their contribution to sulphate and nitrate aerosols respectively) for emissions from France, Germany, Spain and the United Kingdom.

Where the ratio of sector efficiency to all sectors efficiency is less than one, control in the sector of interest is less effective in reducing population exposure per unit emission reduction than the average across all sectors. This tends to be the case for large industrial facilities, as typically tall stacks aid dispersion away from large centres of population. Where the ratio is greater than one,

Table A3.1 UK emissions in tonnes (2008) from the E-PRTR

	Emissions (tonnes)						
Pollutants/SNAP	**1**	**3**	**4**	**5**	**6**	**9**	**10**
As and compounds	0.9	0.33	0.16				
Cd and compounds	0.1	0.2	0.19				
Cr and compounds	1.9	1.8	5.0			0.39	
Hg and compounds	2.1	1.2	0.43			0.029	
NH_3	36	987	3 700		240	105	10 329
Ni and compounds	14	6.6	2.4			0.13	
NMVOC	65 998	3 959	61 592	10 251	18 900	184	
NO_x	446 214	73 766	3 148			6 633	
Pb and compounds	3.8	17	18				
PCDD+PCDF (dioxins+furans)		0.00012	0.00001				
PM10	9 508	7480	2 580	74		100	918
SO_x	370 619	90 582	16 871				
Total	**892 398**	**176 801**	**87 917**	**10 325**	**19 140**	**7 022**	**11 247**
Tonnes allocated to different SNAP	78 058	7 726	27 851	0	0	0	1 111
% of total	9 %	4 %	32 %	0 %	0 %	0 %	10 %

Table A3.2 Relative efficiency of sectoral SO_2 reductions for $PM_{2.5}$ impacts on Europe

	Sector efficiency/all sectors efficiency		
	1 Public power	**3 Industrial**	**8 Other transport**
France	0.74	1.06	
Germany	0.86	1.03	
Spain	1.01	1.03	1.06
United Kingdom	0.86	0.96	
Average	0.87	1.02	1.06
Range	± 0.14	± 0.06	

control in the sector of interest is more effective than the average, as is particularly the case for road transport ([5]).

In the case of sulphur dioxide the relative efficiency of emission reductions for the public power sector is generally below 1 (Spain providing the exception) with an average of 0.87 and a range of ± 0.14. For the industrial sector values are in all cases close to 1 with a small range of ± 0.06.

In the case of NO_x the relative efficiency of emission reductions for the public power sector is below 1 in all cases with an average of 0.78 and a range of ± 0.13. For the industrial sector the average is 0.86 with a range of ± 0.07. For the road traffic sector the value is greater than 1 in all cases, with an average of 1.12 and a range of ± 0.09. The absence of urban factors in the dispersion modelling will bias results significantly for this sector.

The level of variation for $PM_{2.5}$ impacts is greater than for SO_2 and NO_x, with average factors relative to the ALL SECTOR efficiency being around – 50 % for sectors 1 and 3 and +20 % for sectors 2, 4 and 7. For most sectors the variation around these averages is greater than 20 % at one or both ends.

Results from the preceding tables clearly show that there would be some level of error when applying an all-sector transfer factor. The most problematic of the three pollutants is primary $PM_{2.5}$ as its transfer

Table A3.3 Relative efficiency of sectoral NO_x reductions for $PM_{2.5}$ impacts on Europe

	Sector efficiency/all sectors efficiency		
	1 Public power	3 Industrial	7 Road traffic
France	0.91	0.87	1.05
Germany	0.80	0.84	1.06
Spain	0.65	0.93	1.15
United Kingdom	0.74	0.79	1.21
Average	0.78	0.86	1.12
Range	± 0.13	± 0.07	± 0.09

Table A3.4 Relative efficiency of sectoral primary PM reductions for $PM_{2.5}$ impacts on Europe

	Sector efficiency/all sectors efficiency				
	1 Public power	2 Industrial/ commercial	3 Industrial	4 Production processes	7 Road traffic
France	0.64	1.03	0.63	1.08	1.26
Germany	0.51	1.07	0.55	1.38	1.05
Spain	0.39	1.78	0.52	0.84	1.09
United Kingdom	0.47	1.04	0.58	1.31	1.51
Average	0.50	1.23	0.57	1.15	1.23
Range	± 0.14	– 0.20 to + 0.55	± 0.06	– 0.31 to + 0.23	– 0.18 to + 0.28

([5]) Results for the road transport sector are not of great relevance to this work as the sector is not included in the E-PRTR. However, they are included here to show how the reduction in transfer factors for sectors like public power relative to the all sector factors is balanced by increases elsewhere.

factors depart from the all sector averages by a much greater degree than those for SO_2 and NO_X. However, available results from past external costs analysis suggest that emissions of $PM_{2.5}$ from most modern industrial facilities are sufficiently low compared to emissions of SO_2 and NO_X that this is likely to be of rather limited importance.

To investigate this, information from 141 analyses of the external costs of power plants in Europe of different designs and using different fuels were investigated. Fifty-seven of these cases could be considered relevant here ([6]). The external costs of NO_X and SO_2 combined outweigh those of $PM_{2.5}$ by an average factor of 14 (and a median factor of six). This is despite the fact that the version of the ExternE methodology used gives higher weight to primary $PM_{2.5}$ than the CAFE benefits methodology. For only two facilities (both biomass) were the external costs of primary $PM_{2.5}$ estimated to be larger than those of SO_2 and NO_X combined.

