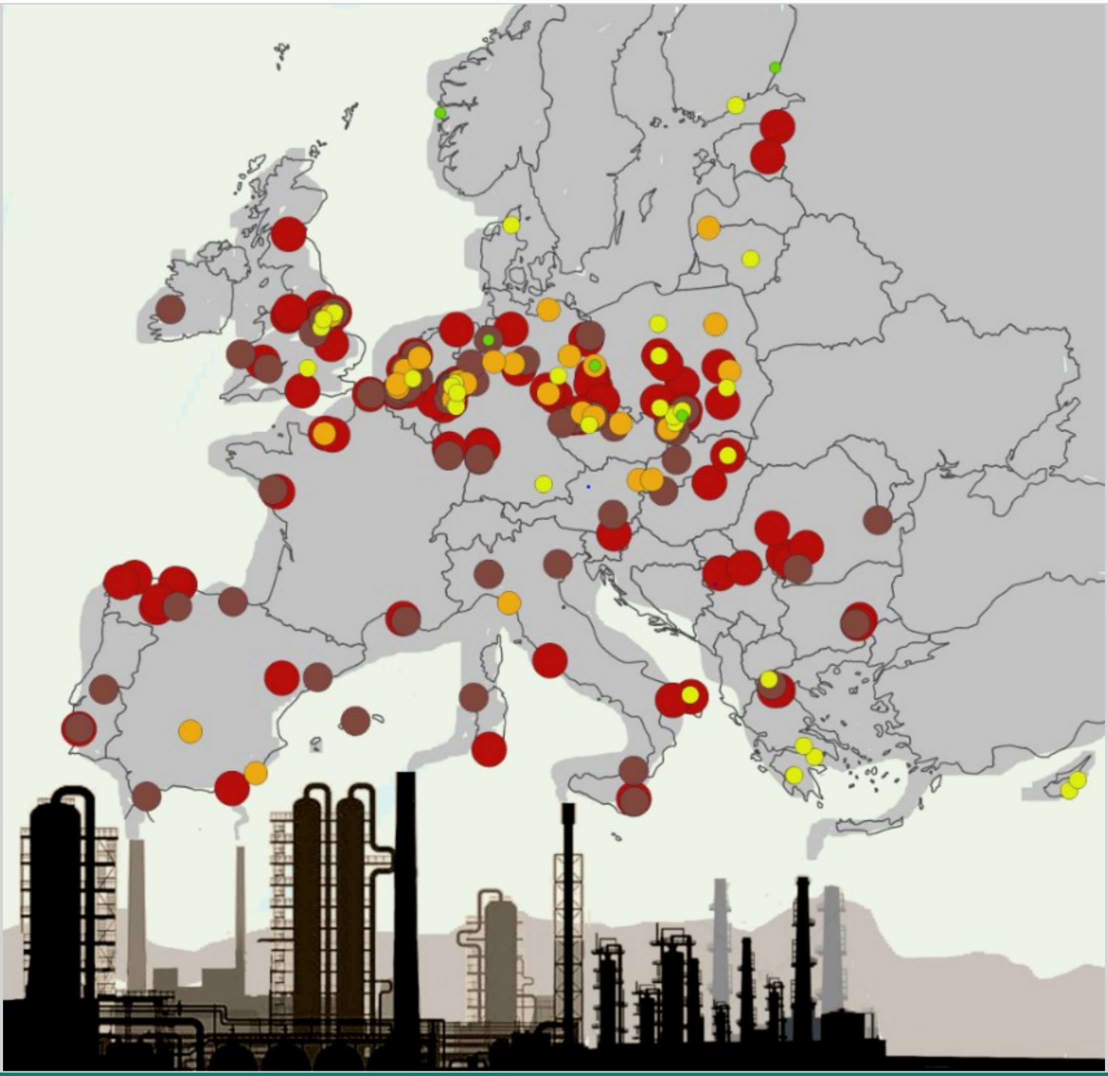
Eionet Report - ETC/ATNI 2020/4

Costs of air pollution from European industrial facilities 2008–2017

July 2021



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European Environment Agency
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The withdrawal of the United Kingdom from the European Union did not affect the production of the report. Data reported by the United Kingdom are included in all analyses and assessments contained herein, unless otherwise indicated.

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Preface

EEA aims at a provision of timely, targeted, relevant, and reliable information to policy-making agents and the public. This aim is shared by the ETC/ATNI.

In the context of the present work, timeliness is related to (sufficient) availability of all the necessary data. Some of the essential data sources provide data first several years later than the nominal year. The lag between the nominal year and the year for which data are available is explained by the fact that the necessary data first need to be collected, reported and then processed before the information is available for the assessment. Other data sources provide information with a time lag, as countries sometimes report data late, leading to incomplete data sets at European or international scale. Incomplete data reduce reliability of international assessments.

The source receptor matrices, constituting a key input to the calculation of marginal damage costs for main air pollutants, represent an example of data available with a time lag. At the time of working on the present assessment, in the first half of 2020, the latest available source-receptor matrices were those referring to the situation in 2017. Despite setting its reference year in 2017, the report is thus indeed timely, having used the latest reasonably complete data that were available.

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Executive summary

Context

In 2011 and 2014 the European Environment Agency (EEA) published two reports assessing in monetary terms the cost of damage to health and the environment caused by air pollutant emissions from industrial facilities officially reported to the European Pollutant Release and Transfer Register (E-PRTR). The first report "Revealing the costs of air pollution from industrial facilities in Europe" was published in 2011 and assessed costs in 2009 (EEA, 2011). The second report "Costs of air pollution from European industrial facilities 2008–2012, an updated assessment" was published in 2014 (EEA, 2014). This report presents an updated assessment of marginal damage costs (damage cost per tonne of pollutant emitted) and costs of air pollution from industrial facilities in Europe.

Scope

The updated assessment for marginal damage costs is carried out for the countries EEA38+UK and the reference year 2017. The updated absolute cost of damage (externalities) to health and the environment in monetary terms from air pollution released is provided for the years 2008 to 2017 and for industrial facilities in the EU-27, Iceland, Norway, Serbia, Switzerland and the UK.

The approach couples reported emission data with existing standard policy tools and methods to determine the related environmental damage costs and externalities. Scientific modelling frameworks and economic methods are applied for estimating the impacts and damage costs of emissions of regulated air pollutants([1]) (nitrogen oxide (NO_X), sulphur dioxide (SO_2), particulate matter (PM), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs)), such as those developed under the European Commission's Clean Air for Europe programme (CAFE) and partly updated under the HRAPIE (Health risks of air pollution in Europe) project (WHO, 2013). These are regularly applied in cost-benefit analyses to support national, EU and international policymaking in air pollution and climate mitigation (e.g. Amann et al. 2017 & 2020). Estimation of damage costs from emissions of heavy metals, organic pollutants and the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) was done as well using existing models and approaches in use to inform European and national policymakers about the damage costs of these pollutants.

Together, the methods are used to calculate an updated set of marginal damage costs for the following pollutants:

- 'main' air pollutants: particulate matter ($PM_{2.5}$, PM_{10}), sulphur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOCs),
- heavy metals: arsenic, cadmium, chromium VI, lead, mercury, nickel,
- organic pollutants: 1,3 butadiene, benzene, formaldehyde, benzo(a)pyrene, dioxins and furans,
- greenhouse gases: carbon dioxide, methane and nitrous oxide.

Concerning the main air pollutants, marginal damage costs have been calculated for impacts on health (from ozone, fine particulate matter and nitrogen dioxide), on crops and forests (from ozone), on building materials (from sulphur dioxide and nitrogen oxides) and on ecosystems (from eutrophication due to ammonia and nitrogen oxides). Furthermore, marginal damage costs for impacts on health have been calculated for heavy metals and organic pollutants. Impacts of greenhouse gases are accounted for using a marginal abatement cost approach.

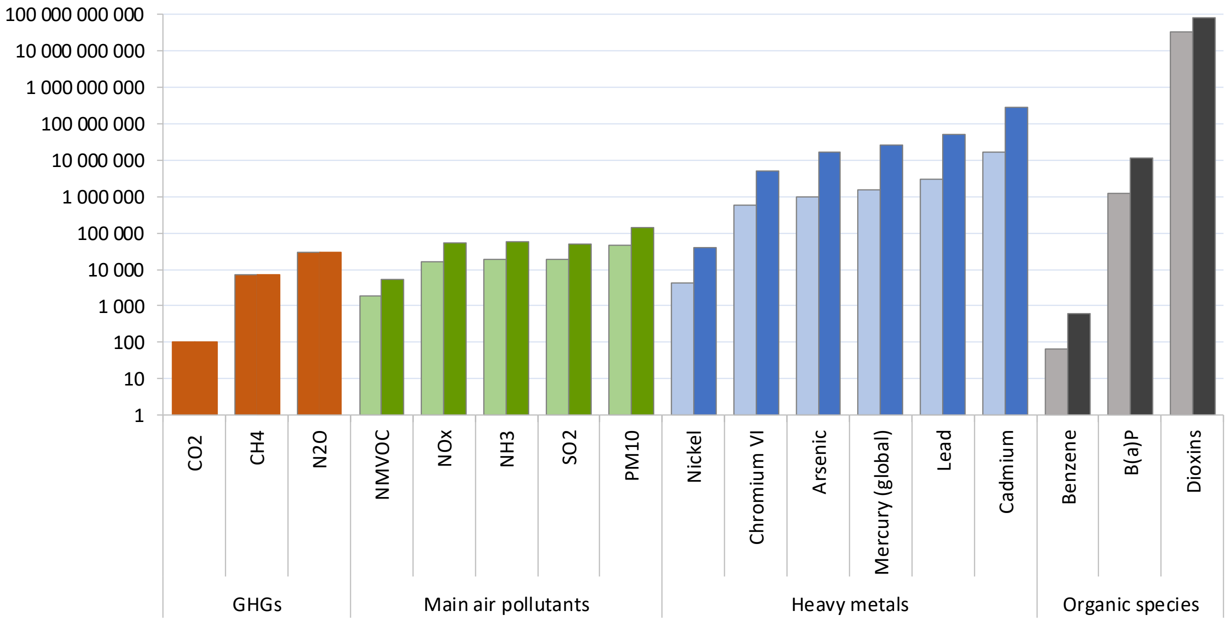
([1]) National Emissions Ceilings (NEC) Directive (2016/2284/EU, Directive on the reduction of national emissions of certain atmospheric pollutants); UNECE Gothenburg Protocol (Protocol to Abate Acidification, Eutrophication and Ground-level Ozone) of 2012, https://unece.org/environment-policyair/protocol-abate-acidification-eutrophication-and-ground-level-ozone. These pollutants are hereafter referred to as 'main' air pollutants.

The set of marginal damage costs was used to quantify the impacts and associated damage costs caused by the industrial facilities having reported their emission releases to the E-PRTR(2).

Key findings

Figure 1 shows the damage costs per unit of emission between pollutants, averaged across countries (country specific damage costs are presented in Chapter 6 of the report). These are averages across Europe, except for mercury and CO_2 for which world-wide estimates are shown. For 'main' regulatory air pollutants, heavy metals and organic pollutants, the figure presents lower and upper bounds of damage costs per tonne emitted. For the main air pollutants, damage costs are expressed as a range, corresponding to the use of two contrasting but complementary approaches for valuing health damage. The lower values relate to the approach accounting for the value of a life year (VOLY), and the higher values to the approach based on the value of statistical life (VSL). The "low" and "high" damage cost estimates for the main air pollutants, therefore, reflect the different indicator choices. For heavy metals and organic species, however, the low and high damage costs refer to confidence intervals.

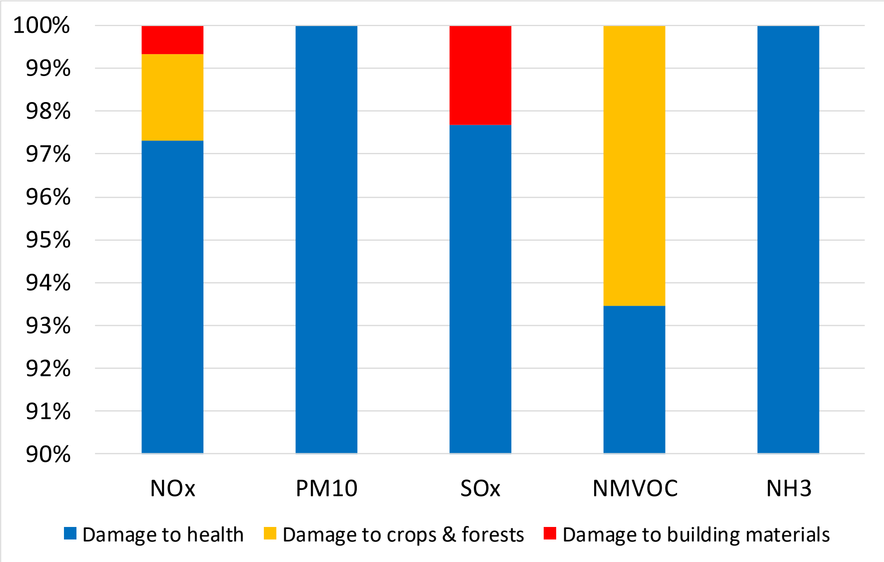
Figure 1: Estimates of average damage cost per tonne emitted all air pollutants considered in € (€$_{2019}$)



For the main air pollutants, average damage costs are clearly dominated by health impacts, that account for 94 % to 98 % of the total in the lower (VOLY) estimate, depending on the pollutant (Figure 2).

(2) This covers all impacts mentioned above (health, crops & forests, building materials), except for ecosystems damage, not yet included in the externality assessment.

Figure 2: Relative share of damage to health, crops & forests and building materials in the overall European average damage costs per tonne of pollutant from main air pollutants – VOLY estimate (note: Y-axis cut off at 90 %)



Damage costs per tonne of emission change significantly between the previous (EEA, 2014) and the current report. For the main air pollutants, the major difference comes from the source receptor matrices. Price increases by 28 % between 2005 (price base used in EEA, 2014) and 2019 (price base used in the current report) contribute also to this result. The remaining variation is due to the update of the monetary unit values for mortality. For heavy metals, major changes between the two data sets are due to additional health impacts included in the present analysis and the update of price base and monetary unit values. Analyses of trajectories of externalities from industrial facilities over time should be based on a single set of the marginal damage costs (not on combinations of different ones).

The aggregated cost of damage over the period 2008–2017 caused by emissions reported from E-PRTR industrial facilities is estimated to amount to a range from 415 to 749 billion € (€$_{2019}$) in 2008 and from 277 to 433 billion € (€$_{2019}$) in 2017 (Table 1). Estimated damage has thus decreased over the period. Damage costs from the main air pollutants are reduced by 54 % in 2017 relative to 2008. The reductions for damage from greenhouse gases, heavy metals and organic pollutants, respectively, are 19 %, 43 % and 60 %. In the same period, the number of reporting facilities has remained relatively stable (11,137 in 2008 and 11,893 in 2017). Most of the quantified damage cost is caused by emissions of greenhouse gases and the main air pollutants. Damage cost estimates associated with heavy metal emissions and organic pollutants are significantly lower, but nevertheless contribute several millions of euros harm to health and the environment.

Table 1: Aggregated damage costs for E-PRTR facilities by pollutant groups from 2008 to 2017 (million €$_{2019}$)

	Aggregated damage costs (million €$_{2019}$)									
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Main air pollutants (NH_3, NO_x, PM_{10}, SO_2, NMVOCs)	148 983-483 692	127 559-413 532	118 781-385 673	117 029-379 726	111 144-360 979	98 069-319 434	88 629-288 937	82 838-270 272	70 896-232 313	68 165-223 350
Greenhouse gases (CO_2, CH_4, N_2O)	244 550	224 766	233 786	221 439	220 081	212 972	206 588	202 595	196 725	197 269
Heavy metals (As, Cd, Cr, Hg, Ni, Pb)	20 770	13 414	16 447	13 090	13 133	12 127	12 068	10 547	11 989	11 775
Organic pollutants (benzene, dioxins and furans, PAHs)	339	163	191	191	112	133	129	144	144	137
Sum	**414 641-749 350**	**365 904-651 876**	**369 205-636 098**	**351 750-614 446**	**344 469-594 304**	**323 302-544 667**	**307 415-507 723**	**296 125-483 559**	**279 753-441 170**	**277 346-432 532**

When interpreting the results, it must be kept in mind that reporting to E-PRTR is required only by industrial facilities with an activity rate exceeding a defined threshold and emissions exceeding the pollutant-specific thresholds([3]). For this reason, the E-PRTR's coverage varies significantly across the different pollutants and sectors. Reporting also varies between countries, for example, Serbia has not reported any CO_2 emissions after 2014, and it is incomplete for individual facilities. Some of the top 30 polluters in 2017 have not reported PM_{10} or CO_2 emissions in several years. Furthermore, non-industrial sectors (transport, residential sector …) do not report to E-PRTR. Damage estimated in this report remains thus below total damage caused by total emissions from the studied countries.

In line with the results of earlier assessments, a limited number of facilities accounts for the major part of the damage. For example, in 2017, 211 facilities accounted for 50 % of estimated damage from main air pollutants and greenhouse gases, 711 for 75 % and 1,572 for 90 % (Figure 3 and Figure 4). This corresponds to 1.8 %, 6.1 % and 13.5 %, respectively, in the total number of facilities (11,655([4])) having reported emissions from main air pollutants and greenhouse gases in 2017.

([3]) Regulation (EC) No 166/2006 on the establishment of a European Pollutant Release and Transfer Register.

([4]) 11,893 facilities reported emissions from main air pollutants, organic pollutants, heavy metals and greenhouse gases in 2017.

Figure 3: Cumulative distribution of the estimated damage costs from main air pollutants and greenhouse gases for E-PRTR facilities, 2017 – mortality valued using the VOLY indicator

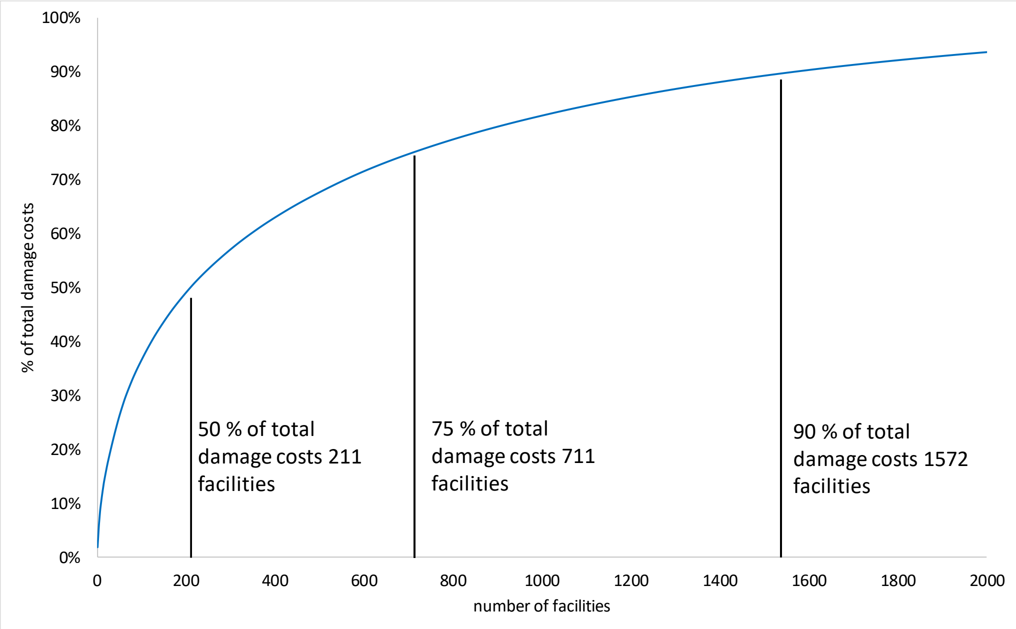
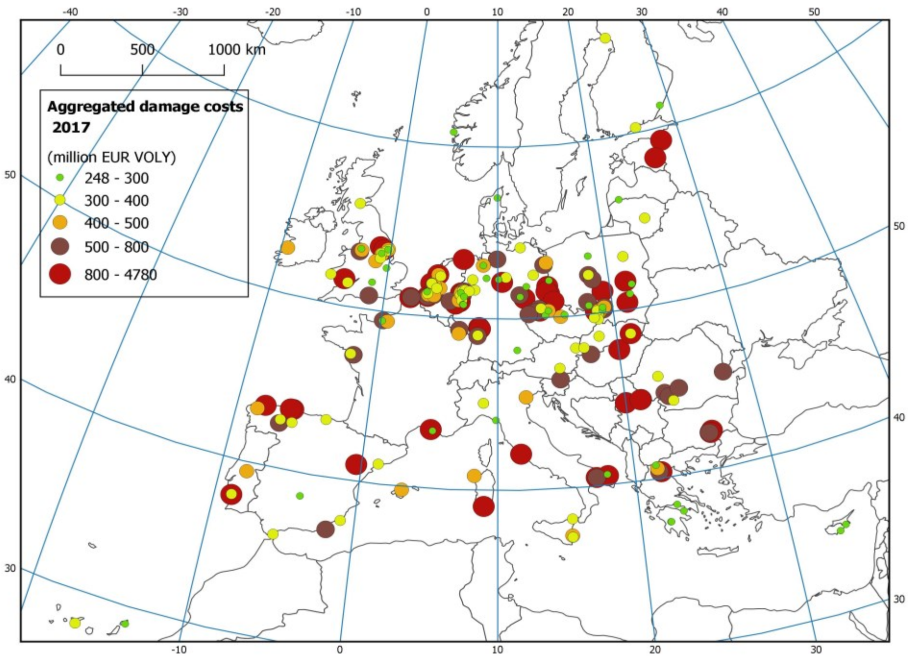


Figure 4: Localisation of the 211 installations accounting for 50 % of the aggregate damage costs for E-PRTR facilities from main air pollutants (VOLY) and greenhouse gases in 2017



Damage from heavy metals and organic pollutants is even more concentrated in a few facilities. In 2017, nine facilities accounted for 50 % of the damage from heavy metals and five facilities accounted for 50 % of the damage from organic pollutants. The facilities responsible for the highest damage from heavy metals are situated in Slovakia and Poland, followed by Estonia and Belgium, and the facilities responsible for the highest damage from organic pollutants are situated in Poland and Greece.