A3.3 Limitations of Eurodelta II

In the course of the present study a number of limitations of the Eurodelta analysis have been identified including:

1. Analysis focuses on emissions from only four countries. The representativeness of these countries is questionable. This could clearly generate uncertainty if the Eurodelta II results were extrapolated more widely across Europe. While it is understood that an additional four countries are to be considered in the near future these data were not available for the present work.

2. One of the objectives of Eurodelta is to compare the results of different European-scale models. With this in mind it was necessary to define a common modelling domain between the five models used in Eurodelta. The effect of this is to limit the overall area of the domain. A number of EU Member States fall wholly or partially outside the modelled domain: Bulgaria, Cyprus, Estonia, Finland, Ireland, Malta (possibly), northern Scotland and much of Latvia, Lithuania, Romania and Sweden. Countries further east (e.g. Ukraine, Moldova and Russia) are also excluded. The results will therefore under-predict exposure to ozone and $PM_{2.5}$ ([7]).

3. No account is taken of enhanced urban exposures, though for the emission sources relevant to E-PRTR this is unlikely to be of great importance.

4. The limitation of most importance may well relate to the treatment of stack height and the effective height of release. This appears to be discussed only in Section B5 of the Eurodelta II report (p. 96/106) which references a single Croatian report. It is not clear how representative the assumptions made here are of emission sources in the various SNAP sectors in the countries considered. Hence, while the assumptions made may be useful for demonstrating that there is an issue that should be addressed in analysis to support of policymaking, it is unclear how relevant the results of that modelling are to facilities across the EU, taking into account different attitudes to stack height calculation and (e.g.) different emissions linked to the use of different fuels. This is most important for SNAP sectors 1 (public stations), 3 (industrial plants) and 9 (waste) ([8]), which are those of most relevance to the E-PRTR.

A3.4 Approach adopted for this study

There are several ways of responding to the Eurodelta II results:

1. apply existing damage-per-tonne factors without adjustment for sector;

2. adjust by sector using the average of available sector/all sector transfer factors applied to all countries;

([6]) The studies excluded from consideration here covered fuels for which emissions of $PM_{2.5}$ are very low or non-existent, such as nuclear, natural gas and most renewables (biomass excluded); small facilities that are not relevant to E-PRTR; and studies prior to 1998 (the time when chronic mortality impacts were brought fully into the ExternE Project methodology).

([7]) The results presented in the Eurodelta II report were derived using only one of the five models, understood to be the EMEP model. Results should therefore be available to extend the exposure assessment well beyond the Eurodelta II modelling domain. This would clearly require additional effort, either from the EMEP modelling team or from (e.g.) AEA who could process the EMEP-generated files. Were this to be done, the concern about limitation of the modelling domain would be very largely addressed.

([8]) SNAP sector 9 (Waste) was not considered in the Eurodelta II report.

3. adjust by sector using country-specific sector/all sector transfer factors.

Option 1 would be followed if it were considered that the identified limitations were so great that they negated the value of the Eurodelta II results. However, while recognising these problems it is logical that there will be some degree of sector-to-sector variation, and it would be better to take this into account than not to do so. At the other extreme, option 3 is only available for four countries, so could not be applied universally. An intermediate position has been taken, between options 2 and 3, applying country-specific data where they are available, and an average of country-specific factors for countries currently not covered by the analysis.

A3.5 Impacts of Eurodelta II on this study

The following conclusions were drawn from a review of Eurodelta II performed at the start of the present study:

1. Inter-sector variation for country-to-country pollutant transfer factors is significant, particularly for primary $PM_{2.5}$.

2. The method for estimating external costs should therefore be adapted to account for differences in transfer factors between sectors.

3. It is recommended that the work be started with a view to using the average sector-specific transfer factors from Eurodelta II, where country-specific factors are not yet available. There is sufficient consistency across countries for the sectors of most interest for the E-PRTR that associated errors should be manageable.

4. This position should be reviewed when further results become available that cover more countries.

5. The uncertainty associated with inter-sector differences is not great compared to some of the uncertainties that have been successfully addressed in past externalities work. It is also not great compared to the observed variation in transfer factors between the countries of Europe.

6. Ideally the sector-specific transfer factors would be calculated using the whole EMEP domain, rather than the restricted domain used in Eurodelta II.

European Environment Agency

Revealing the costs of air pollution from industrial facilities in Europe

2011 — 72 pp. — 21 x 29.7 cm

ISBN 978-92-9213-236-1
ISSN 1725-2237
doi:10.2800/84800

TH-AK-11-015-EN-N
doi:10.2800/84800

European Environment Agency
Kongens Nytorv 6
1050 Copenhagen K
Denmark

Tel.: +45 33 36 71 00
Fax: +45 33 36 71 99

Web: eea.europa.eu
Enquiries: eea.europa.eu/enquiries

ISBN 978-92-9213-236-1

Publications Office

European Environment Agency