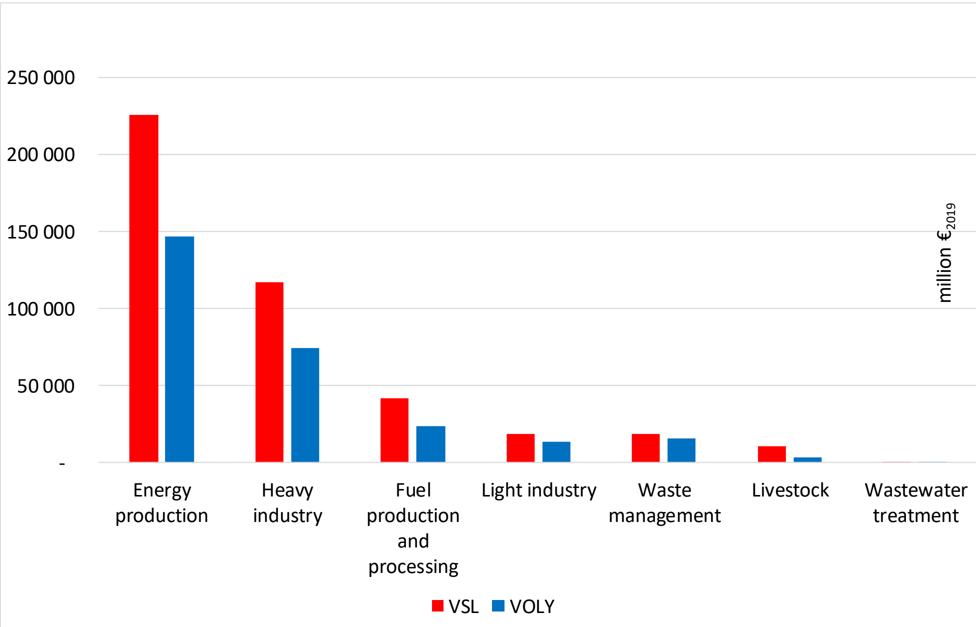
The report also presents the top 30 facilities identified as causing the highest damage from main air pollutants and greenhouse gases across the five-year period 2008–2012 covered by the previous EEA (2014) report, across the period 2013-2017 and for the latest year, 2017, individually. In 2017, 24 facilities amongst the top 30 polluters were thermal power stations, mainly using coal or lignite, and situated predominantly in Germany, Spain and the UK and Eastern Europe. Amongst the top 30 polluters were also three iron and steel plants, one facility for the processing of ferrous metals, one metal ore roasting or sintering installation and one chemical installation producing basic organic chemicals.

A ranking of facilities according to their aggregate damage cost from emissions may imply a bias against facilities just because of their size. To prevent this, damage could be weighted by plant output for facilities of the same sector, or output in economic terms (e.g. value added) for cross-sector comparisons, but this information has not been required to be reported to E-PRTR (production volumes will be required from 2022). As an alternative approach, damage has here been normalised against CO_2 emissions as a proxy of fuel consumption and the results have been compared to those assessed without normalisation by CO_2. Normalisation by CO_2 is only a second-best solution as (energy) efficiency of facilities varies. Also, the work covers many different sectors with different types of output (power, heat, glass, metals, cement, fuel processing, etc.) and direct comparison between them is questionable (the metric is best adapted to power generating facilities). Finally, not all facilities report their CO_2 emissions.

With normalisation by CO_2 emissions, none of the facilities assessed as top 30 polluters in 2017 would remain amongst the top 100 polluters and most would take positions beyond the first 500 facilities. This suggests that the emissions of the top polluters are at least to some extent explained by the size of their production.

Estimated damage aggregated over Europe and over all pollutants by EEA sub-sector is dominated by emissions from energy production and heavy industry, followed by fuel production and processing (Figure 5)([5]). This is also the case for damage from main air pollutants and greenhouse gases, whereas for heavy metals and organic pollutants damage is clearly dominated by heavy industry, followed by energy production. For organic pollutants, the sector waste management is more important than for the other pollutants.

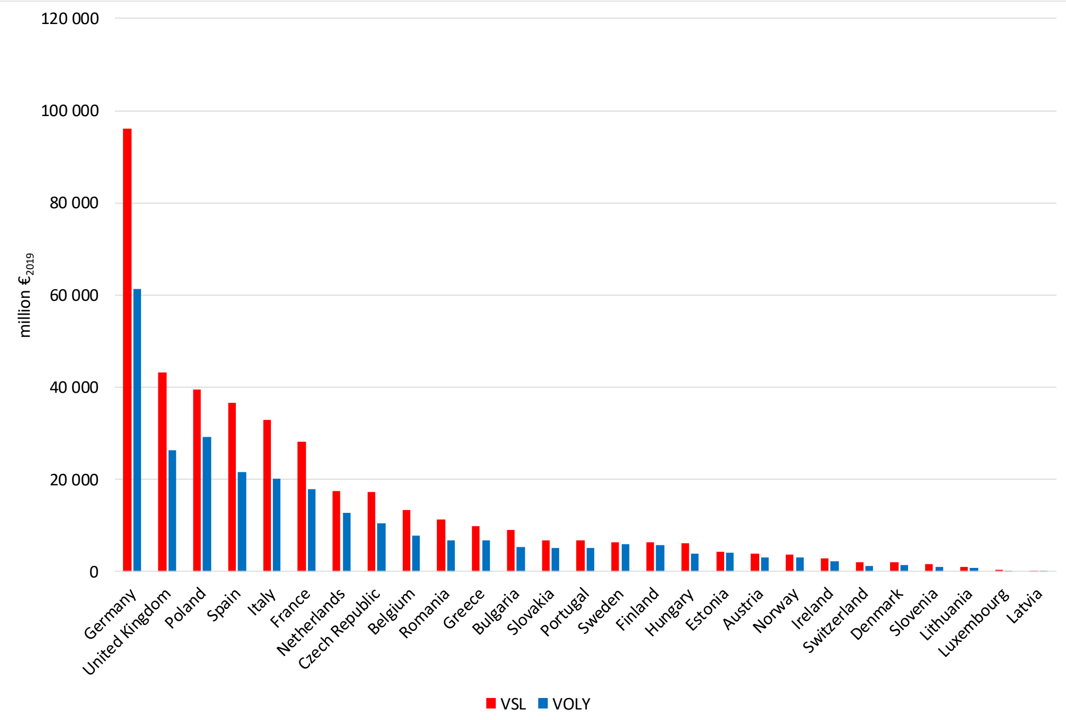
Figure 5: Damage costs by EEA sector for E-PRTR facilities in 2017 aggregated over all pollutant groups, in million €$_{2019}$



([5]) No normalisation by CO_2 emissions was applied in calculating the results presented in the following three figures.

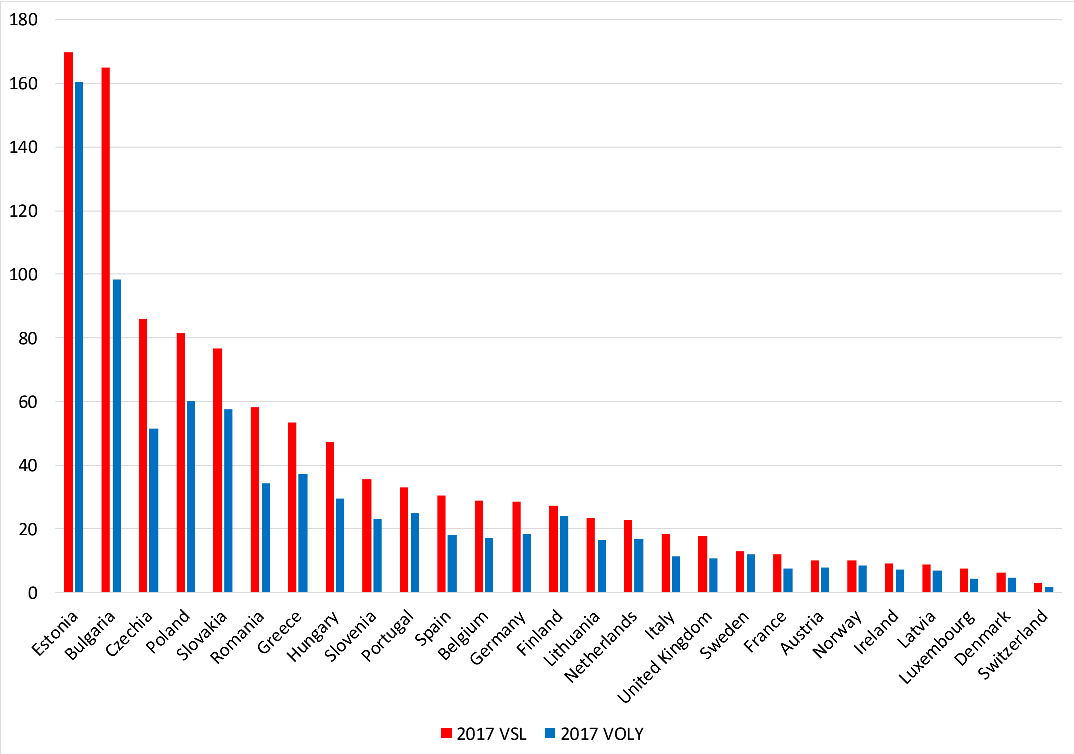
When aggregating damage over all pollutants and impacts by country, countries having a high number of facilities, such as Germany, the UK, Poland, Spain, Italy and France, contribute the most to total estimated damage costs (Figure 6).

Figure 6: Damage costs for E-PRTR facilities by country in 2017 aggregated over all pollutant groups (million €$_{2019}$)



As an alternative to weighting damage costs by CO_2 emissions, as was done for individual facilities, gross domestic product (GDP) was used as an indicator of national production to normalise the national damage costs against the respective level of services generated by the national economies. When applying this measure, some of the countries showing the highest damage costs in the Figure 6 (Germany, the United Kingdom, Spain, Italy or France), drop down the ranking and Estonia, Bulgaria and Czechia rise to the top (Figure 7). Poland remains toward the top of the ranking, indicating high amounts of pollutants relative to GDP emitted at Polish facilities.

Figure 7: Damage costs for E-PRTR facilities by country in 2017 aggregated over all pollutant groups normalised against GDP, 2017



The assessment also showed that results are sensitive to the indicator used for valuing mortality. Not only are absolute damage costs higher when using the VSL estimate, also the ranking of facilities is to a limited extent affected by this choice of indicator.

Main changes compared to the previous assessment

Compared to the earlier assessments the current report uses updated data and knowledge. It also introduces new impact categories and additional results.

Updates of data and knowledge in the current report:

- Dispersion and exposure modelling for the main air pollutants relies on the latest EMEP source receptor matrices (SRMs) that have been updated since the last report. These country-to-grid SRMs link emission reductions for each pollutant in each country to changes in concentrations and depositions of pollutants across Europe at grid level with a horizontal resolution of 0.2°×0.3°. They are based on data (emissions, meteorology) for the year 2017.
- For toxic metals and organic pollutants, exposure modelling has also been updated. It relies on the uniform world model and is based on the calculation of European population pollutant-specific intake fractions (through inhalation and ingestion).
- As far as health effects from the main air pollutants are concerned, in the core analysis we continue using the exposure-response functions from HRAPIE (WHO, 2013) that were also applied to the calculation of damage costs in EEA (2014). However, in a sensitivity analysis we test for the impact of revised exposure-response functions for chronic mortality from $PM_{2.5}$ and for additional impacts not included in earlier analyses from stroke and non-fatal myocardial infarction from $PM_{2.5}$.

- Monetary unit values for mortality valuation are updated relative to the previous report. The assessment here uses the VSL from OECD (2012) and a VOLY consistent with this VSL, that are also applied in recent assessments for DG ENV (e.g. Second Clean Air Outlook, Amann et al., 2020).
- Impacts of ozone on crops are assessed for a higher number of crops (121 compared to 20 in the older report).
- Unit costs for valuing CO_2 (or CO_2 eq) impacts are updated and use the values from the DG Move Transport Cost Handbook (EC, 2019).
- The previous assessment calculated damage costs for the year 2010. Given that the most recent SRMs from EMEP relate to 2017 emissions and concentration levels and to meteorological conditions of the same year, and in order to produce a data set as coherent as possible, wherever feasible impacts contributing to the damage costs were calculated for 2017. This means that data on receptors (population, crops, forests…) relate also to 2017, unless specifically stated otherwise.
- In the previous assessments, marginal damage costs and external costs of facilities were expressed in Euro price base of 2005. In the current assessment all monetary values are expressed in € price base 2019.

Impact categories calculated for the first time and additional pollutants covered:

- For the first time, health impacts (mortality and morbidity) of nitrogen dioxide are included in the damage costs. NO_2 requiring a higher resolution of exposure modelling than what is available via EMEP SRMs, the surrogate model SHERPA([6]) is used to derive Source-Receptor Relationships (SRRs) for NO_2. Exposure response functions used are those recommended by HRAPIE (WHO, 2013) except for chronic mortality for which a response function based on Huangfu and Atkinson (2020), COMEAP (2018) and Ricardo (2020) is used.
- Further health impacts are also included for toxic metals. This refers above all to mortality impacts from arsenic, cadmium, lead and mercury, but also to additional morbidity indicators (chronic bronchitis, IQ loss and diabetes for arsenic, osteoporosis for cadmium, anaemia for mercury).
- Impacts of ozone on forests are calculated for the first time in the present report. As is the case for the crop assessment, they rely on the AOT40 indicator. EMEP SRMs for the newer, scientifically recommended indicator PODy are not yet available.
- Marginal damage costs for ecosystems impacts are calculated for the first time in the current assessment (although not yet included in the externalities assessment). Impacts accounted for are exceedances of critical loads for eutrophication in Natura 2000 areas from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen). Valuation is based on Christie et al. (2012).([7])
- The scope of the calculation of externalities is extended to include two additional greenhouse gases: methane and nitrous oxide. The previous reports calculated externalities only for CO_2 emissions.

([6]) https://aqm.jrc.ec.europa.eu/sherpa.aspx
([7]) The reasons why the calculation of ecosystems effects is limited to Natura 2000 sites are the following. Monetisation of ecosystems damage here relies on a willingness to pay estimate, from a study assessing response to the UK's biodiversity action plan (Christie et al., 2012). There is a question of whether willingness to pay will be similar when sites are not restored (Holland et al., 2015a, b), and Member States are legally responsible for preserving Natura 2000 sites. The assessment here is limited to eutrophication because exceedances of critical loads for acidification are currently much less important than for eutrophication. The rationale is that including impacts from acidification would not have an important impact on overall results.

Additional analyses and results:

- In previous assessments marginal damage costs covered the impact of one tonne of emission of a given pollutant from a country wherever the impacts occur across Europe. In the current assessment, damage costs for the main air pollutants are additionally calculated for the damage occurring only in the emitter country and presented for information only. Damage cost occurring in the emitter country is a subset of the damage cost occurring in EEA38+UK. The two sets represent alternative indicators and must not be added together. The preferred indicator set is the one presenting damage costs covering impacts wherever they occur across Europe.
- Emission dispersion varies between different emission sources, particularly with respect to emission height. Also, some sources tend to be more closely situated to population than others. In order to account for such differences, for the first time, a set of sectoral adjustment factors is calculated for exposure to $PM_{2.5}$ and NO_2 for each country based on the SHERPA model and used to adapt the average marginal damage costs for the main air pollutants to the different sectors. In the previous EEA report, sectoral adjustment factors developed in the EURODELTA II project in 2008 and available only for 4 countries were applied to all countries.

In updating the marginal damage costs an attempt has been made to ensure consistency in methods and parameters chosen between this study and other ongoing and recent studies. Full consistency with the recent DG ENV Clean Air Outlook (Amann et al., 2020) has been reached in the use of exposure-response functions and monetisation of health impacts from the main air pollutants. Using the VSL for valuing mortality from OECD (2012) our approach is also consistent with the DG MOVE Transport cost handbook (EC, 2019).

Recommendations

Some recommendations are unchanged from earlier reports.

As a first issue, completeness of emissions from individual facilities might still be improved. Several instances were identified during this assessment that demonstrate that certain facilities are not reporting emissions of certain pollutants which are expected to occur above the release thresholds set in the E-PRTR Regulation. Member States should further improve the quality checking of facility information before it is reported to the E-PRTR, particularly to address completeness of data and identify outlying values.

The analysis would profit from the availability of production data and data on economic output that complements emission reporting. This would allow assessing the efficiency of the facilities' production. Without this, it is difficult to know whether a given facility causes high damage costs because of their size and level of activity, or because of inefficient processes or abatement equipment. It is noted that much of this production and economic data is publicly available through company reporting, though separate collation of it would be extremely time consuming. This is issue is expected to be resolved from 2022, once reporting production volumes becomes compulsory. As a second-best approach, we have normalised externalities by CO_2 emissions. This approach assumes that CO_2 emissions are related to the size of facilities and their level of production. Of course, as stated above, this is an imperfect proxy.

Some further recommendations result from the present update of the assessment.

The results of the current report highlight the importance of not limiting damage cost assessments to the "internal" damage of a country (damage perceived only in the emitter country), but to account for transboundary impacts. The ranking of countries by damage from air emissions also underlined the importance of the work extending beyond the European Union and the EEA countries to include cooperating countries such as Serbia.

During this study it has become apparent that a systematic approach is needed to understand the temporal dependence of the source receptor matrices. The current study uses EMEP SRMs as of 2017. An important impact of changes in SRMs between 2010 (EEA, 2014) and 2017 on marginal damage costs was identified in the report. New country-to-country SRMs (for 2018) have just been published. They appear to vary significantly from the 2017 edition. It is obvious that SRMs change over time, due to changes in meteorological conditions between years, emission source characteristics that can vary with time, evolutions in the EMEP modelling methodology and variation in the relative levels of pollutants in the atmosphere that will influence pollutant chemistry... Therefore, it would be helpful to explore the time trend of the SRMs and understand the reasons behind any observed variance, and then to seek to identify some appropriate solutions for their use in deriving marginal damage costs.

In a future update, priorities for refining the methods are (i) updating of the health response functions to account for new information on response-coefficients and the range of effects to be included in the analysis, and (ii) valuation of new health endpoints.

Also, the scientifically recommended indicator to assess impacts on crops and forests from ozone, the stomatal ozone flux, should be used. For the future we, therefore, recommend the creation and publication of POD SRMs.

For the calculation of sectoral adjustment factors, it has been necessary to map the E-PRTR nomenclature to the SNAP nomenclature used in the SHERPA model. This mapping has remained incomplete and required the calculation of adjustment factors for several aggregations of different SNAP sectors. For a more accurate use of sectoral adjustment factors it would be useful to improve the mapping from the E-PRTR sector nomenclature to SNAP.

A specific effort was conducted here to increase the spatial resolution of exposure modelling, especially for NO_2. We reach out to a granularity of about 7km. Further efforts to increase the spatial refinement should be sought.

The possibility of extending the assessment of ecosystems impacts beyond the Natura 2000 sites should be considered.

Finally, while marginal damage costs related to impacts from ozone, fine particulate matter, heavy metals and organic pollutants are calculated using 2017 population data and emissions, this has not been possible for impacts related to NO_2. For this pollutant, the SHERPA model had to be used which relies on emissions for 2010. Consistency in all input data would, of course, be preferable.

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Other EEA contributors were Ian Marnane for the preparatory work in 2019, and Daniel Montalvo for discussions.

This report was prepared by the European Environment Agency's (EEA) European Topic Centre on Air Pollution noise, transport and industrial pollution (ETC/ATNI). The study was coordinated by Simone Schucht (INERIS). INERIS was also in charge of the analysis of source receptor matrices, quantification of exposure to, and impacts from, main air pollutants, estimation of sectoral adjustment factors, and calculation of externalities (Elsa Real, Laurent Létinois, Simone Schucht, Augustin Colette). Further lead authors of the report are Mike Holland (EMRC) and Joseph V. Spadaro (SERC) who have been involved in the previous EEA reports on Costs of air pollution from European industrial facilities. We are grateful for them bringing in their expertise on marginal damage cost calculation, impact assessment and the tools they developed for the calculation of impacts from main air pollutants, toxic metals and organic pollutants (the models Alpha-RiskPoll and RiskPoll). Calculation of externalities from industrial facilities relies on data reported by European facilities to E-PRTR. These data were prepared and provided within the ETC/ATNI team by Laurence Opie, Rosie Brook, Lucy Garland and Mark Gibbs (Aether).

The ETC/ATNI work used source receptor matrices developed by EMEP (Anna Maria Katarina Benedictow, Hilde Fagerli) at the Meteorological Synthesizing Centre – *West* (MSC-W). Key inputs also came from Thomas Scheuschner and Christin Loran from the CCE (Coordination Centre for Effects, hosted by the Umweltbundesamt, Germany), who performed the calculations for exceedances of critical loads for eutrophication.

The analysis in the current report follows closely that carried out in EEA (2014).

Several EEA managers have been involved this study, Ian Marnane in the preparatory work in 2019, Bastian Zeiger for the first half of 2020 and finally Juan Calero. Their comments and views have been valuable in preparing this report.

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Acronyms

AOT40	Accumulated Ozone exposure over a Threshold of 40 ppb
As	Arsenic
BaP	Benzo[a]pyrene
Cd	Cadmium
CH_4	Methane
CO_2	Carbon dioxide
Cr	Chromium
CrVI	Hexavalent chromium
CTM	Chemistry transport model
EC	European Commission
EEA	European Environment Agency
ETC/ATNI	European Topic Centre on Air Pollution noise, transport and industrial pollution
E-PRTR	European Pollutant Release and Transfer Register
ERF	Exposure-Response Function
GDP	Gross Domestic Product
GTP	Global Temperature Potential
GVA	Gross Value Added
GWP	Global Warming Potential
Hg	Mercury
IPA	Impact pathway approach
MDC	Marginal damage cost, the damage cost per tonne of pollutant
NH_3	Ammonia
N_2O	Nitrous oxide
Ni	Nickel
NMVOC	Non-methane volatile organic compounds
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Unspecified mixture of nitrogen oxides
Pb	Lead
PAH	Polycyclic aromatic hydrocarbons
PCDD/PCDF	Dioxins and furans (polychlorinated dibenzo-p-dioxins, PCDD, and polychlorinated dibenzofurans, PCDF)
PM	Particulate matter
$PM_{2.5}$	Atmospheric particulate matter (PM) of aerodynamic diameter less than 2.5 micrometres
PM_{10}	Atmospheric particulate matter (PM) of aerodynamic diameter less than 10 micrometres
PODy	Phytotoxic ozone dose above a threshold y (stomatal ozone flux indicator)
PPM	Primary particulate matter (PM_{10})
RYL	Relative Yield Loss
SF	Slope Factor
SO_2	Sulphur dioxide
SRM	Source Receptor Matrix
SRR	Source Receptor relationship
TEF	Toxic equivalency factors
TEQ	Toxic equivalent quantity
UNECE	United Nations Economic Commission for Europe
URF	Inhalation unit risk factor
VCM	Value of Cancer Morbidity
VC_{NF}	Value of Non-Fatal Cancer

VOLY	Value Of Life Year
VSL	Value of Statistical Life
YOLL	Years Of Life Lost

1 Introduction

1.1 Context

The European Environment Agency (EEA) has published two reports assessing the cost of damage to health and the environment in monetary terms caused by air pollutant emissions from industrial facilities officially reported to the European Pollutant Release and Transfer Register (E-PRTR). The first report "Revealing the costs of air pollution from industrial facilities in Europe" was published in 2011 and assessed costs in 2009 (EEA, 2011). The second report "Costs of air pollution from European industrial facilities 2008–2012, an updated assessment" was published in 2014 (EEA, 2014). These reports were carried out based on best practice at the time, with the 2014 report presenting an updated assessment of the 2011 report.

Calculating the impacts of pollutants on human health and the environment requires application of a modelling framework that links knowledge of pollutant emissions with their impacts and consequent damage costs and which follows the impact pathway approach (IPA, ExternE 1995 & 2005). The EEA reports coupled reported emission data with existing standard policy tools and methods to determine the related environmental externalities. Scientific modelling frameworks and economic methods applied for estimating the impacts and damage costs of the 'traditional' main air pollutants (nitrogen oxide (NO_X), sulphur dioxide (SO_2), particulate matter (PM), ammonia (NH_3) and non-methane volatile organic compounds (NMVOCs)) have been developed through research funded by the European Commission and Member States since the early 1990s (e.g. Holland et al., 2005a and 2005b; Hurley et al., 2005). They have been subject to international peer review (e.g. Krupnick et al., 2005). Methods such as those developed under the European Commission's Clean Air for Europe programme (CAFE) and partly updated under the HRAPIE (Health risks of air pollution in Europe) project (WHO, 2013) are regularly applied in cost-benefit analyses to support national, EU and international policymaking in air pollution and climate mitigation (e.g. Amann et al. 2017 & 2020). Estimation of damage costs from emissions of heavy metals, organic pollutants and the greenhouse gas carbon dioxide (CO_2) was done again using existing models and approaches in use to inform European and national policymakers about the damage costs of these pollutants.

This report updates the earlier assessments of the costs of air pollution from European industrial facilities, following a review in 2019 (Schucht et al., 2019b) of the methods used in the previous reports.

As was the case in the previous reports, only ambient air pollution is considered. Indoor air pollution (the impact of industrial emissions within the facilities) and its impact on workers is therefore not part of the assessment.

1.2 Objectives

The major objectives of this work are (i) to update the calculation of damage costs per tonne of pollutant emission (also referred to as marginal damage cost, MDC) based on the above mentioned methods quantifying and monetising health and environmental impacts from pollutant emissions, and (ii) to apply this updated set of marginal damage costs to emission data reported to the E-PRTR for the years 2008 to 2017 in order to calculate the externalities caused by European industrial facilities.

1.3 Scope of this report

In the present report marginal damage costs are developed for the following pollutant groups

- 'main' air pollutants: particulate matter ($PM_{2.5}$([8]), PM_{10}), sulphur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOCs),
- heavy metals: arsenic, cadmium, chromium VI, lead, mercury, nickel,
- organic pollutants: 1,3 Butadiene, benzene, formaldehyde, Polycyclic Aromatic Hydrocarbons, dioxins and furans,

([8]) Note that in EMEP SRMs the precursor PM is PM_{10}. Marginal damage costs are therefore calculated for PM_{10} as a precursor of $PM_{2.5}$. PM emissions reported to E-PRTR are also PM_{10}. To convert PM_{10} to $PM_{2.5}$ the factor 1.54 is used (cf. section 6.1).

- greenhouse gases: carbon dioxide, methane and nitrous oxide.

The damage costs calculated cover health impacts from main air pollutants, heavy metals and organic pollutants, impacts on crops and forests from ozone, impacts on ecosystems through eutrophication, impacts on materials from SO_2 and NO_X and damage from greenhouse gases through the use of the surrogate approach "marginal abatement costs"([9]). The impacts covered are listed in more detail in Table 2 and Table 3. Impacts included for the first time in the current report are marked in bold.

Table 2: Health impacts quantified in the present report

QUANTIFIED HEALTH IMPACTS				
Human exposure to $PM_{2.5}$	Chronic effects	Mortality	Adults 30 years and older	Core analysis
			Infants 1-12 months	
		Bronchitis	Adults	
			Children	
Human exposure to $PM_{2.5}$	Acute effects	Respiratory hospital admissions		Core analysis
		Cardiac hospital admissions		
		Restricted activity days		
		Asthma symptom days	Children	
		Lost working days		
		Stroke		Sensitivity analysis only
		Non-fatal myocardial infarction		Sensitivity analysis only
Human exposure to O_3	Acute effects	Mortality		Core analysis
		Respiratory hospital admissions		
		Cardiac hospital admissions		
		Minor restricted activity days		
Human exposure to NO_2	Chronic effects	**Mortality**	Adults 30 years and older	Core analysis
		Bronchitis	Children	
Human exposure to NO_2	Acute effects	**Respiratory hospital admissions**		Core analysis
Human exposure to arsenic	Human exposure route: Inhalation and Ingestion	**All-cause mortality**		Core analysis
		Non cancer mortality		
		Cancer mortality		
		Non-fatal cancers		
		Chronic bronchitis		
		IQ loss		
		Diabetes		

([9]) Marginal abatement costs represent the minimum costs necessary to reach a given objective, more precisely, the cost to achieve the last unit of emission reduction necessary. Not directly assessing damage, they are not included in the following tables.

		QUANTIFIED HEALTH IMPACTS	
Human exposure to cadmium	Human exposure route: Inhalation and Ingestion	**All-cause mortality**	Core analysis
		Non-fatal cancers	
		Osteoporosis (hip fractures)	
Human exposure to chromium (hexavalent)	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to lead	Human exposure route: Inhalation and Ingestion	**All-cause mortality**	Core analysis
		IQ loss	
Human exposure to mercury	Human exposure route: Inhalation and Ingestion	**Cardiovascular mortality**	Core analysis
		IQ loss	
		Anaemia	
Human exposure to nickel	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to 1,3 Butadiene	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to benzene	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to dioxins and furans	Human exposure route: Inhalation and Ingestion	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to formaldehyde	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	
Human exposure to PAH (as BaP equiv.)	Human exposure route: Inhalation only	Cancer mortality	Core analysis
		Non-fatal cancers	

Table 3: Non-health impacts quantified in the present report

QUANTIFIED NON HEALTH IMPACTS		
Exposure of crops to O_3	Yield loss for **121 crops** (details in Annex 2)	Core analysis
Exposure of forests to O_3	**Loss in total biomass production for coniferous and deciduous trees**	Core analysis
Exposure of ecosystems to eutrophication from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen)	**Ecosystems damage in Natura 2000 areas (*)**	Core analysis
Exposure of utilitarian buildings to NO_x and SO_2	Degradation of stone and metalwork, particularly zinc, galvanised steel	Core analysis

(*) For ecosystems damage marginal damage costs are calculated but they are not used in the calculation of externalities in Part B of this report (cf. section 3.5).

Damage costs are calculated, to the extent possible, for EEA38 + UK. They are calculated for the year 2017 and are applied to pollutant emissions from 2008 to 2017 to calculate externalities.

1.4 Major changes compared to the previous assessment

In previous assessments marginal damage costs covered the impact of one tonne of emission of a given pollutant from a country wherever the impacts occur across Europe. Europe was then defined as what corresponds today to EEA38+UK. In the current assessment, damage costs for the main air pollutants are additionally calculated for the damage occurring only in the emitter country. Damage costs occurring in the emitter country (Annex 4) are only presented for information and comparison. They are a subset of the damage cost occurring in EEA38+UK. The two sets represent alternative indicators and must not be added together. The preferred indicator set is the one presenting damage costs covering impacts wherever they occur across Europe.

Dispersion and exposure modelling for the main air pollutants relies on the latest EMEP source receptor matrices (SRMs) that have been updated since the last report. These country-to-grid SRMs link emission reductions for each pollutant in each country to changes in concentrations and depositions of pollutants across Europe at grid level with a horizontal resolution of 0.2°×0.3°. They are based on data (emissions, meteorology) for the year 2017. In EEA (2014) the reference year for which damage costs were calculated was 2010.

For the first time, health impacts (mortality and morbidity) of nitrogen dioxide are included in the damage costs. NO_2 requiring a higher resolution of exposure modelling than what is available via EMEP SRMs, the surrogate model SHERPA([10]) available at a horizontal resolution of 0.06°×0.12° is used to derive Source-Receptor Relationships (SRRs) for NO_2. Here, the reference years of the related input data are different: 2010 for emissions, 2015 for population).

Emission dispersion varies between different emission sources, particularly with respect to emission height. Furthermore, some sources tend to be more closely situated to population than others. In order to account for such differences, sectoral adjustment factors were in the past applied to the average damage costs per tonne of pollutant for the main air pollutants and their impact on $PM_{2.5}$ exposure, dependent on the source of emissions for which externalities were to be calculated. In the previous EEA report, sectoral adjustment factors developed in the EURODELTA II project in 2008 and available only for 4 countries were applied to all countries. In the current assessment, such adjustment factors are calculated for each country based on the SHERPA model and for exposure both to $PM_{2.5}$ and NO_2.

([10]) https://aqm.jrc.ec.europa.eu/sherpa.aspx.

For toxic metals and organic pollutants, exposure modelling has also been updated. Dispersion and exposure modelling for heavy metals and organic pollutants relies on the uniform world model discussed in (Rabl, Spadaro & Holland, 2014) and applied in (Spadaro and Rabl, 2004). The model is used to calculate the European population pollutant-specific intake fraction. The total intake dose comprises two pathways: direct human exposure to contaminated air (inhalation), and indirectly from consumption of contaminated water and food (ingestion). The pollutant transport in water and soil is modelled using the methodology developed by the U.S. EPA (2005).

As far as health effects from the main air pollutants are concerned, in the core analysis we continue using the exposure-response functions from HRAPIE (WHO, 2013) that were also applied to the calculation of damage costs in EEA (2014), except for chronic mortality from NO_2. In a sensitivity analysis we test for the impact of revised response functions for chronic mortality from $PM_{2.5}$, an alternative response function for chronic mortality from NO_2, and for additional impacts not included in earlier analyses from stroke and non-fatal myocardial infarction from $PM_{2.5}$ (Table 2). We continue also using two complementary approaches for valuing mortality: the value of a life year (VOLY), and the value of statistical life (VSL) (e.g. OECD, 2012). However, monetary unit values for mortality are updated, using the VSL from OECD (2012) and a consistent VOLY (Table 4). These updates are also applied in recent assessments for DG ENV (e.g. Clean Air Outlook, Amann et al., 2020).

Table 4: Monetary values for mortality valuation in EEA 2014 and in the present report (in thousands)

ASSESSMENT	VOLY	VSL
EEA 2014 (k€, €$_{2005}$)	58	2 220
EEA 2014 (k€, €$_{2019}$)	74	2 832
EEA 2020 (k€, €$_{2019}$)	101	3 904

Further health impacts are also included for toxic metals. Table 5 indicates in bold font those health effects taken into account this year but not in EEA (2014).

Table 5: Additional health effects calculated in the present report for toxic metals

POLLUTANT	CURRENT STUDY
Arsenic*	**All-cause, non-cancer mortality,** Cancer (fatal & non-fatal), **Chronic bronchitis, IQ loss and diabetes**
Cadmium*	**All-cause mortality,** Non-fatal cancers and **Osteoporosis (hip fractures)**
Chromium (hexavalent)†	Cancer (fatal & non-fatal)
Lead*	**All-cause mortality** and IQ loss
Mercury*	**Cardiovascular mortality**, IQ loss and **Anaemia**

Human exposure route: (*) Inhalation and Ingestion; (†) Inhalation only.

The previous EEA report accounted for damage from SO_2 on materials. In the current report impacts of NO_X are also accounted for. Unlike for other effects, these are not calculated using up to date exposure modelling. Instead, previous unit cost data for repair & replacement are updated in line with inflation.

Concerning impacts of ozone, they are, as in the previous report, assessed using the AOT40 indicator. The major difference compared to EEA (2014) consists in a significantly higher number of crop species accounted for in the present report (121 compared to 20 in the older report). Impacts of ozone on forests are calculated for the first time in the present report.

MDCs for ecosystems impacts are also calculated for the first time in the current assessment. Impacts accounted for are exceedances of critical loads for eutrophication in Natura 2000 areas from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen). The approach used is the one developed in the ECLAIRE project (Holland et al., 2015 a & b) with valuation based on Christie et al. (2012).

Compared to earlier assessments, the scope of the calculation of externalities is extended to include two additional greenhouse gases: methane and nitrous oxide. The previous reports calculated externalities only for CO_2 emissions.

Unit costs for valuating CO_2 (or CO_2 eq) impacts are updated (Table 6). In the previous assessment CO_2 impacts were valued using marginal abatement costs based upon modelled carbon price forecasts for the EU Emissions Trading System (ETS) used in policy modelling by the European Commission. In the present report we use the values used in the DG Move Transport Cost Handbook (EC, 2019).

Table 6: Changes in monetary values for CO_2 valuation between EEA 2014 and the present report

	€ / tonne CO_2 eq
EEA 2014 (€ 2005)	9.5 - 38.1
EEA 2014 (€ 2019)	12.1 - 48.6
EEA 2020 (€ 2019)	63 - 199 (central: 105)

As further new element in this report, an attempt has been made to account for the fact that biomass combustion is not necessarily carbon neutral. Installations can report two categories of carbon emissions to E-PRTR: Total CO_2 emissions and CO_2 emissions excluding biomass. Unfortunately, only a limited subset of facilities reports both. For those who do, damage from total CO_2 emissions and from CO_2 emissions excluding biomass combustion are presented.

The previous assessment calculated damage costs for the year 2010. Given that the most recent SRMs from EMEP relate to 2017 emissions and concentration levels and to meteorological conditions of the same year, and in order to produce a data set as coherent as possible, wherever feasible impacts contributing to the damage costs were calculated for 2017. This means that data on receptors (population, crops, forests…) relate also to 2017, unless specifically stated otherwise.

In the previous assessments, marginal damage costs and external costs of facilities were expressed in Euro price base of 2005. In the current assessment all monetary values are expressed in € price base 2019.

1.5 Structure of the report

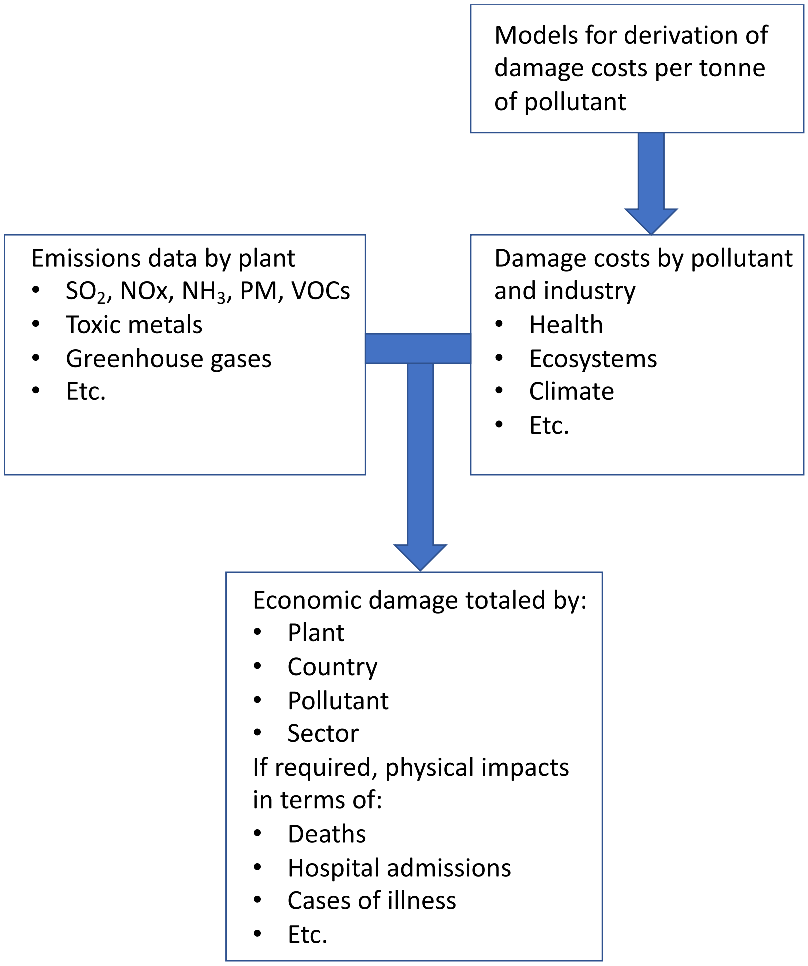
The report is structured as follows. Chapter 2 presents the overall framework for quantifying externalities, with information on the calculation and use of damage per tonne estimates. A detailed description of the modelling undertaken to develop national average damage costs per tonne of pollutant is provided in Part A, for the main air pollutants in Chapter 3 and for the heavy metals and organic pollutants in Chapter 4. The approach to valuing carbon emissions is presented in Chapter 5. The updated sets of marginal damage costs are shown in Chapter 6. Part B presents the results of the assessment of externalities of European industrial facilities. It starts in Chapter 7 with a quick assessment of completeness of emission data reported to E-PRTR. In Chapter 8 a few comments on how externalities are calculated are provided. Chapter 9 presents the results on aggregated damage costs (externalities) caused by the industrial facilities reporting to E-PRTR. These are aggregated over Europe, individual countries and by sectors. In Chapter 10 damage costs are presented for individual facilities. Part C concludes with a discussion on the use of damage costs and perspectives for future work.

2 The framework for quantifying externalities

2.1 The overall framework for analysis

The approach for quantifying externalities is outlined in Figure 8. The key inputs to the analysis are data on emissions, taken from the E-PRTR, and marginal damage costs per tonne emission, averaged over all source sectors or specific to industrial facilities through the use of sectoral adjustment factors. Multiplying emission by marginal damage cost provides the estimate of economic damage (externalities) linked to the release of a pollutant. With those two types of input it is possible to calculate a variety of damage estimates, as indicated in the figure.

Figure 8: Outline for quantifying externalities of industrial plant



Part A of this report concerns the models for derivation of the marginal damage costs, i.e. the damage costs per tonne of emission (top right in the figure). Coverage of the models, input data, detailed assumptions and calculations are presented, that result in the calculation of an updated set of marginal damage costs (per tonne of pollutant).

A description of the E-PRTR data set used and the combination of E-PRTR emissions with damage costs are the issue of part B, resulting in the calculation of externalities for European industrial facilities (cf. economic damage totalled by plant, country …, lower part of Figure 8). Results are presented for different aggregations (individual facilities (top polluters), sector and country aggregates, for specific pollutant groups or aggregated over all pollutants …).

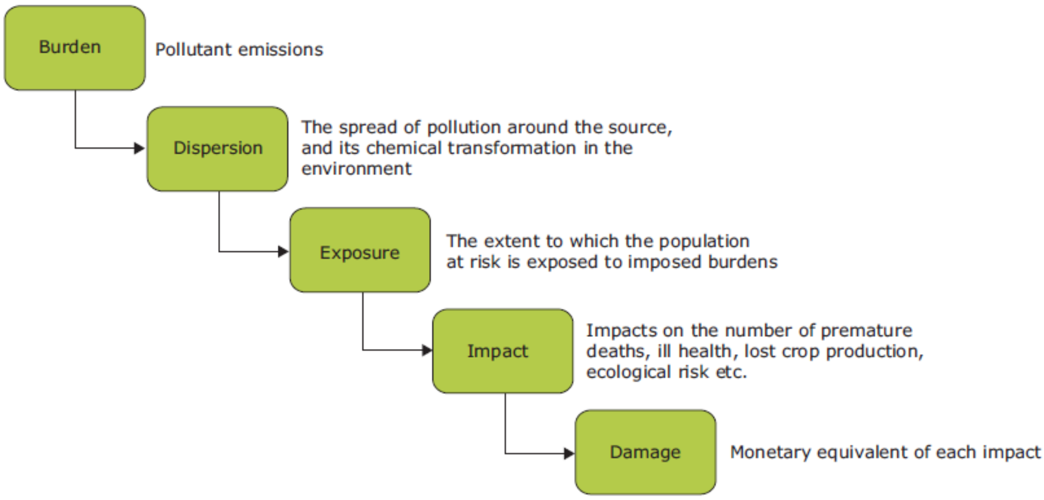
2.2 The impact pathway approach for deriving damage per tonne estimates

The impact pathway approach (IPA) was developed in functional form under the ExternE (Externalities of Energy) study funded by the European Commission in the early 1990s (ExternE, 1995, 1998, 2005). The externalities, or external costs, referred to in ExternE are effects on third parties arising from an activity that are not accounted for by those undertaking the activity. For the development of a coal-fired power station, air pollution externalities include damage to human health, ecosystems and building materials.

The framework was developed to be able to address in a consistent manner that made use of the latest available scientific information any pressure that would generate external costs. As such it was designed to address damage from occupational disease and accidents, noise, visual intrusion of industrial plant, water pollution and various other stresses. In all cases it provides a simple logical progression from the generation of a burden (e.g. increased risk of accidents, or pollutant emission) through exposure of sensitive receptors (people, ecosystems, buildings, etc.) to the burden, quantification of impact and finally valuation.

An overview of the IPA for pollutant emissions is shown in Figure 9. It shows a logical progression from emission to monetary valuation, through pollutant dispersion and transformation, exposure of receptors including people, materials and ecosystems, impact quantification and the translation of physical damage into monetary value. Whilst the overall framework for analysis has not changed for over 25 years, the inputs to the modelling have been revised as knowledge of pollutant emission, exposure, effects and valuation has grown.

Figure 9: The impact pathway approach as it relates to pollutant emissions



In the present study, pollutant emissions (the burden) are extracted from E-PRTR data base for the submission years 2008 to 2017. Pollutants considered are:

- 'main' air pollutants: particulate matter ($PM_{2.5}$([11]), PM_{10}), Sulphur dioxide (SO_2), ammonia (NH_3), nitrogen oxides (NO_X) and non-methane volatile organic compounds (NMVOCs),
- heavy metals: arsenic, cadmium, chromium, lead, mercury, nickel,
- organic pollutants: benzene, Polycyclic Aromatic Hydrocarbons, dioxins and furans([12]),
- greenhouse gases: carbon dioxide, methane and nitrous oxide.

([11]) Cf. footnote 8 and section 6.1.

([12]) Damage costs per tonne of emission are additionally calculated for 1,3 Butadiene and formaldehyde, two pollutants that are not included in the E-PRTR database.

Dispersion modelling allows simulating changes in air quality (concentrations and depositions) due to changes in emissions of atmospheric pollutants. Dispersion modelling for the main air pollutants relies on runs from the EMEP([13]) MSC-West chemistry transport model (EMEP, 2019) for 2017 (in the form of source receptor matrices, see below). This concerns the precursor pollutants NO_X, SO_2, PM_{10}, NH_3 and NMVOC and their contribution to the formation of concentrations of $PM_{2.5}$ and to the formation of depositions of total nitrogen, and the precursor pollutants NO_X and NMVOC for their contribution to the formation of concentrations and deposition of O_3. It relies also on the SHERPA model (Thunis et al., 2016), for instance for the precursor pollutant NO_X and its contribution to the formation of NO_2. The contributions of the other precursors, SO_2, PM_{10}, NH_3 and NMVOC, to NO_2 formation are negligible and therefore not considered any further in the current assessment.

Information on air quality from dispersion modelling is combined with data on the stock at risk (population, crops & forests, ecosystems, buildings …) exposed to concentrations and/or deposition of pollutants, thus calculating the exposure they are subject to. The sources for these data are presented in the respective Chapters of Part A.

For the toxic metals and organic pollutants, the European population pollutant-specific intake fractions are calculated using a multimedia impact pathway analysis based on the implementation of the *uniform world model* (Rabl, Spadaro & Holland, 2014; Spadaro and Rabl, 2004). The total intake dose comprises two pathways: direct human exposure from inhalation, and indirectly through dietary intake (ingestion). The pollutant transport in water and soil is modelled using the methodology developed by the U.S. EPA (2005). The environmental fate analysis begins with the pollutant being emitted to air at a particular physical location, followed by atmospheric dispersion, removal by dry and wet deposition onto land and water surfaces, accumulation and transport in water and soil compartments, uptake by plants and animals, and finally dietary intake of contaminated agricultural and animal products, including fruits and vegetables, meats and milk by-products, and consumption of tap water (Figure 10). Bioavailability may extend for decades into the future until the pollutant is either fixed to soils or ultimately settles in waterbed sediment. Health burdens of pollutants are calculated using pollutant-specific exposure-response associations for quantifying premature mortality (cancers and other causes of death) and morbidity outcomes (anaemia, diabetes, osteoporosis, neurological disorders and respiratory impacts). Physical burdens are then monetised considering health care expenditures, costs to the individual, and the impact of illness on quality of life due to pain and suffering.

In a next step, the impact of a change of exposure on health, crop yield, forest biomass production and exceedance in critical loads is calculated in physical terms. This relies on exposure response functions, linking changes in exposure to an increase in impacts. Based on incidence data, they allow calculation of an attributable fraction of impacts to the change in exposure. These calculations are implemented in the models Alpha-RiskPoll and RiskPoll, respectively, for the quantification of impacts of main air pollutants, on the one hand, and toxic metals and organic pollutants, on the other hand. For crops, forests and ecosystems, methods used are those presented in the Modelling and Mapping Manual (CLRTAP, 2017, ICP Vegetation, 2018) of the Convention on Long-Range Transboundary Air Pollution([14]), and for building materials methods presented in ExternE (2005). These approaches are described in Chapters 3 and 4.

The monetary equivalent of each impact is calculated by simple multiplication([15]) of each impact category with a corresponding marginal damage cost factor. This yields the monetary equivalent (damage) of the change in impacts following from a given change in exposure.

([13]) https://emep.int/mscw/.
([14]) http://www.unece.org/env/lrtap/welcome.html.html.
([15]) This is possible only because the exposure-response functions used here are linear associations with exposure.

This is the typical calculation chain following the impact pathway approach. It can be applied to quantifying and monetizing the impacts of an emission source, a country or region or of emission mitigation measures and scenarios.

In the present study, where the ultimate aim is to develop marginal damage costs per tonne of pollutant, the damage calculated due to a change in exposure is divided by the delta in emissions having led to the change in exposure studied.

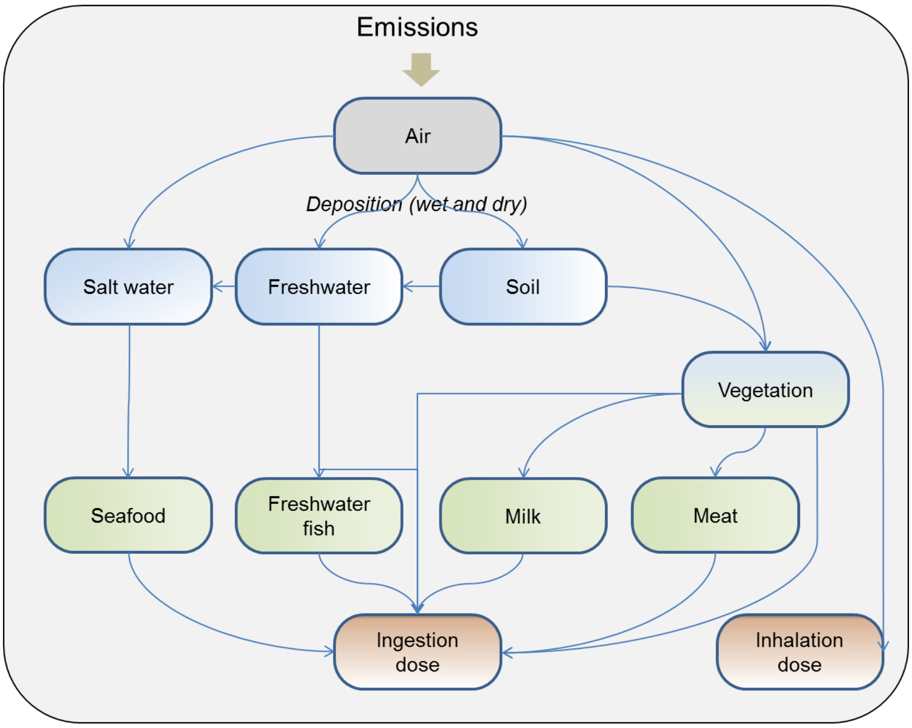
The IPA approach is applied widely for EC decision-making([16]). It is a simple, logical and sequential description of the evolution of impact following release of a pollutant and can integrate the latest scientific data. Historically, the IPA has been used most extensively in characterisation of air pollutant damages for example in the context of developing the emission ceilings directive or air quality directives (e.g. Holland, 2014). In recent years, socio-economic assessments for chemicals have used the IPA in relation to analysis carried out under the EU's REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation following guidance provided by ECHA (2011). Further examples exist, for example in relation to assessment of pesticides (Fantke et al., 2012).

The precise form of the IPA varies from pollutant to pollutant. In order of increasing modelling complexity these are:

- Unreactive fine particles, and some metals and organics for which risk is assessed against inhalation only (least complex) where exposure is modelled against the concentration of the pollutant which stays in the form in which it is emitted.
- Reactive pollutants such as SO_2, NH_3, NO_X and VOCs for which conversion to secondary aerosol and ozone needs to be modelled.
- Some metals and organics where risk is associated with ingestion as well as inhalation, and for which flows through the environment to food, water and milk may need to be modelled (Figure 10, complex, showing the pathways focussing on human exposure via emissions to air).

([16]) It is the generally favoured approach, at least in terms of informing, directing and supporting EU Commission policy measures.

Figure 10: Pathways to exposure



The IPA has not been used so extensively in policy development and appraisal of global problems, for example in relation to the release of greenhouse gases (GHGs) and ozone depleting substances. Concerning the economic damage linked to climate change, the issue is the presence of significant uncertainties in the modelling of impacts, for example in relation to the size and wealth of the future global population, its ability to adapt to a changing climate, and emission rates. As an example, Dong et al. (2019) find an order of magnitude difference in GHG damage costs. Auffhammer (2018) reviews the current state of science, albeit with a particular focus on the damage costs used in the USA, and finds significant deficiencies, both in the costs that are recommended and the studies that feed into them. The complexity of this modelling and associated uncertainties has caused alternative approaches to be considered. Several European studies including EEA (2014) have applied marginal abatement costs for valuation of the GHG emissions rather than damage costs although this raises questions of consistency for the overall assessment of damage.

2.3 The use of damage per tonne estimates to calculate externalities of industrial facilities

The use of MDC estimates to calculate externalities of industrial facilities represents a simplified approach compared to an analysis where all steps of the impact pathway approach were applied to each individual facility. The latter would be extremely resource intensive and costly.

In the simplified approach the following steps are applied:

1. Calculation of averaged (averaged over all economic sectors) country-specific damage costs per tonne of each (precursor) pollutant,
2. Estimation of factors to account for any systematic variation in damage cost per tonne between the national average and specific sectors (e.g. to account for typical differences in the location and height at which emissions from industrial sources are released, which will affect dispersion and hence exposure of people and ecosystems);
3. Multiplication of E-PRTR emission data for each facility and pollutant by the national average damage cost per tonne estimates for each reported pollutant, with the sector-specific adjustment factors applied to the main air pollutants.

Part A: Calculation of marginal damage costs – methods and results

3 Deriving marginal damage costs for the major air pollutants

3.1 Dispersion and exposure modelling for the pollution precursors NO_X, SO_2, O_3, NMVOCs and PM_{10}

Except for CO_2, impacts of all pollutants on human health and the environment are evaluated based on the Impact Pathway Approach. Depending on the complexity of the pollutant chemistry, on its dispersion and on the exposure route, different models may be utilised. For the main air pollutants, such as particles and their precursors or O_3 and their precursors, inhalation is the only relevant exposure route for the human health impact. SO_2, NO_X and NH_3 have also environmental impacts through deposition of sulphur and nitrogen compounds responsible for eutrophication and acidification of water and terrestrial ecosystems. Furthermore, ozone has harmful impacts on crops and forest, and can be responsible for loss in agricultural yields. The complexity of transformation and chemistry of these pollutants that involves non-linear processes requires the implementation of chemistry-transport models (CTMs) for the quantification of health and environmental impacts of those pollutants, for which inhalation and deposition are the main pathways for harmful impacts on health and ecosystems, respectively.

Modelling of main air pollutant dispersion and chemistry tracks pollutants in the atmosphere and follows their chemical reactions, enabling quantification of the atmospheric transport and transformation resulting from the release of primary emissions. An important consequence is that effects caused by secondary particulates or ozone are assigned to the primary pollutant (precursors) emissions from which they are formed (e.g.in the case of $PM_{2.5}$: SO_2 for sulphate aerosol, NO_x for nitrate aerosol and NH_3 for ammonium aerosol). The modelling also allows accounting for non-linear chemical interactions between air pollutants, for example the effects of NMVOC emissions on secondary organic aerosols, or the effects of NO_2 and NMVOC emissions on ground-level (tropospheric) ozone formation.

CTM models are adapted to calculate air concentrations of pollutants over large regions such as Europe with spatial resolutions varying from 2km×2km to 50km×50km. Because the objective of the IPA here is to estimate a country-specific avoided damage cost associated with emission reductions of NO_X, PM_{10}, SO_2, NMVOC and NH_3, a full run with a CTM reducing independently each pollutant over each country would be heavily consuming in terms of computational time. For this reason, both the 2011 and 2014 EEA reports were based on the use of EMEP Source Receptor Matrices (SRMs) released each year by EMEP/MSC-W under the UNECE LRTAP Convention. These matrices are based on sensitivity simulations of the full EMEP/MSC-W Chemistry Transport Model. In a country-to-grid configuration, they give the change in various pollution levels (concentrations, deposition) in each receptor grid resulting from a change in anthropogenic emissions from each individual country (or natural emitter region). Such matrices are generated by reducing emissions for each country (or region) of one or more precursors by a given percentage (15 % has been the choice). Over each country, the emission reductions of the five main air pollutant precursors (NO_X, PM_{10}, SO_2, NMVOC and NH_3) are modelled independently. But the reduction is not specific to the different anthropogenic sectors (industry, transport, domestic, agriculture, etc., cf. Chapter 3.2).

In the current assessment, the most recent EMEP SRMs (for the year 2017) at the time of writing the report are used (EMEP, 2019) for calculating damage costs relative to health impacts and impacts on crops, forests and ecosystems from major air pollutants. Compared to the SRMs used in earlier EEA reports, the calculation of damage costs in the present report benefits from recent developments in the EMEP SRMs (EMEP, 2018) associated to developments in the EMEP CTM model itself. In particular, the improvement of secondary organic aerosol modelling had a strong impact on modelled concentrations of $PM_{2.5}$ (cf. Chapter 5 in EMEP (2019)). We can also mention changes in modelled emissions, including shipping emissions.

The EMEP SRMs are calculated for a 15 % change in 2017 emissions. The 2017 emission data is given in Table 7.

Table 7: National total emissions and emissions from sea regions for 2017 in the EMEP domain (in kt)

AREA/POLLUTANT		NH_3	SO_2	NO_X	$PM_{2.5}$	NMVOC	CO	PM_{10}
Albania	AL	24	13	25	15	39	177	19
Austria	AT	69	13	145	16	120	529	28
Belgium	BE	67	38	176	23	109	293	33
Bosnia and Herzegovina	BA	21	170	31	14	33	96	26
Bulgaria	BG	49	103	103	32	77	242	47
Croatia	HR	38	13	55	17	63	197	25
Cyprus	CY	6	16	15	1	12	14	2
Czechia	CZ	67	110	163	40	207	819	51
Denmark	DK	76	10	112	20	102	241	31
Estonia	EE	10	39	33	9	22	138	14
Finland	FI	31	35	130	18	88	359	29
France	FR	606	144	807	164	612	2695	254
Georgia	GE	31	11	38	17	41	177	22
Germany	DE	673	315	1188	99	1069	2832	206
Greece	GR	56	57	255	26	199	323	56
Hungary	HU	88	28	119	48	142	423	69
Iceland	IS	5	50	23	1	6	113	2
Ireland	IE	118	13	110	12	113	88	27
Italy	IT	384	115	709	165	935	2331	196
Latvia	LV	17	4	37	18	38	125	25
Liechtenstein	LI	0	0	0	0	0	1	0
Lithuania	LT	30	13	53	7	46	140	14
Luxembourg	LU	6	1	18	1	12	22	2
Malta	MT	1	1	5	0.24	3	6	0.38
Republic of Moldova	MD	23	9	28	11	51	85	17
Monaco	MC	0	0	0	0	0	1	0
Montenegro	ME	2	47	14	5	8	26	12
Netherlands	NL	132	27	252	14	252	564	27
North Macedonia	MK	10	56	24	9	29	57	16
Norway	NO	33	15	163	28	153	437	37
Poland	PL	308	583	804	147	691	2543	246
Portugal	PT	58	48	159	51	168	325	73
Romania	RO	164	107	232	112	240	783	143

AREA/POLLUTANT		NH_3	SO_2	NO_X	$PM_{2.5}$	NMVOC	CO	PM_{10}
Russian Federation	RU	1204	1663	3239	369	3734	12369	809
Serbia	RS	65	420	148	39	125	268	53
Slovakia	SK	27	27	66	18	89	365	23
Slovenia	SI	19	5	35	11	30	105	13
Spain	ES	518	220	739	105	618	1309	172
Sweden	SE	53	18	124	20	147	384	40
Switzerland	CH	55	5	61	7	78	155	15
Turkey	TR	740	2350	785	388	1099	2033	765
Ukraine	UK	286	839	637	145	519	2481	216
United Kingdom	GB	283	173	893	107	809	1555	171
Baltic Sea	BAS	0	9	287	9	2	19	9
Black Sea	BLS	0	40	90	6	1	7	6
Mediterranean Sea	MED	0	603	1171	86	9	79	86
North Sea	NOS	0	29	609	20	5	45	20
NE Atlantic Ocean	ATL	0	403	773	57	6	54	57

In the present study we use the SRM data from EMEP for the $PM_{2.5}$ concentration precursor pollutants NO_X, SO_2, PM_{10}, NH_3 and NMVOCs, for the ozone (SOMO35 and AOT40) precursor pollutants NO_X and NMVOCs and for the oxidized and reduced nitrogen deposition precursors NO_X and NH_3.

Health impacts from the main air pollutants are calculated not only for $PM_{2.5}$ and O_3 but also for NO_2. EMEP SRMs are not used for the NO_2 precursor pollutants. NO_2 is a local pollutant exhibiting high concentrations close to sources and a sharp decrease when moving away from them. Therefore, the calculation of NO_2 exposure (i.e. the sum over all grids in the domain of the grid concentration multiplied by the grid population) requires high resolution modelling. A 0.2 × 0.3 degree resolution as in the 2017 EMEP-SRMs is not enough to represent these spatial variations. A report published by VITO for the European Commission (Maiheu et al., 2017) focused on NO_2 exposure assessment at a European scale. It highlighted the sensitivity of NO_2 population exposure to different modelling parameters. Model resolution was one important factor. The authors evaluated errors introduced by NO_2 concentrations smoothing over the model grid. For exposure-response functions with no NO_2 threshold, the errors introduced by smoothing NO_2 concentrations over a 7 km^2 grid were evaluated to range from 5 % to 17 %. Even if errors on this order are not negligible, this grid resolution starts to be acceptable for assessing NO_2 exposure. This grid resolution is almost attained with the SHERPA model developed by the JRC([17]). These errors are evaluated to be much larger if the exposure-response function used for NO_2 health impacts includes a 20 $\mu g.m^{-3}$ threshold (VITO, 2017) as is the case for the chronic mortality response function recommended by HRAPIE (WHO, 2013). Indeed, the smoothing effect will lead to reducing most of the NO_2 grid concentrations below this threshold. In that case, the spatial resolution of the above-mentioned tools (7, 10 or 25 km^2) is probably not satisfactory.

Based on these findings, the following two decisions were taken:

- The SHERPA model at 7 km^2 grid is used in the current study to develop SRRs for NO_2 precursor pollutants
- In the health impact assessment, the HRAPIE response function for chronic mortality from NO_2 is replaced by a more recent response function without cut-off point (cf. Chapter 3.2).

([17]) https://ec.europa.eu/jrc/en/news/sherpa-computational-model-better-air-quality-urban-areas.

SHERPA is a surrogate model trained on a full chemistry-transport model (EMEP and CHIMERE). SHERPA grid to grid Source-Receptor Relationships (SRRs) are constructed on the basis of a few full-CTM simulations (around 10). Two versions of the SHERPA tool exist. One is based on the CTM CHIMERE (Menut et al., 2014) run at horizontal resolution of about 7km^2 (0.06°× 0.12°) for the meteorological year 2009, with emissions based on GAINS total emissions per country-pollutant-sector for 2010 and gridded with proxies from the MACC-TNO emission inventory from the year 2010 and specific national inventories for France and the UK (Thunis et al., 2016). Another version has been developed more recently (Pisoni et al., 2019) based on the EMEP MSC-W model 4.9([18]), for meteorological conditions from 2014, with a resolution of 0.1° × 0.1° and with emissions provided by JRC for the year 2014 (Trombetti et al., 2017). The latter is used for the calculation of sectoral adjustment factors (cf. Chapter 3.2). However, it only calculates concentrations of $PM_{2.5}$, but not of NO_2. Therefore, the older version, based on the CTM CHIMERE, which is also at higher spatial resolution (7km compared to 10km), is used for SRR development for NO_2. As is the case for the EMEP SRMs, the method used consists in reducing emissions of a selected precursor pollutant in each country individually and to estimate the associated reduction in concentrations to NO_2 in all European countries (the emitter country itself and all European receptor countries). Based on SHERPA grid to grid SRRs, the impact of NO_X emission reductions on NO_2 exposure was calculated. The impacts of reductions in the emissions of all other precursors on NO_2 exposure have also been calculated with SHERPA and found to be negligible. Therefore, our further assessment here is limited to the NO_2 precursor NO_X.

Table 8: National total emissions for 2010 for EEA38+UK countries in the SHERPA domain (in kt)

AREA/POLLUTANT	ISO CODE	NO_X
Albania	AL	22
Austria	AT	192
Belgium	BE	271
Bosnia and Herzegovina	BA	39
Bulgaria	BG	152
Croatia	HR	65
Cyprus	CY	16
Czechia	CZ	245
Denmark	DK	133
Estonia	EE	37
Finland	FI	110
France	FR	1113
Germany	DE	1252
Greece	GR	252
Hungary	HU	134
Ireland	IE	95
Italy	IT	949
Latvia	LV	32
Liechtenstein	LI	1
Lithuania	LT	53
Luxembourg	LU	21
Malta	MT	9
Montenegro	ME	6
Netherlands	NL	250
Norway	NO	67
Poland	PL	813

([18]) https://acp.copernicus.org/articles/12/7825/2012/.

AREA/POLLUTANT	ISO CODE	NO_X
Portugal	PT	193
Romania	RO	218
Serbia	RS	147
Slovakia	SK	68
Slovenia	SI	37
Spain	ES	841
Sweden	SE	139
Switzerland	CH	66
Turkey	TR	821
United Kingdom	GB	966

To summarise, we use three surrogate models which are trained either on the EMEP or CHIMERE Chemistry-Transport models. The combinations of models differ depending on the main air pollutant considered:

- $PM_{2.5}$: EMEP SRMs at 0.2x0.3degree resolution, subsequently refined with EMEP/SHERPA correction factors calculated at 10km resolution;
- O_3, N-deposition: EMEP SRMs at to 0.2x0.3degree resolution;
- NO_2: CHIMERE/SHERPA SRRs at 7km resolution.

Exposure of the population for $PM_{2.5}$, O_3 and NO_2 are calculated by matching the gridded concentrations (from EMEP SRMs for $PM_{2.5}$ and O_3 and from SHERPA SRRs for NO_2) with the most recent GHS population data([19]) developed by the JRC that applies to the year 2015 (population data gridded at 1km^2).

Note therefore that the calculation of health effects from NO_2 relies on input data for which the reference year (2010 for emissions, 2015 for population) diverges from the reference year chosen (2017) for the other impacts.

3.2 Calculating sectoral adjustment factors

We have used the SHERPA tool to calculate sectoral adjustment factors([20]) that are applied to the calculations presented in Part B of this report. Indeed, this tool makes it possible to apply emission reductions over a particular sector (at SNAP level 1), instead of assuming homogeneous reductions over all sectors, as is the case in EMEP SRMs (Source Receptor Matrices). The estimation of adjustment factors relies on the calculation of sector SRRs (Source Receptor Relationships) and on the assessment of the deviation between the SRRs from different sectors. Correction factors reflect the normalised impact of an emission reduction over one sector compared to the normalised impact of a homogeneous reduction over all sectors. A factor higher than one implies that control measures will be more efficient in terms of reduction in exposure for this targeted sector than calculated with the average SRM. By construction, the correction values for the different sectors are interdependent (correction factor values cannot exceed 1 for all sectors, there must be one or more sector with factors below one).

([19]) https://ghsl.jrc.ec.europa.eu/ghs_pop2019.php.
([20]) EEA (2014) chose the terminology « correction factor », Thunis et al. (2018) refer to them as sector "efficiencies".

The calculated SHERPA SRRs relate gridded emission changes to gridded concentration changes simulated by the CTM. This feature is not exempt from assumptions as the actual CTM sensitivity simulations underlying SHERPA do not explicitly isolate each activity sector. This means that when reproducing gridded concentration changes due to a reduction in an industrial sector, SHERPA estimates the response of CHIMERE to an averaged reduction applied over the mean vertical profile of all sectors (at the ground and at the height of the industrial source if included on the grid), and not to the specific height of the industrial sources targeted. This assumption has been addressed in the recent update of EMEP-SHERPA (Pisoni et al., 2019) which includes sectoral validation tests (albeit only for relative changes and not for absolute deltas). Validation is however not complete as no tests of the ability of SHERPA to capture the model sensitivity country by country, and for both sectors and precursors, have been performed. Nevertheless, this particularity can be used to construct updated sector adjustment factors, accounting for sectoral adjustments for each of the 31 European countries covered in SHERPA (EU27 + UK, Switzerland, Norway and Montenegro).

SHERPA relies on the sector nomenclature SNAP([21]). The same nomenclature was used to calculate sector correction factors in the EURODELTA II study, from which correction factors applied in EEA (2014) were derived.

E-PRTR emissions are reported according to their own specific nomenclature. An attempt was made in the current project to create a mapping between E-PRTR and SNAP activity codes. The result is presented in Annex 8.

For sectors for which a one-to-one mapping was possible, adjustment factors were calculated for the individual SNAP sectors:

- SNAP 01 (Combustion in the production and transformation of energy)
- SNAP 03 (Industrial combustion plants)
- SNAP 04 (Industrial processes without combustion)
- SNAP 05 (Extraction and distribution of fossil fuels and geothermal energy)
- SNAP 06 (Use of solvents and other products)
- SNAP 09 (Waste treatment and disposal)

However, various E-PRTR activity classes refer to a combination of two or more SNAP sectors. Where unambiguous matching between E-PRTR and SNAP activities has not been possible, we calculated aggregated adjustments factors over several SNAP classes (see Annex 7 and 8 for more details).

On this basis, adjustment factors were calculated in order to correct the impact of changes in emissions of precursor pollutants (NO_X, SO_2, PM_{10}, NMVOC and NH_3) on $PM_{2.5}$ and the impact on NO_2 due to changes in emissions of the precursor pollutant NO_X. The resulting adjustment factors are multiplied with the marginal damage costs for the respective precursor pollutant and the emissions of each facility. The adjustment factors are presented in Annex 7. No adjustment factors were calculated for correcting marginal damage costs for ozone precursors. Ozone is a pollutant with a long lifetime that can be created far from the zones where its precursors are emitted, and it shows regional patterns. Therefore, the exposure of the population to O_3 will not be impacted much by the localisation of the sectors that emits the precursors.

It is the first time that adjustment factors are calculated for each country and sector, so this is a real advancement compared to earlier work. In Annex 7 the adjustment factors are presented in detail and the impact they have on the calculated externalities in Part B of this report is discussed.

([21]) Selected Nomenclature for Air Pollution, http://en.eustat.eus/documentos/elem_13173/definicion.html.

3.3 Quantification and valuation of health impacts from $PM_{2.5}$, O_3 and NO_2

The overall approach for the quantification is the same as in earlier EEA reports. The SRMs from EMEP for $PM_{2.5}$ and O_3 precursors and the SRRs developed with SHERPA for NO_2 precursors, combined with population data, provide information about the reduction in the exposure to $PM_{2.5}$, O_3 and NO_2 due to a 15 % reduction in each of the precursor emissions. Based on exposure-response functions, the associated reduction in health impacts and health costs can then be calculated. By dividing the avoided health costs by the quantity of precursor emissions reduced, a country-specific external cost per tonne of pollutant is estimated. It should be noted that current response functions are developed to link outdoor concentrations to sanitary effects, even if the population spends part of the time indoor. Therefore, the method is limited to outdoor exposure responses to emission reductions.

3.3.1 Quantification of health impacts from main air pollutants

The HRAPIE (Health Risks of Air Pollution In Europe) study led by WHO-Europe in 2013 (WHO, 2013) remains the most recent comprehensive review of air pollution epidemiology in Europe, covering both response functions for mortality and morbidity for a range of pollutants ($PM_{2.5}$, PM_{10}, NO_2 and ozone). Since HRAPIE was completed, however, there has been a substantial expansion of literature in the field. The following summarises key findings since HRAPIE was published, first for mortality and then morbidity.

The WHO Systematic Review for $PM_{2.5}$ (Chen and Hoek, 2020) carried out as part of the review of the WHO Air Quality Guidelines, and Pope et al. (2020) indicate that the HRAPIE function for mortality effects of long-term exposure to $PM_{2.5}$ is conservative. This is particularly important as the effect of $PM_{2.5}$ on mortality dominates most economic analyses not only for impacts associated with direct emissions of $PM_{2.5}$ but also for emissions of NH_3, NO_X and SO_2 through the formation of secondary $PM_{2.5}$ which is formed in reactions between pollutants in the atmosphere. Some increase above the best estimate of the response function from HRAPIE of a relative risk (RR) for mortality of 1.062 / 10ug.m^{-3} $PM_{2.5}$ is warranted given that new peer-reviewed analyses all give best estimates of response that are higher. However, there is significant variation between analyses and between the regions considered in those analysis for the RR per unit concentration of $PM_{2.5}$:

- 1.07 / 10ug.m-3 estimate of Chen and Hoek (2020) from 5 European studies included in their review
- 1.08 / 10ug.m-3 estimate from Chen and Hoek (2020) for all 107 studies included in their review
- 1.08 / 10ug.m-3 estimate of Pope et al. (2020) for 33 selected studies included in their review
- 1.12 / 10ug.m-3 estimate from Pope et al. (2020) for 10 European studies included in their review([22])

The Systematic Review carried out on mortality impacts of NO_2 exposure for WHO (Huangfu and Atkinson, 2020) assessed 41 studies. The analysis indicates a lower mortality response per unit exposure with a relative risk of 1.02/ 10ug.m^{-3} compared to 1.055/10ug.m^{-3} under HRAPIE. However, Huangfu and Atkinson found no evidence for non-linearity down to low concentrations, drawing on observations down to a few ug.m^{-3}, whereas HRAPIE had recommended a cut-point for analysis of 20ug.m^{-3}, with quantification only applied to higher concentrations, reflecting the lack of evidence at lower concentrations in the literature at the time. The two components of the conclusions of Huangfu and Atkinson (2020) have different consequences: the reduction in RR clearly reduces effects, whilst the conclusion of linearity to lower concentrations increases effects amongst those exposed to concentrations below 20ug.m^{-3}. The indication that there should be no cut-off point for analysis is a significant and useful simplification for analysis at the European scale, removing one step in the analysis, the quantification of the number of people exposed over the cut-off point. Huangfu and Atkinson found no evidence of a response to long-term exposure to ozone([23]).

([22]) It is understood that the relative risk of 1.12 from the Pope et al. (2020) review of the European studies is likely to be reduced following further review of the studies included in the estimate.
([23]) This is inconsistent with Turner et al. (2016). Therefore, further work is needed.

A third paper from the WHO Systematic Reviews (Orellano et al., 2020) considered mortality impacts of short-term exposure to pollutants. Their findings indicate an increase in the RR for ozone, from the 1.0029/10ug.m^{-3} from HRAPIE, to 1.0043/10ug.m^{-3}.

Turning to morbidity, numerous studies published since HRAPIE indicate significant association between pollutants and additional impacts, for example on asthma (e.g. Jacquemin et al., 2015; Khreis et al., 2017), coronary heart disease (e.g. Cesaroni et al., 2014), dementia (Wang et al., 2020), stroke (e.g. Scheers et al., 2015) and diabetes (e.g. Eze et al., 2015) that could add significantly to the benefits quantified under HRAPIE. Analysis in the UK (Ricardo, 2020; Defra, 2020) goes so far as to indicate that the inclusion of a range of morbidity effects with long-term consequences would exceed mortality impacts when impacts are monetised. Some other European analyses have shown potential for additional morbidity impacts to add significantly to overall damage, but not to exceed damage related to mortality (Amann et al., 2020). Some others, however, indicate that additions to overall economic damage may be modest (e.g. Van de Vel and Buekers, 2020).

Analysis in a number of countries continues to use the HRAPIE functions to a large extent if not entirely (e.g. Denmark: DCE, 2018; Finland: Savolahti et al., 2018; France: Schucht et al., 2015; and Germany: UBA, 2018, 2019). Review in a study undertaken to inform the EU's Second Clean Air Outlook (Amann et al., 2020) found no consensus across health impact assessment and economic studies in Europe and North America regarding which additional effects should be included and what precise response function should be adopted. For the present analysis, the following positions are adopted:

- That the HRAPIE function set remains in use for the core estimates. This is acknowledged as a conservative position, biased to underestimation of health impacts. There is one exception to this:
    - Use of the relative risk of 1.02 per 10µg/m^3 from Huangfu and Atkinson (2020) for mortality impacts from chronic exposure to NO_2, applied without cut point at 20µg/m^3, but reduced to 1.008 per 10µg/m^3 to account for double counting of impact with the function used for $PM_{2.5}$ mortality (reflecting the discussion on double counting in COMEAP (2018) and Ricardo (2020)).
- Supplementary analysis is used to provide an indication of possible levels of underestimation of impacts by using the HRAPIE functions. The supplementary analysis applied here includes:
    - An increased estimate of $PM_{2.5}$ related mortality, using the relative risk of 1.08 per 10µg/m^3 overall estimate from Chen and Hoek (2020), compared to 1.062 per 10 µg/m^3 from HRAPIE. This is applied in the supplementary analysis rather than core because of variability in estimates from the Chen and Hoek (2020) and Pope et al. (2020) studies. The overall estimate from Chen and Hoek is preferred to their estimate based on European studies only, given the much larger number of studies included in the former.
    - Use of the relative risk of 1.02 per 10µg/m^3 from Huangfu and Atkinson (2020), applied without cut point at 20µg/m^3.
    - Adoption of additional response functions for stroke and cardiovascular disease via incidence of non-fatal myocardial infarction linked to $PM_{2.5}$ exposure.

Inclusion of additional response functions for childhood asthma and diabetes was considered and rejected as these effects were only included in UK analysis (Ricardo, 2020, Defra, 2020). Inclusion of lung cancer morbidity was rejected although it was included in a few studies, because associated estimates of economic damage were insignificant.

Table 9 summarised the response functions used in the core analysis.

Table 9: Response functions used in the core analysis

END POINT	IMPACT	POLLUTANT	RELATIVE RISKS	SOURCE FOR RESPONSE FUNCTION
Acute Mortality (All ages)	Premature deaths	O_3	1.0029, 95%CI 1.0014 to 1.0043 per 10 µg.m-3	Katsouyanni et al., 2009
Respiratory hospital admissions (>64)	Cases		1.0044, 95%CI 1.0007 to 1.0083 per 10 µg.m-3	
Cardiovascular hospital admissions (>64)	Cases		1.0089, 95%CI 1.0050 to 1.0127 per 10 µg.m-3	
Minor Restricted Activity Days (MRADs all ages)	Days		1.0154, 95%CI 1.0060 to 1.0249 per 10 µg.m-3	Ostro and Rothschild, 1989
Chronic Mortality (All ages (*)) YOLL	Life years lost	$PM_{2.5}$	1.062, 95%CI 1.040 to 1.083 per 10 µg.m-3	Hoek et al., 2013
Chronic Mortality (30yr +) deaths	Premature deaths	$PM_{2.5}$	1.062, 95%CI 1.040 to 1.083 per 10 µg.m-3	
Infant Mortality (1 month-1yr)	Premature deaths	PM_{10}	1.04, 95%CI 1.02 to 1.07 per 10 µg.m-3	Woodruff et al., 1997
Chronic Bronchitis (27yr +)	Cases	PM_{10}	1.117, 95%CI 1.040 to 1.189 per 10 µg.m-3	Abbey et al., 1995a, b, Schindler et al., 2009
Bronchitis in children aged 6 to 12	Added cases	PM_{10}	1.08, 95%CI 0.98 to 1.19 per 10 µg.m-3	Hoek et al., 2012
Respiratory Hospital Admissions (All ages)	Cases	$PM_{2.5}$	1.019, 95%CI 0.9982 to 1.0402 per 10 µg.m-3	APED study, 2000-2009 (***)
Cardiac Hospital Admissions All ages)	Cases	$PM_{2.5}$	1.0091. 95%CI 1.0017 to 1.0166 per 10 µg.m-3	
Restricted Activity Days (all ages)	Days	$PM_{2.5}$	1.047, 95%CI 1.042 to 1.053 per 10 µg.m-3	Ostro, 1987
Asthma symptom days (children 5-19yr)	Days	PM_{10}	1.028, 95%CI 1.006 to 1.051 per 10 µg.m-3	Weinmayr et al., 2010
Lost working days (15-64 years)	Days	$PM_{2.5}$	1.046, 95%CI 1.039 to 1.053 per 10 µg.m-3	Ostro, 1987
Bronchitis in children aged 5 to 14	Added cases	NO_2	1.021. 95%CI 0.99 to 1.06% per 1 µg.m-3	McConnell et al., 2003
Respiratory Hospital Admissions (All ages)	Cases		1.018, 95%CI 1.0115 to 1.0245 per 10 µg.m-3	APED study, 2000-2009 (***)
Chronic Mortality (All ages) YOLL	Life years lost		1.02, 95%CI 1.01 to 1.04 per 10 µg.m-3	Huangfu and Atkinson (2020), COMEAP (2018) and Ricardo (2020)
Chronic Mortality (30yr +) deaths	Premature deaths		1.008, 95%CI 1.004 to 1.016 per 10µg/m³ (**)	

(*) The YOLL calculation is based on analysis that considered the over 30 years population only but expressed the result as the change in YOLL per ug.m-3 spread across the whole population. (**) Reduced to 1.008 per 10µg/m³ from 1.02, 95%CI 1.01 to 1.04 per 10 µg.m³ to account for double counting of impact with the function used for $PM_{2.5}$ mortality. (***) Reference to APED refers to a series of European studies reporting between 2000 and 2009 (Amann et al., 2020): further details are provided in the HRAPIE report (WHO, 2013).

Information on the incidence of morbidity (hospital admissions, rates for chronic bronchitis, etc.) were taken from an earlier review by Holland (2014a). Data on population, mortality and life expectancy are taken from the UN World Population Prospects 2019([24]), medium variant.

([24]) https://population.un.org/wpp/.

3.3.2 Monetisation of health impacts from main air pollutants

With respect to valuation, the development of recommendations for updating the unit values is not straightforward, given a lack of consistency in the literature and the diversity of health metrics (values per case of new incidence, per prevalent case, per day, etc.) covering different effects. A review has been carried out (Amann et al., 2020) covering European and international valuation studies to identify best estimates for valuations of each health impact covered by the impact assessment. These are presented in Table 10, updated to 2019 values (Amann et al. cite values in 2015 prices).

Table 10: Values adopted for health impact valuation (€, 2019 values)

Effect	Updated figures	Main source(s)
	Effects included by HRAPIE	
Mortality – value of statistical life (VSL)	€3.90 million	Based on OECD (2012)
Mortality – value of a life year (VOLY)	€101,426	Previous median estimate increased in proportion to the increase in mean VSL to reflect OECD (2012)
Infant Mortality (per death)	€5.86 million	Based on OECD (2012) (factor 1.5 higher than average for adults)
Chronic Bronchitis in adults (per case)	€68,383	Maca (2011), Holland (2014b) with concerns over severity of air pollution related bronchitis
Bronchitis in children (per event)	€384	Hunt et al. (2016)
Respiratory Hospital Admissions (per case)	€5,103	Broadly mid-range from estimates and similar to DCE (2018)
Cardiac Hospital Admissions (per case)	€6,379	Broadly mid-range from estimates and similar to DCE (2018)
Restricted Activity Days (per day)	€140	Hunt et al. (2016)
Minor restricted activity days (per day)	€51	Hunt et al. (2016)
Work loss days (per day)([25])	€166	Amann et al. (2017)
Asthma symptoms, asthmatic children (per day)	€54	Holland (2014), U.S. EPA (2011)
	Additional effects for supplementary analysis	
Stroke (per case)	€502,665	Average of Åstrom (2019) and Ricardo (2020)
Non-fatal myocardial infarction (per case)	€59,963	Average of Åstrom (2019) and Ricardo (2020)

As the table indicates, two alternative approaches are used for valuing mortality: the value of a life year (VOLY), and the value of a statistical life (VSL). VSL is an estimate of damage costs based on how much people are willing to pay for a reduction in their risk of dying from adverse health conditions. VOLY is an estimate of damage costs based upon the loss of life expectancy (expressed as potential years of life lost). This measure takes into account the age at which deaths occur. In the following, when presenting marginal damage costs (Part A) and externalities of industrial facilities (Part B), it will always be indicated whether the underlying health damage relies on mortality valuation using VOLY or VSL. The lower estimate is the one using VOLY, the higher the one using VSL.

([25]) The European Chemicals Agency (ECHA) has adopted an approach to valuing the social cost of unemployment (https://echa.europa.eu/documents/10162/13555/seac_unemployment_evaluation_en.pdf/af3a487e-65e5-49bb-84a3-2c1bcbc35d25) that includes aspects, such as the value of productivity loss, that are also relevant in the valuation of work loss days. ECHA's work should be assessed for a possible inclusion in a future update of work loss day valuation.

3.4 Quantification and valuation of impacts on crops and forests from O_3

In the quantification of ozone impacts on crops, the EEA (2014) analysis used the concentration based AOT40 (Accumulated Ozone exposure over a Threshold of 40 ppb)([26]) indicator. Over the last years, various studies have used the more recent stomatal ozone flux indicator (PODy) to assess damage from ozone to crops and forests (Mills & Harmens, 2011; Anav et al., 2016; cf. also Castell & Le Thiec, 2016, Holland et al., 2015a & b, Schucht et al., 2019a, for an overview of recent studies). The flux-based approach is the one currently supported by science as it produces results that coincide better with observations of ozone damage on vegetation than the results of the metric AOT40 (Hayes et al., 2007). The choice of the metric can also matter when it comes to assessing policy effectiveness. An Eionet report (Colette et al., 2018) found that using the AOT40, ozone detrimental impacts on crops would decrease from 18.2 %in 1990 to 10.2 % in 2010, whereas using the PODy, no substantial improvement is found (change from 14.9 % to 13.3 % in the same period), using the same original information in terms of ozone concentrations.

However, currently no PODy SRMs are available. For the time being, the calculation of impacts of ozone on crops and forests hence needs to continue using the AOT40 indicator.

Impacts of ozone on crops and forests are estimated by the ICP Vegetation of the Air Convention (CLRTAP). The methodologies for crop impact assessment and dose-response functions for Europe are published in the CLRTAP mapping manual (CLRTAP, 2017), Chapter 3 and the Scientific background document A (ICP Vegetation, 2018).

3.4.1 Crop assessment

EMEP SRMs linking reductions in NO_X and NMVOC emissions to changes in O_3 concentrations (expressed in the AOT40 indicator) are available for the EEA38+UK emitter countries and quantify changes in ozone for the same countries.

Dose-response functions link the impact on the relative yield of a crop to the exposure to ozone. Whereas response functions in ICP Vegetation (2018) are expressed with a positive intercept, Van Dingenen et al. (2009) scale these into functions with a zero intercept at zero ozone, thus allowing to calculate the impact on crop yield (the relative yield loss, RYL) by multiplying the AOT40 with the response function.

$$RYL = AOT40 * \alpha$$

with RYL: relative yield loss

This is done for four crops: wheat, maize, rice, soy.

Table 11: The α coefficients for the exposure-response equations

	Wheat	Rice	Soy	Maize
$\boldsymbol{\alpha}$	0.0163	0.00415	0.0113	0.00356

Source: Van Dingenen et al. (2009)

In the present study, response functions for other crops are estimated by scaling with the relative sensitivities of crops presented in ICP Vegetation (2010/11) (Table 12).

([26]) The sum of the differences between hourly ozone concentration and 40 ppb for each hour when the concentration exceeds 40 ppb during a relevant growing season, e.g. for forest and crops.

Table 12: Grouping of crops by relative sensitivity score (in brackets)

Sensitive	Moderately sensitive	Tolerant
Peas and beans (including peanut) (0.70)	Alfalfa (0.86)	Strawberry (0.99)
Sweet potato (0.72)	Water melon (0.86)	Oat (1.00)
Orange (0.73)	Tomato (0.87)	Broccoli (1.05)
Onion (0.77)	Olive (0.87)	
Turnip (0.78)	Field mustard (0.88)	
Plum (0.78)	Sugar beet (0.89)	
Lettuce (0.81)	Oilseed rape (0.89)	
Wheat (0.82)	Maize (0.90)	
Soybean (0.82)	Rice (0.91)	
	Potato (0.91)	
	Barley (0.94)	
	Grape (0.95)	

The response function for potatoes, as an example, is calculated as

$$RYL_{potatoes} = 0.0163 * (1 - 0.91)/(1 - 0.82)$$

This is the approach applied in ECLAIRE (Holland et al., 2015 a & b). We chose wheat as reference because there is far more European literature on wheat than on rice, soy or maize. For crops not explicitly stated in this table we also follow the approach applied in ECLAIRE, considering that “simple cereals such as rye are regarded like oat as being tolerant, and legumes generally are regarded like peas and beans as being highly sensitive. Other crops not covered by the functions derived so far are taken to have similar sensitivity to grape, the least sensitive of the crops in the ‘moderately sensitive’ class of the table above. The logic for adopting the function for the least sensitive of the ‘moderately sensitive’ crops is that experimentation tends to focus on species and cultivars for which a significant response has been observed at some time. A lack of data for a crop might therefore suggest that it is unlikely to be highly sensitive, and hence that it is either tolerant or moderately sensitive. The sensitivity of grape is thus taken as indicative of the break point between the two sensitivity classes”.

Multiplying the response functions with AOT40 data gives a relative yield loss in percent. This needs to be combined with crop data in order to assess the value of the crop yield lost due to ozone exposure. The response functions indicate a linear relationship between the selected metric of ozone exposure and yield. Further following the ECLAIRE approach we assume that the value of yield loss over the range of possible changes in ozone exposure is also linear. This makes it possible to use the change in economic production directly([27]).

We use European crop production data for 2016 (2017 was not available) from the UN Food and Agriculture Organization (FAO([28])) expressed as Gross Production Value in 000 $int (constant 2004-2006). We converted from US Dollar to 2004-2006 Euro using the PPP exchange rate([29]) (cf. Annex 3) of 0.8416 (average over the three years) and corrected for inflation for the update to €$_{2019}$ using the HICP([30]) (cf. Annex 3) correction factor 1.2755 for EU28 (using the average for 2004-2006). Production value data for each crop at country level was thus obtained for about 120 crop species (cf. Annex 2). Production data summed over all crops at country level are given in Table 13.

([27]) A more detailed assessment, leaving possibility for the value of crops varying in a non-linear fashion with yield over the range of interest, would go first through a calculation of the change in yield and then to valuation.
([28]) http://www.fao.org/faostat/en/#data/QV.
([29]) OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.
([30]) EUROSTAT, https://ec.europa.eu/eurostat/web/hicp/data/database.

Table 13: Crop production 2016 – totals by country (in 000 €$_{2019}$)

ISO:	COUNTRY NAME:	TOTALS BY COUNTRY
AL	Albania	921 556
AT	Austria	1 749 969
BA	Bosnia and Herzegovina	832 890
BE	Belgium	2 513 345
BG	Bulgaria	2 942 961
BY	Belarus	3 579 731
CH	Switzerland	665 030
CY	Cyprus	125 748
CZ	Czechia	2 381 501
DE	Germany	14 682 998
DK	Denmark	2 088 782
EE	Estonia	245 167
ES	Spain	24 041 507
FI	Finland	748 231
FR	France	21 319 604
GB	United Kingdom	6 790 553
GR	Greece	6 878 750
HR	Croatia	1 597 955
HU	Hungary	4 326 048
IE	Ireland	645 786
IS	Iceland	4 211
IT	Italy	21 736 958
LI	Liechtenstein	132
LT	Lithuania	1 439 235
LU	Luxembourg	37 268
LV	Latvia	724 707
MD	Republic of Moldova	1 577 964
ME	Montenegro	53 778
MK	North Macedonia	782 260
MT	Malta	34 178
NL	Netherlands	4 147 199
NO	Norway	332 123
PL	Poland	12 729 648
PT	Portugal	2 664 664
RO	Romania	7 276 036
RS	Serbia	3 610 803
SE	Sweden	1 376 410
SI	Slovenia	283 979
SK	Slovakia	1 180 955
TR	Turkey	32 994 017
Source: FAO, http://www.fao.org/faostat/en/#data/QV/metadata		

With crop data available only at national level (not at grid level), the grid level ozone concentration data was aggregated at national level. Based on this data, the economic value of crop loss was calculated for each crop at the national scale. Crop loss was then aggregated over all crops at country level. In more detail, for each emitter country, the crop loss value in the emitter country and in all other countries, due to a 15 % emission reduction of each ozone precursor (NO_X, NMVOCs) in the emitter country, was calculated. In this way, the crop loss value resulting in the emitter country and the damage resulting in EEA38+UK was calculated.

Dividing finally the production loss value by the quantity in precursor emissions corresponding to 15 % of the emitter country's 2017 emissions yields the damage per tonne of pollutant result.

3.4.2 Forest assessment

The approach applied to forests follows that of crops. Dose-response functions for a limited number of tree species (birch, beech; oak; Norway spruce, Scots pine) are available in ICP Vegetation (2018). They present the relationship between AOT40 exposure and percentage reduction in total and above-ground biomass production. We assume that coniferous trees can be represented by the dose-response function for Norway spruce (0.00154) and deciduous trees by the function for beech and birch (0.00732).

Following the ECLAIRE approach (Holland et al., 2015 a & b), we use forest production data for 2017 and associated data on the gross value added (GVA) of forestry and logging activity, both taken from Eurostat. Gross value added of the forestry industry is available at basic prices in €$_{2017}$ for EU27+UK([31]). We convert these data to €$_{2019}$ through adjustment for inflation (correction factor of 1.03393, cf. HICP data in Annex 3, using the values for EU28).

Table 14: Gross value added of the forestry industry in 2017, at basic prices (in million €, €$_{2019}$)

COUNTRY	ISO	2017
Albania	AL	
Austria	AT	1 108
Bosnia and Herzegovina	BA	521
Belgium	BE	86
Bulgaria	BG	241
Switzerland	CH	341
Cyprus	CY	4
Czechia	CZ	1 241
Germany	DE	3 294
Denmark	DK	306
Estonia	EE	258
Spain	ES	1 029
Finland	FI	3 912
France	FR	3 435
United Kingdom	GB	663
Greece	GR	68
Croatia	HR	202
Hungary	HU	257
Ireland	IE	55
Iceland	IS	

([31]) https://ec.europa.eu/eurostat/databrowser/view/tag00058/default/table?lang=en.

COUNTRY	ISO	2017
Italy	IT	2 231
Liechtenstein	LI	
Lithuania	LT	219
Luxembourg	LU	33
Latvia	LV	406
Montenegro	ME	
North Macedonia	MK	
Malta	MT	0
Netherlands	NL	146
Norway	NO	666
Poland	PL	1 970
Portugal	PT	901
Romania	RO	1 352
Serbia	RS	
Sweden	SE	3 642
Slovenia	SI	276
Slovakia	SK	440
Turkey	TR	
Kosovo	XK	

No damage costs were calculated for the countries missing in Table 14. For the others, needing to divide GVA data between coniferous and deciduous tree species, we use Eurostat data on coniferous and non-coniferous production([32]) under bark in 2017 in 1000 m^3, calculate the ratio of coniferous and non-coniferous production in the sum of the two, and apply this ratio to the total roundwood GVA in 2017, assuming that the GVA for total roundwood production is proportional to the share of the productions of coniferous and non-coniferous species.

Table 15: Coniferous and non-coniferous roundwood production in 2017 (in thousand cubic metres)

COUNTRY	COUNTRY ISO	CONIFEROUS	NON-CONIFEROUS
Albania	AL	:	:
Austria	AT	14 595	3 052
Belgium	BE	:	:
Bulgaria	BG	2 998	3 200
Switzerland	CH	2 924	1 559
Cyprus	CY	14	1
Czechia	CZ	17 735	1 652
Germany	DE	40 895	12 596
Denmark	DK	:	:
Estonia	EE	5 773	4 175
Spain	ES	9 211	8 354
Finland	FI	50 206	13 074
France	FR	19 301	31 899

([32]) **T**he term “roundwood production” is used as a synonymous term for "removals". Data comprise all quantities of wood removed from the forest and other wooded land or other felling site during a certain period of time. It is reported in cubic metres underbark (i.e. excluding bark). Source: https://ec.europa.eu/eurostat/data/database, Roundwood production [TAG00072].

COUNTRY	COUNTRY ISO	CONIFEROUS	NON-CONIFEROUS
United Kingdom	GB	10 289	645
Greece	GR	:	:
Croatia	HR	875	4 433
Hungary	HU	951	4 738
Ireland	IE	3 119	102
Iceland	IS	:	:
Italy	IT	2 500	10 552
Liechtenstein	LI	5.84	2.77
Lithuania	LT	3 747	3 000
Luxembourg	LU	252	181
Latvia	LV	:	:
Montenegro	ME	:	:
North Macedonia	MK	:	:
Malta	MT	0	0
Netherlands	NL	957	2194
Norway	NO	10 863	1 355
Poland	PL	34 947	10 402
Portugal	PT	3 980	9 553
Romania	RO	5 278	9 213
Serbia	RS	:	:
Sweden	SE	65 880	7 000
Slovenia	SI	2 905	1 604
Slovakia	SK	5 518	3 843
Turkey	TR	:	:

For countries for which data are missing in Table 15, the share between coniferous and non-coniferous roundwood production was estimated as indicated in Table 16. No data was found for Malta.

Table 16: Gap filling data and sources for countries missing in the previous table

ASSUMPTION ABOUT RELATIVE SHARES OF CONIFEROUS AND NON-CONIFEROUS IN TOTAL FOREST BIOMASS PRODUCTION			
Country	**Coniferous**	**Non-coniferous**	**Source**
Belgium	0.44	0.56	https://www.cnc-nkc.be/sites/default/files/report/file/national_forest_accounting_plan_-_belgium.pdf
Denmark	0.54	0.46	http://docs.gip-ecofor.org/public/echoes/Echoes-DenmarkReport-February2010.pdf
Greece	0.43	0.57	https://ypef.weebly.com/greece.html
Latvia	0.46	0.54	https://ypef.weebly.com/latvia.html

As was the case for crops, forest data is available only at national level (not at grid level). Grid level ozone data, therefore, were aggregated at national level. Based on the AOT40 data corresponding to a 15 % emission reduction of ozone precursors (NO_X, NMVOCs) in each emitter country and based on the dose response functions, the economic value of forest production loss in the emitter country and in all EU27+UK countries was calculated. Dividing finally the production loss value by the quantity in precursor emissions corresponding to 15 % of the emitter country's 2017 emissions yields the damage per tonne of pollutant (MDC) result.

Note that ozone impacts on forests cannot be calculated for the complete EEA38 +UK country list as is the case for health impacts from fine particulate matter, ozone, toxic metals and organic pollutants, but only for EU27+UK.

3.5 Quantification and valuation of impacts on ecosystems from eutrophication

Ecosystems impacts are also included for the first time in the calculation of MDCs. Although uncertainty in quantifying ecosystems and biodiversity impacts is still high, it was decided to calculate biodiversity effects from exceedances of critical loads for eutrophication in Natura 2000 areas. In this we follow the approach of the ECLAIRE study (Holland et al., 2005 a & b). The reasons why the calculation of ecosystems effects is limited to Natura 2000 sites are the following. A willingness to pay estimate is used for monetisation, from a study assessing response to the UK's biodiversity action plan (Christie et al., 2012). There is a question of whether willingness to pay will be similar when sites are not restored, and Member States are legally responsible for preserving Natura 2000 sites. The assessment here is limited to eutrophication because exceedances of critical loads for acidification are currently much less important than for eutrophication. The rationale is that including impacts from acidification would not have an important impact on overall results. Even though the monetised impacts are low compared to health impacts, the political importance of biodiversity, and the extent of critical loads exceedances for nitrogen, are high.

Impacts accounted for are exceedances of critical loads for eutrophication in Natura 2000 areas from total deposition of nitrogen (dry and wet, oxidised and reduced nitrogen). The reference scenario and the EMEP SRMs representing changes in the deposition of oxidised, reduced and total nitrogen for the precursors NO_X and NH_3([33]) were provided to the Coordination Centre for Effects under the LRTAP Convention, hosted by the Umweltbundesamt (UBA) in Germany, who develops and maintains the critical loads data base. Critical loads represent an estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge. On behalf of the ETC/ATNI the CCE carried out the calculation of the changes in exceedances of critical loads for eutrophication due to changes in oxidised and reduced nitrogen represented by the EMEP SRMs.

The CCE based their calculations on the most recent European critical loads dataset (as described in Hettelingh et al., 2017) and the provided deposition data (including the reference and reduction scenarios). The exceedance was calculated for every available critical load value and later aggregated on the basis of the deposition grids. The delivered results contain information about the share of the receptor area with critical load exceedance within each analysis grid and the total receptor area.

The gridded results were then matched with the localisation of Natura 2000 areas (https://www.eea.europa.eu/data-and-maps/data/natura-11) from which lakes are subtracted (https://www.eea.europa.eu/data-and-maps/data/wise-large-rivers-and-large-lakes) and the surface area of the Natura 2000 areas calculated, for which critical loads are exceeded.

A limitation for the calculation of ecosystems damage is that the EMEP grids are relatively big and Natura 2000 areas sometimes only concern part of the grid. Several assumptions had to be made for matching grid area with critical loads exceedances to Natura 2000 areas in a given grid.

([33]) We also calculated the impact of emission reductions of the other precursors for eutrophication (PM_{10}, NMVOC and SO_2) on the N deposition but these turned out to be negligible and were those excluded from the assessment.

A first assumptions was made when matching information on CL exceedances with Natura 2000 areas per grid: If exceedances exist in a grid and if the grid contains a Natura 2000 area, we assume that the exceedance is situated in the Natura 2000 area (these are sensitive areas). There may then be several cases for which we made the following assumptions:

- The exceedance in a given grid concerns an area of the same size as, or larger than, the Natura 2000 area in the same grid => we calculate the damage for the whole Natura 2000 surface in the grid,
- The exceedance in a given grid concerns an area smaller than the Natura 2000 area in the same grid => we calculate the damage for the area with the exceedance (i.e. for the part of the Natura 2000 that corresponds to the area size with exceedance).

The difference in area exceedances between the reference and the two reduction scenarios yields the damage avoided due to 15 % emission reductions of NO_X and NH_3. Dividing them by the quantity of emissions corresponding to the 15 % reduction yields damage per tonne of emission estimates. The caveat of this approach is that benefits are only accounted for where area goes from exceedance to non-exceedance and that no benefit is attached to other reductions in deposition.

With respect to the monetisation of damage to ecosystems, the current report follows also the approach developed in the ECLAIRE project, by basing valuation on Christie et al. (2012). ECLAIRE (Holland et al., 2015 a & b) compared the results obtained with this willingness to pay study to results obtained with alternative approaches (repair costs and regulatory revealed preference) and found that the different methods generated estimates of a similar order of magnitude. These authors considered the Christie et al. (2012) approach as the most robust, even though it does not account for differences in preference between countries (given that studies similar to Christie et al. have not been performed elsewhere).

Based on this study, ECLAIRE calculated a monetary value of €80 to 240/ha/yr (€$_{2005}$) for protected UK sites at risk. This corresponds to a range in values that reach from €102 to 306/ha/yr (€$_{2019}$)([34]). As was the case in ECLAIRE, we apply the lower value to exceedances of critical loads in protected sites at risk in all countries. No consideration is given to unprotected sites, recognising that the Christie et al. (2012) work was performed against the background of the UK's Biodiversity Action Plan.

Damage costs for ecosystems effects are not included in the externality assessment in Part B of this report, as the MDCs became available too late for inclusion in the calculations.

3.6 Quantification and valuation of impacts on building materials for SO_2 and NO_X

There has been no significant development of the methods and response functions for quantification of materials damage, or the inventories of stock at risk (describing the quantities of sensitive materials such as stone, mortar and metal exposed to the atmosphere) since the previous report (EEA, 2014). The methods for calculating impacts on building materials, and in particular the response functions, are described in ExternE (2005).

Values for materials damage per tonne emission of NO_X and SO_2 are taken from earlier results of the CASES study, using methods described in ExternE (2005) and NEEDS (2008), updated for inflation using the correction factor 1.4427 to convert price in €$_{2000}$ to prices in €$_{2019}$. Results represent damage to utilitarian buildings only and take no account of damage to cultural heritage (monuments and fine buildings).

([34]) Through multiplication with the factor 1.2758 from HICP (Eurostat) for EU28.

4 Deriving marginal damage costs for toxic metals and organic pollutants

4.1 Dispersion and exposure modelling

For metals and organic compounds, a multi-media approach is necessary in order to model dispersion and to quantify exposure, since not only inhalation is relevant for human exposure but also and predominantly for several pollutants, ingestion through consumption of foods and drinks. Modelling heavy metals and organic compounds therefore includes transfers in air, water and soil together with data related to ingestion of food and drinks to account for all exposure routes. Chemistry of these pollutants is, generally, less complex and simpler 'passive' models can be used for the atmospheric air dispersion part than for the 'main' air pollutants. The exposure pathways were illustrated above in Figure 10 and cover inhalation and ingestion of contaminated agricultural produce, fish and water. The model used in the present study is the uniform world model (Rabl, Spadaro & Holland, 2014; Spadaro and Rabl, 2004).

4.2 Quantification of health impacts

Many micropollutants emitted to air by industrial facilities, including activities related to waste management and from combustion of fossil fuels, are toxic to human health. Of major concern are public and occupational exposure to the heavy metals: arsenic (inorganic), cadmium, mercury (through exposure to methyl-mercury), lead, hexavalent chromium and nickel, and the organic compounds: 1,3 butadiene, formaldehyde, benzene, polycyclic aromatic hydrocarbons PAH (particularly, benzo[a]pyrene and several isomers in the family of dibenzopyrenes), and dioxin-like substances (more precisely, polychlorinated dibenzo-p-dioxins, PCDD, and polychlorinated dibenzofurans, PCDF).

Both PAH and dioxins are a mixture of many components each one having a different human toxicity potential. The most studied PAH substance is benzo[a]pyrene (BaP), and the relative potency of other PAH species is stated in terms of the benchmark BaP toxicity using toxic equivalency factors (TEF). The toxicity of the PAH mixture is then assessed as the toxic equivalent quantity (TEQ) of BaP (the underlying assumption being that the health effects of individual components are additive). Similarly, for dioxin compounds, the TEQ dose for the mixture is stated in terms of the most toxic species, namely, 2,3,7,8-tetracholorodipenzo-p-dioxin (TCDD). TEQ factors are source dependent. For municipal solid waste incineration, as an example, TCDD TEQ is roughly 1/60th of the total dioxin mass emitted to air.

Micropollutants enter the human body via inhalation, food and water consumption, and by dermal contact, though not all pathways may be equally toxic, and the intake dose may not be fully absorbed by the body. For hexavalent chromium and nickel, and the organic compounds, excluding dioxins, the inhalation dose is of greatest concern as these substances have been shown to be carcinogenic to humans (IARC 2012a, b). Adverse health effects linked to ingestion dose is the main exposure pathway for inorganic arsenic, cadmium, lead, mercury and dioxins. These substances contribute to premature death, excess cancer risks, and various morbidity outcomes across the exposed population from chronic exposure (Nedellec and Rabl, 2016a, b, c). Table 17 summarises the health outcomes included in this study and those considered in a previous analysis of marginal costs of air pollution in 2014 (EEA, 2014).

Table 17: Health endpoints included in the economic assessment of damage from toxic metals and organic pollutants

POLLUTANT	CURRENT STUDY	PREVIOUS ANALYSIS EEA (2014)
Arsenic (inorganic)*	Non-cancer and Cancer mortality, Chronic bronchitis, IQ loss, diabetes	Cancer (fatal & non-fatal)
Cadmium*	All-cause mortality, Non-fatal cancers, Osteoporosis (hip fractures)	Cancer (fatal & non-fatal) from inhalation only
Chromium (hexavalent, VI)†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
Lead*	All-cause mortality, IQ loss, Anaemia	IQ loss
Mercury*	Cardiovascular mortality, IQ loss	IQ loss
Nickel†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
1,3 Butadiene†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
Benzene†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
Dioxins/Furans (TCDD equiv.)*	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
Formaldehyde†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)
PAH (as BaP equiv.)†	Cancer (fatal & non-fatal)	Cancer (fatal & non-fatal)

Human exposure route: (*) Inhalation and Ingestion; (†) Inhalation only

4.2.1 Calculating marginal damage costs of atmospheric emissions due to inhalation dose

The marginal damage cost (MDC) for pollutant emissions that impact human health via inhalation only are quantified using the set of equations (1) through (4). The health endpoint is cancer (Table 18), and the damage cost is stated as euros € (2019 prices) per kg of pollutant emitted to air.

$$C = \eta \cdot \frac{Q}{10^3 \cdot k} \qquad [1]$$

$$I_{dose} = \frac{C}{10^9} \cdot B_R \cdot Pop \qquad [2]$$

$$Cancers = \frac{URF}{70} \cdot I_{dose} \cdot \frac{1000}{B_R} \qquad [3]$$

$$MDC = 10^6 \cdot \left[\binom{fatal}{cancers} \cdot (VSL + VCM) + \binom{non\,fatal}{cancers} \cdot VC_{NF}\right] \cdot \left(\frac{1 + i_R}{1 + d_R}\right)^{lat_C} \qquad [4]$$

where,

C	Concentration in picogram per meter cubed (units: pg/m^3)
Q	Pollutant emission rate (1 kg per year)
k	Depletion velocity in cm/s (see Table 30)
η	Multiplier (dimensionless)
I_{dose}	Population-total intake dose (pollutant intake in milligrams per day, mg/day)
B_R	Daily mean breathing rate (13.3 m^3/day per person; based on U.S. EPA 2011)
Pop	Population at risk (544 million persons for EU27 plus GB, LI, CH, NO, Balkans; based on Eurostat data)

URF	Inhalation unit risk factor (excess number of cancers assuming a continuous exposure to a concentration of 1 µg/m³ over a 70-year lifetime)

VSL	Value of a statistical life (based on the OECD 2012 VSL after adjustment for inflation and income growth using Eurostat historical information)

VCM	Value of cancer morbidity (0.491 million $€_{2019}$; based on ECHA 2016 after adjustment for inflation and income growth)

VC_{NF}	Value of a non-fatal cancer (0.130 million $€_{2019}$; based on Hofmarcher et al., 2020 and Nedellec and Rabl, 2016a after adjustment for inflation and income growth, based on Eurostat data)

lat_C	Cancer latency period (time elapsed from exposure to disease diagnosis in years)

i_R	Real income growth rate applied during latency period (1 % is assumed)

d_R	Discount rate applied during latency period (4 % is assumed; ECHA 2016)

MDC	Marginal damage cost ($€_{2019}$ per kg of pollutant emitted to air)

Equation (1) is the pollutant spatially averaged air concentration estimate across the impact domain of interest using the assessment methodology detailed in (Rabl, Spadaro & Holland, 2014, Chapter 7). In order to improve the estimate of the population-weighted air concentration for country-specific calculations, equation (2) is modified as indicated in equation (5):

$$I_{dose} = \frac{C}{10^9} \cdot B_R \cdot Pop \cdot \frac{\rho_{eff}}{\rho_{Europe}} \qquad [5]$$

where,

ρ_{Europe}	European population density in persons per squared km (112 pers/km², based on Eurostat data)

ρ_{eff}	Effective population density, that is, the population living within a circular area of radius 1000 km centred in the middle of the country (see Table 30)

η is a calibration factor with a typical range between 1 and 2. For this study, a value of 2 was assumed after comparing (1) for nickel and BaP with data published by two EEA reports (EEA 2019; Guerreiro et al., 2015). The depletion velocity k (Table 30) accounts for atmospheric pollutant removal by dry and wet deposition processes plus chemical transformation (e.g., hexavalent chromium is remarkably acidic). The VCM is the willingness to pay to avoid a cancer occurrence (ECHA 2016). It comprises the valuation in the change of cancer risk plus the impact of illness on the quality of life. A cancer premium was not included, that is to say there is no difference in the valuation of a cancer death compared to a death from any other risk factor. Meanwhile, the non-fatal cancer morbidity (VC_{NF}) reflects the treatment cost, loss in productivity, and the willingness to pay to account for pain and suffering. Deaths are valued using the VSL which is the willingness to pay to save an anonymous death. A non-fatal cancer is an incidence with a survival prospect greater than 5-years. The number of non-fatal cancers is calculated as the product of the 5-year survival probability (%) times the number of excess cancers calculated from dose-response modelling in equation (3). One minus the 5-year survival probability times the number of excess cancers is the cancer mortality. The latency period and other cancer-specific input data are summarised in Table 18.

Table 18: Pollutant-specific input data for inhalation dose modelling

POLLUTANT	CANCER INFORMATION
1,3 butadiene (C_4H_6) Butadiene emissions are related primarily to the production of synthetic rubbers and polymers. Ambient air concentrations of 1,3 Butadiene in Europe have decreased significantly since the 1990s. Urban concentrations are less than 1 ug/m^3, while rural exposures are an order of magnitude lower. Acute exposures to high concentrations of 1,3 butadiene can lead to adverse effects to the central nervous system. IARC has classified 1,3 butadiene as a carcinogen to humans (Group 1), targeting the lymphohematopoietic system (leukaemia and non-Hodgkin's lymphomas).	Type: Lymphohematopoietic Latency period: 20 years 5-year survival chance: 43 % URF: 3.0×10^{-5} cancers per 1 µg/m^3
Benzene (C_6H_6) Benzene is a highly volatile substance. The main pathway of exposure to benzene is inhalation. Benzene emissions to ambient air include cigarette smoke, combustion and evaporation of benzene-containing petrol, petrochemical industries, and combustion processes. Acute health effects include narcosis and skin/eye irritation. Chronic exposure to benzene is associated with haematotoxicity, genotoxicity and carcinogenicity in human. The carcinogenicity of benzene in humans is well established (IARC classification Group 1). Benzene is a multisite carcinogen (leukaemia, liver, mammary gland and nasal cavity).	Type: Acute myeloid leukaemia Latency period: 25 years 5-year survival chance: 9 % URF: 6.0×10^{-6} cancers per 1 µg/m^3
Formaldehyde (CH_2O) The main pathway of exposure to Formaldehyde is inhalation (10 % of dose is from ambient air exposure, while 65 % is due to indoor air exposure, and 25 % from occupational exposure). Cigarette smoking is a major source of exposure. For acute exposures around 0.1 mg/m^3, nasal and throat irritation will occur. The typical ambient air concentration is 1 ug/m^3 in rural areas and 20 ug/m^3 in urban environments. IARC classifies formaldehyde as a substance that is carcinogenic to humans (Group 1) on the basis of epidemiological evidence that suggest a causal association between chronic exposure and leukaemia and nasopharyngeal cancer risk.	Type: Nasopharynx & leukaemia Latency period: 20 years 5-year survival chance: 45 % URF: 6.0×10^{-6} cancers per 1 µg/m^3
PAH (mixture of chemicals) Polycyclic aromatic hydrocarbons is a group of chemicals produced during incomplete combustion of organic matter (e.g., from the burning of fossil fuels and biomass, and vehicle exhaust; tobacco smoke and food preparation are major contributors to PAH exposure). There is considerable variability regarding human toxicity and carcinogenic potency of individual PAH components. A large share of PAHs in ambient air are attached to particles, while a small mass fraction of PAH exist as volatiles, and synergistic and antagonist interactions in the presence of other airborne species are likely to modify the toxicity of PAH mixtures. The most studied PAH substance is Benzo[a]pyrene, which contributes to an elevated chance of onset of lung cancer (IARC classification Group 1) and genotoxic effects.	Inputs for BaP impact assessment Type: Lung Latency period: 13.6 years 5-year survival chance: 14 % URF: 8.7×10^{-2} cancers per 1 µg/m^3 Note: *In this study, it is assumed that the total BaP equivalent dose is 30 % of the PAH mass emitted to air. This value was calculated on the basis of typical literature speciation data weighted by the TEF of each component in the mixture.*

POLLUTANT	CANCER INFORMATION
Hexavalent Chromium (Cr-VI) Emissions of chromium VI occur during industrial processes, including production of textile dyes, paints, corrosion inhibitors, wood preservatives and metal finishing. Smoking releases chromium VI, which is a major concern for indoor air quality. Human exposure to chromium VI is mainly through inhalation and ingestion of contaminated drinking water. Chromium intake from food consumption is primarily in the trivalent state (which is considered an essential nutrient). Information on human health effects comes from industry-based cohort studies. The strongest evidence of adverse health effects following exposure to chromium VI compounds concern excess lung cancers (IARC classification Group 1).	Type: Lung Latency period: 13.6 years 5-year survival chance: 14 % URF: 4.0×10^{-2} cancers per 1 μg/m³ Note: *In this study, we have assumed that 20 % of the total chromium emitted to air is in the hexavalent state (same proportion as in the EEA 2014 impact assessment report).*
Nickel Nickel is ubiquitous in nature, being emitted into the environment naturally and as a consequence of anthropogenic activity. Urban and rural air concentrations across Europe in 2017 were below 5 ng/m³ (EEA 2019), although exposures in heavily industrialised areas were several-fold higher. Human daily uptake via respiration represents only a tiny share (<0.25 %). Allergic skin reaction is a common side effects following exposure to nickel compounds. IARC classifies nickel compounds as carcinogenic to humans (classification Group 1). Epidemiological evidence has identified excess lung and nasal cancers.	Type: Lung & nasal Latency period: 18.3 years 5-year survival chance: 20 % URF: 3.8×10^{-4} cancers per 1 μg/m³

Key input data sources: Allemani et al. (2018); European Cancer Information System (ECIS) database (https://ecis.jrc.ec.europa.eu); California Office of Environmental Health Hazard Assessment (OEHHA), https://oehha.ca.gov/chemicals); IARC (2012a,b); Nadler et al. (2014); US EPA Integrated risk information system (IRIS) database (https://www.epa.gov/iris); WHO (2000)

4.2.2 Calculating marginal damage costs of atmospheric emissions of arsenic, cadmium, lead and mercury

The same health and economic impact assessment methodology developed in Nedellec and Rabl (2016a,b,c) was applied in this study, however, modelling assumptions were revised and input data were updated to reflect typical European demographics and illness-specific statistics on incidence and treatment costs, rather than relying on French population and other national data. The marginal damage cost (MDC) is calculated with equation (6):

$$MDC = S_{ERF} \cdot iF \cdot \frac{Incidence}{cost} \cdot f_{thr} \qquad [6]$$

where,

S_{ERF}	Exposure-response function slope for a particular pollutant-outcome pair, assuming a linear association (unit: annual excess cases per mg intake per year)
iF	Intake fraction, that is, the pollutant intake by inhalation and ingestion in mg for a 1 kg pollutant emission to ambient air (mg/kg_{air}, or parts per million, ppm)
f_{thr}	Fraction of exposure increment above the maximum "safe" intake guideline established for the protection of human health (dimensionless)
Incidence cost	Cost per case of illness or death (€$_{2019}$ per case)

Input data for each of the four parameters in equation (6) are summarised in Table 19. Although there is some evidence in the epidemiological literature for a non-linearity in the population response to exposures to heavy metals via ingestion (e.g., arsenic from drinking water), an average slope for the exposure-response function (SERF) was assumed in this study. Thus, over the range of exposures considered, the risk change is proportional to the incremental exposure. For carcinogens, the ERF is assumed linear, so the incremental risk is independent of the background concentration. Future incidence costs are adjusted for income growth (annual rate of 1 %), and discounted to present value (year 2019) assuming a discount rate of 4 % applied over a 10-year lag period, except for cancers in which case the costs of fatal and non-fatal events are evaluated considering the appropriate latency delay between exposure and health outcome manifestation. For neurotoxic impacts, the cost per IQ point lost is the time series of the total future income losses discounted to the time of birth.

The European population pollutant-specific intake fraction was calculated using a multimedia impact pathway analysis based on the implementation of the *uniform world model* discussed in (Rabl, Spadaro & Holland, 2014, Chapter 7) and applied in (Spadaro and Rabl, 2004). The total intake dose comprises two pathways: direct human exposure to contaminated air (inhalation), and indirect contact from consumption of contaminated water and food (ingestion). The pollutant transport in water and soil was modelled using the methodology developed by the U.S. EPA (2005). The environmental fate analysis begins with the pollutant being emitted to air at a particular physical location, followed by atmospheric dispersion, removal by dry and wet deposition onto land and water surfaces, accumulation and transport in water and soil compartments, uptake by plants and animals, and finally dietary intake of contaminated agricultural and animal products, including fruits and vegetables, meats and milk by-products, and consumption of tap water. Bioavailability may extend for decades into the future until the pollutant is either fixed to soils or ultimately settles in waterbed sediment. Although atmospheric concentrations vary considerably with distance from the source, the inhalation dose contribution is typically only a few percent of the population-total pollutant intake (Spadaro and Rabl, 2004). To adjust for the heterogeneous distribution of the inhalation dose due to concentration gradients and the geographical population density distribution an adjustment factor (η) was applied in equation (1). On the other hand, because of food trade and transportation to markets located far from the production site, the food concentration tends to be more uniformly distributed over space. The uniform world model is predicated on the assumption that the representative dietary intake is fairly uniformly distributed across consumers.

The unit cost of illness accounts for treatment cost, productivity loss, and the impact of illness on quality of life due to pain and suffering. Mortality is monetised using the value of a statistical life when counting cancer deaths, while changes in life expectancy or years of life lost (YOLL) are costed using the value of a statistical life year lost (VOLY). Life expectancy changes are calculated using life table methods (Miller and Hurley, 2003).

Table 19: Input data for damage cost calculations of arsenic, cadmium, lead and mercury

Pollutant	Health outcome	S_{ERF} cases per mg intake	Incidence cost €$_{2019}$ per case
Arsenic (inorganic) $iF = 175\ ppm$ $f_{thr} = 80\ \%$	Non-cancer mortality (YOLL†)	2.36×10^{-4}	87,300
	Cancer mortality		
	• Bladder–fatal	1.82×10^{-6}	2.36 million
	• Bladder–non-fatal	2.57×10^{-6}	62,400
	• Kidney–fatal	2.32×10^{-7}	1.92 million
	• Kidney–non-fatal	2.51×10^{-7}	50,900
	• Lung–fatal	4.43×10^{-6}	3.29 million
	• Lung–non-fatal	5.55×10^{-7}	87,200
	• Skin–fatal	5.49×10^{-7}	2.55 million
	• Skin–non-fatal	1.34×10^{-6}	67,500
	Chronic bronchitis	1.52×10^{-5}	58,800
	IQ points lost	4.34×10^{-4}	16,100
	Diabetes	1.52×10^{-4}	192,000
Cadmium $iF = 362\ ppm$ $f_{thr} = 98\ \%$	Mortality (YOLL†)	5.88×10^{-3}	87,300
	Non-fatal cancers	2.38×10^{-5}	72,300
	Non-fatal hip fractures	6.48×10^{-5}	91,300
Lead $iF = 255\ ppm$ $f_{thr} = 1$	Mortality (YOLL†)	1.21×10^{-3}	87,300
	IQ points lost	1.37×10^{-3}	16,100
	Anaemia	7.24×10^{-7}	324,000

Mercury $f_{thr} = 44\ \%$

The atmospheric residence time of mercury is long enough for the pollutant to be globally dispersed. Hence, the burden is calculated using a different methodology than that used for the other heavy metals in this table. The mercury damage cost is calculated using the expression (see Rabl, Spadaro & Holland, 2014, Chapter 8):

$$\begin{matrix} MDC\ of \\ mercury \end{matrix} = T \cdot \bar{b} \cdot \begin{matrix} World \\ Pop \end{matrix} \cdot S_{ERF} \cdot \begin{matrix} Incidence \\ cost \end{matrix} \cdot f_{thr}$$

T is the comprehensive transfer factor (4.0×10^{-7} µg of methyl mercury (MeHg) intake per day for 1 kg/year of mercury released to air), and the world population is 7.54×10^{9} persons. The other variables are dependent on the outcome of interest.

Health outcome	$\bar{b}$ global birth rate weighted by GDP	S_{ERF} cases per µg/day MeHg intake	Incidence cost €$_{2019}$ per case
IQ points lost	0.002325	3.62×10^{-2}	16,100
Mortality (YOLL†)	0.003266	3.99×10^{-2}	87,300

† YOLL – Years of Life Lost are calculated using life table methods (see Miller and Hurley, 2003).

4.2.3 Calculating marginal damage costs of atmospheric emissions of dioxins and furans

Dioxins arise as combustion by-products formed in the presence of chlorine and organic matter, for example, during steel and pesticide production, and released during waste incineration. These compounds are highly toxic, contributing to an increase in cancer risk in animals and endocrine disruption, and persist in the environment for a very long time. Acute human exposure at high doses has been linked to skin disease (chloracne). Exposure is primarily through dietary consumption, which usually accounts in excess of 96 % of the total intake dose. The damage cost (health endpoint is liver cancer) per kg of dioxins/furans (expressed as equivalent TCDD dose) is calculated with equations (7) through (9):

$$I_{dose} = \frac{\omega}{10^{12} \cdot k} \cdot B_R \cdot Pop \qquad [7]$$

$$Cancers = \frac{SF}{70 \cdot kg_{BW}} \cdot I_{dose} \qquad [8]$$

$$MDC = 10^6 \cdot \left[\binom{fatal}{cancers} \cdot (VSL + VCM) + \binom{non\,fatal}{cancers} \cdot VC_{NF} \right] \cdot \left(\frac{1 + i_R}{1 + d_R} \right)^{lat_C} \qquad [9]$$

where,

ω	Total to inhalation intake dose ratio
I_{dose}	Population-total intake dose, including inhalation and ingestion (mg/day)
SF	Oral slope factor, that is, number of excess lifetime cancers for a continuous daily dose of 1 mg per kg of body weight over an exposure period of 70 years (2 × 10^5 excess lifetime cancers per mg/(day·kg_{BW}) based on Searl 2005)
kg_{BW}	Body weight in kg (64 kg is assumed in this study)

The value of parameter ω varies widely (easily by a factor of two) on the basis of regional dietary habits, time trends, and proximity to the source of emissions. In this study, a value of 37.3 was selected based on information compiled in U.S. EPA (2003) for studies carried out in four European countries, including Germany, Spain, the Netherland, and the UK. An earlier U.S. EPA (1994) report had estimated ω = 54.1 for the U.S. population (inhalation contribution was 1.8 % of the total dose), while a report by Health Canada (1990) indicated ω = 60 for the Canadian population. The Government of Japan (2003) estimated ω = 43 for the Japanese population. For the cancer latency period a value of 10.8 years was chosen, while the 5-year survival probability is 13 % (based on data in Nadler ed al., 2014; Allemani et al., 2018).

5 Choosing marginal damage costs for greenhouse gases

5.1 Marginal abatement costs as a proxy for carbon valuation

There are two approaches to deriving costs factors for greenhouse gas emissions which both have their uncertainties:

- Quantify impacts associated with climate change following an IPA approach for future scenarios. Such estimates exist, from various authors but are prone to significant uncertainty, reflecting differences in possible scenarios of the future (economic growth, population growth, climate sensitivity, etc.) and the range of impacts considered. The largest potential impacts also tend to be associated with the most uncertain aspects, for example relating to the possibility of conflict and extreme climatic effects.
- Direct monetisation of emissions using the marginal costs of greenhouse gas abatement. The logic for this approach is in part based on the assumption that climate damage will be prevented by legislation to curb emissions. Under this assumption, an increase in emission from one source would need to be countered by a reduction in another to the extent that overall emissions would remain at the legislated level and hence there would be no net impact from these changes on climate: the only change in cost would then relate to the costs of controlling emissions. Under current trajectories for emissions, the assumption of validity of the marginal costs approach is clearly questionable. Values based on marginal abatement costs are also sensitive to assumptions in the scenarios from which they are derived.

However, with the Paris Agreement in place, it can be argued that increased emission from one source, needs to be balanced by reduced emission elsewhere. On this basis, the impact of an increase in emission from one facility will not be experienced in terms of climate related effects but will be experienced through an increase in the costs of compliance with the provisions of the Paris Agreement. This makes the use of marginal mitigation costs a logical route for valuation.

Climate change costs in the DG MOVE Handbook on the External Costs of Transport (EC, 2019) are based on the avoidance cost approach. Avoidance costs here are assessed as the costs necessary to reach the objective of the Paris agreement, i.e. to limit the global temperature rise to 1.5 – 2 °C. This implies a target of 80-95 % reduction in CO_2 emissions by 2050 compared to 1990 levels. Based on a literature review the study concludes on the avoidance costs presented in Table 33.

5.2 Valuation of impacts including greenhouse gases other than CO_2

The valuation of greenhouse gases other than CO_2 is performed in two steps. The first converts pollutant emission to CO_2-equivalent using appropriate global warming potentials, and the second applies the values described above per tonne emission of CO_2. Table 20 provides data on Global Warming Potentials (GWP) and Global Temperature change Potentials (GTP) for the pollutants of interest (IPCC, 2014).

Table 20: GWP and GTP for CO_2, CH_4 and N_2O.

	GWP		GTP	
Pollutant	**Cumulative forcing over 20 years**	**Cumulative forcing over 100 years**	**Temperature change after 20 years**	**Temperature change after 100 years**
CO_2	1	1	1	1
CH_4	84	28	67	4
N_2O	264	265	277	234

The European Commission's Knowledge for policy Glossary defines the GTP as follows. Compared to the GWP, the GTP goes one step further down the cause-effect chain and is defined as the change in global mean surface temperature at a chosen point in time in response to an emission pulse - relative to that of CO_2. Whereas GWP is integrated in time, GTP is an end-point metric that is based on temperature change for a selected year, t. Like GWP, the GTP values can be used for weighting the emissions to obtain CO_2 equivalents.

Given the objectives of the Paris Agreement are focused on the medium term, around the middle of the current century, and are expressed relative to global average temperature change, the use of the 20-year GTPs is appropriate.

6 Set of updated marginal damage costs

If not explicitly stated otherwise, damage costs presented hereafter reflect the damage over the receptor region EEA38+UK resulting from one tonne of pollutant emitted in a given emitter country. Damage costs incurred only in the emitter country are presented in Annex 4. In this chapter, damage costs for the core health impacts are presented. For sensitivity assessments cf. Annex 5.

The country-specific marginal damage costs presented below can vary significantly among emitting countries. Explanations for this include the following:

- Differences in the density of exposed receptors (population, crops, forests…) across European countries,
- Differences in pollutant dispersion patterns and in atmospheric chemistry (such as chemical transformation rates), depending upon the location of emissions,
- Differences in location of the countries, with emissions in countries with extensive coastlines partly dispersing out to sea.

For some pollutants the site of release is relatively unimportant in determining the magnitude of damage costs. This is the case for the global pollutant CO_2 and also for pollutants for which the ingestion route is relatively more important than the inhalation route.

6.1 Marginal damage costs for the major air pollutants

Table 21 shows the health damage associated to a tonne of emission from the precursor pollutants to fine particulate matter and ozone that are indicated in the columns. The emitter region also includes 5 sea regions, which are not used in the calculation of externalities in Part B.

These marginal damaged costs are calculated based on EMEP SRMs.

Note that in this table, damage for EEA38+UK countries covers damage perceived in the emitter country and damage over the other EEA38+UK countries due to transboundary effects. For countries not part of the EEA38+UK region, such as Russia, damage presented here only shows damage due to transboundary air pollution perceived across the EEA38+UK region, but not the damage perceived within the emitter country. This explains the higher numbers for this country in Table 50.

Table 21: Marginal damage costs of major air pollutants – impacts on health from fine particulate matter and ozone

		Damage over EEA38 + UK (*) - €$_{2019}$/tonne of pollutant emissions for $PM_{2.5}$ and O_3 precursors											
		NO_X (VOLY)	NO_X (VSL)	$PM_{2.5}$ (VOLY)	$PM_{2.5}$ (VSL)	PM_{10} (VOLY)	PM_{10} (VSL)	SO_2 (VOLY)	SO_2 (VSL)	VOC (VOLY)	VOC (VSL)	NH_3 (VOLY)	NH_3 (VSL)
AL	**Albania**	9 268	22 962	66 949	163 868	43 474	106 408	19 436	50 678	808	2 129	9 456	24 028
AM	**Armenia**	1 688	2 757	4 013	6 596	2 606	4 283	2 979	5 099	257	444	594	998
AT	**Austria**	16 187	53 751	69 268	227 195	44 979	147 529	34 115	112 608	2 528	8 094	22 838	75 210
AZ	**Azerbaijan**	297	530	336	622	218	404	1 286	2 441	95	184	89	170
BA	**Bosnia and Herzegovina**	9 613	29 943	36 312	115 067	23 579	74 719	14 007	44 712	973	2 952	17 505	55 647
BE	**Belgium**	13 143	43 697	159 127	512 037	103 329	332 491	48 642	158 596	2 534	7 784	49 903	162 757
BG	**Bulgaria**	8 176	24 849	82 132	309 647	53 333	201 070	14 813	46 067	951	2 735	16 472	57 968
BY	**Belarus**	1 215	3 479	3 112	9 760	2 021	6 338	3 778	11 176	283	741	1 782	5 631
CH	**Switzerland**	30 633	96 937	101 182	306 655	65 703	199 126	74 294	231 497	3 882	12 056	20 629	64 689
CY	**Cyprus**	3 841	6 803	22 448	48 390	14 576	31 422	10 153	17 838	524	851	6 621	14 690
CZ	**Czechia**	10 470	33 768	88 092	282 451	57 202	183 409	21 809	70 558	2 569	7 994	41 050	131 597
DE	**Germany**	13 211	44 736	75 797	266 647	49 219	173 147	33 985	115 821	1 809	5 540	26 428	90 380
DK	**Denmark**	4 900	15 790	39 174	124 113	25 437	80 593	16 926	53 926	495	1 429	8 030	25 429
EE	**Estonia**	811	2 482	7 941	26 735	5 157	17 360	2 105	6 652	172	478	3 702	12 426
ES	**Spain**	5 448	17 013	63 795	201 671	41 425	130 955	22 484	71 851	1 184	3 496	7 116	22 620
FI	**Finland**	975	2 998	20 346	65 365	13 212	42 445	5 286	16 997	210	603	4 185	13 494
FR	**France**	12 947	41 221	65 395	208 191	42 464	135 189	34 225	110 898	1 981	6 034	13 167	42 289
GB	**United Kingdom**	9 628	30 821	86 815	268 250	56 373	174 188	37 445	117 145	1 552	4 614	32 816	102 432
GE	**Georgia**	824	1 448	1 709	3 099	1 110	2 012	2 338	4 307	253	472	419	786
GR	**Greece**	1 973	5 045	41 820	145 705	27 156	94 614	11 773	36 422	1 189	3 396	11 940	40 964
HR	**Croatia**	12 633	41 877	54 289	192 306	35 252	124 874	22 942	78 640	1 624	5 119	17 409	59 766
HU	**Hungary**	12 384	39 822	77 977	261 548	50 635	169 836	23 636	76 953	1 539	4 714	22 556	74 032
IE	**Ireland**	7 907	23 601	19 612	50 219	12 735	32 609	26 740	77 829	595	1 739	5 115	15 412
IT	**Italy**	19 257	68 375	165 372	592 650	107 384	384 838	26 774	93 561	4 568	15 406	25 980	92 536

		Damage over EEA38 + UK (*) - €$_{2019}$/tonne of pollutant emissions for $PM_{2.5}$ and O_3 precursors											
		NO_X (VOLY)	NO_X (VSL)	$PM_{2.5}$ (VOLY)	$PM_{2.5}$ (VSL)	PM_{10} (VOLY)	PM_{10} (VSL)	SO_2 (VOLY)	SO_2 (VSL)	VOC (VOLY)	VOC (VSL)	NH_3 (VOLY)	NH_3 (VSL)
LT	**Lithuania**	2 125	6 807	17 633	62 144	11 450	40 353	7 575	25 328	224	609	5 888	20 409
LU	**Luxembourg**	16 366	54 384	80 297	247 472	52 141	160 696	45 317	149 590	1 478	4 477	25 404	82 699
LV	**Latvia**	1 399	4 505	26 831	98 627	17 423	64 043	8 096	28 519	224	627	4 742	16 887
MD	**Moldova**	3 738	10 628	10 733	33 341	6 969	21 650	9 970	28 561	532	1 463	5 018	14 927
ME	**Montenegro**	5 596	16 157	13 370	40 341	8 682	26 195	9 550	29 148	674	1 896	11 058	33 796
MK	**North Macedonia**	5 232	14 931	55 022	152 981	35 729	99 338	13 094	37 938	1 191	3 252	17 857	50 921
MT	**Malta**	66	998	52 496	150 194	34 088	97 529	5 401	16 703	848	2 433	30 502	87 032
NL	**Netherlands**	14 428	48 586	95 143	294 599	61 781	191 298	41 868	135 101	1 935	5 918	34 773	112 094
NO	**Norway**	1 616	4 852	20 096	56 741	13 049	36 845	5 082	15 339	377	1 072	3 332	9 673
PL	**Poland**	4 241	13 181	42 634	129 265	27 684	83 938	13 572	41 882	1 026	2 958	22 895	70 230
PT	**Portugal**	3 660	11 986	67 543	234 012	43 859	151 956	10 506	35 235	709	2 128	7 339	25 279
RO	**Romania**	10 147	32 035	64 723	217 324	42 028	141 119	19 532	61 292	1 246	3 685	14 949	48 566
RS	**Serbia**	7 366	22 994	57 921	185 863	37 611	120 690	15 725	48 616	1 040	3 043	25 220	81 845
RU	**Russian Federation**	247	598	462	1 256	300	815	751	1 964	152	382	215	599
SE	**Sweden**	2 045	6 307	16 854	53 538	10 944	34 765	6 298	20 025	312	899	5 456	17 332
SI	**Slovenia**	18 908	63 747	112 372	373 078	72 969	242 259	27 745	93 029	3 050	9 934	23 949	80 286
SK	**Slovakia**	10 327	32 141	76 992	233 434	49 995	151 580	19 286	59 894	1 862	5 657	33 896	104 013
TR	**Turkey**	6 628	11 089	61 497	99 897	39 933	64 868	15 484	25 939	1 139	1 884	15 691	25 728
ATL	**NE Atlantic Ocean**	2 241	6 787	9 945	31 273	6 458	20 307	5 900	18 762	887	2 707		
BAS	**Baltic Sea**	2 807	8 959	21 233	68 505	13 788	44 484	7 527	24 155	1 200	3 505		
BLS	**Black Sea**	6 370	11 751	59 595	109 859	38 698	71 337	17 688	32 646	1 706	3 220		
MED	**Mediterranean Sea**	3 121	9 277	44 078	112 472	28 622	73 034	10 945	31 509	2 360	6 423		
NOS	**North Sea**	9 430	30 546	66 407	209 322	43 121	135 923	19 137	61 269	3 688	11 289		
(*) Missing emitter countries: Iceland, Liechtenstein, Kosovo													

Table 22 indicates the health damage associated to a tonne of emission from the precursor pollutant NO_X to nitrogen dioxide. These marginal damage costs are derived based on calculated SHERPA SRRs.

Table 22: Marginal damage costs of major air pollutants – impacts on health from nitrogen dioxide

Damage over EEA38 + UK (*) - €$_{2019}$/tonne of pollutant emissions for the NO_2 precursor NO_X			
		NO_X (VOLY)	**NO_X (VSL)**
AT	**Austria**	5 489	21 037
BE	**Belgium**	6 194	23 567
BG	**Bulgaria**	3 212	14 273
CH	**Switzerland**	12 696	45 006
CY	**Cyprus**	3 023	7 947
CZ	**Czechia**	3 916	14 679
DE	**Germany**	6 886	29 526
DK	**Denmark**	2 499	9 286
EE	**Estonia**	1 078	4 296
ES	**Spain**	6 452	24 376
FI	**Finland**	2 962	11 296
FR	**France**	5 771	21 650
GB	**United Kingdom**	6 797	24 650
GR	**Greece**	5 044	21 290
HR	**Croatia**	3 928	16 943
HU	**Hungary**	7 059	28 094
IE	**Ireland**	2 397	5 973
IT	**Italy**	8 964	39 045
LT	**Lithuania**	2 733	11 227
LU	**Luxembourg**	5 101	17 133
LV	**Latvia**	3 340	14 358
ME	**Montenegro**	2 143	7 341
MT	**Malta**	1 783	5 992
NL	**Netherlands**	8 620	30 728
NO	**Norway**	3 616	11 746
PL	**Poland**	3 837	13 351
PT	**Portugal**	4 524	18 794
RO	**Romania**	4 922	19 594
SE	**Sweden**	3 176	12 056
SI	**Slovenia**	5 052	19 660
SK	**Slovakia**	5 113	17 254
TR	**Turkey**	12 592	22 207
(*) Missing emitter countries: Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo.			

The fact that the marginal damage cost from indirect exposure to NO_X through formation of secondary species (O_3, secondary $PM_{2.5}$, Table 21) exceeds the marginal damage cost from direct exposure to NO_X emissions (reflected in the contribution to NO_2 health impacts, Table 22) appears plausible. This occurs because beyond some distance from the source the secondary pollutant concentration profile exceeds that of the primary pollutant, and hence the size of the population at risk is larger. The discrepancy is less noticeable when the regional population density is low, e.g., in the case of Scandinavian countries. For the Iberian countries, cost estimate differences are also small because the pollution spreads over water after exiting the peninsula. On the other hand, the indirect damage cost rises significantly in the case of Luxembourg because the transboundary transport of secondary pollutants greatly impacts people living in the surrounding countries (France, Belgium and Germany, the Netherlands).

Table 23 shows the crop damage associated to a tonne of emission from the precursor pollutants to ozone (measured as AOT40) indicated in the columns. The emitter region also includes 5 sea regions. They are not used in the calculation of externalities in Part B.

Table 23: Marginal damage costs of major air pollutants – impacts on crops

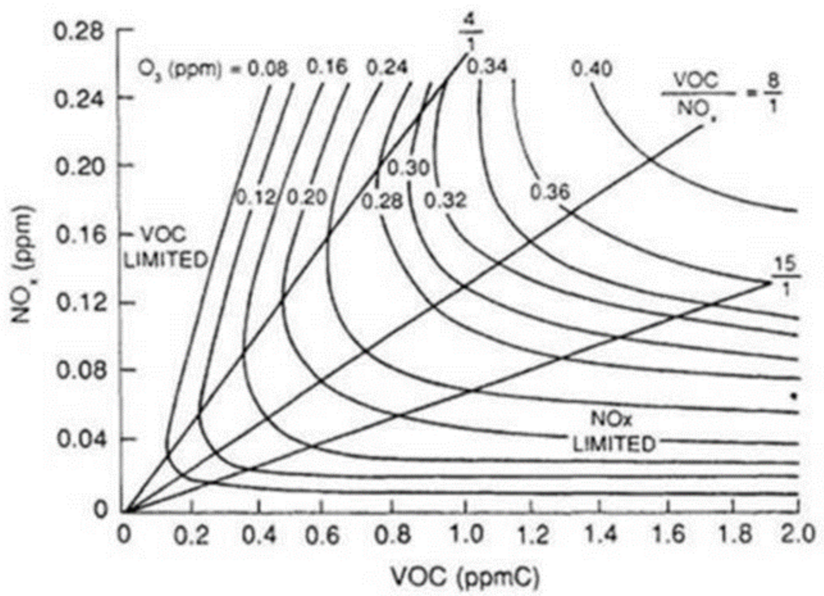
Emitter country		Damage over EEA38 + UK (*) - €$_{2019}$/tonne of pollutant emissions for O_3 precursors	
		NO_X	NMVOC
AL	**Albania**	392	42
AT	**Austria**	485	94
BA	**Bosnia and Herzegovina**	502	48
BE	**Belgium**	12	121
BG	**Bulgaria**	398	47
CH	**Switzerland**	530	160
CY	**Cyprus**	273	38
CZ	**Czechia**	337	108
DE	**Germany**	162	132
DK	**Denmark**	56	35
EE	**Estonia**	75	22
ES	**Spain**	533	91
FI	**Finland**	78	22
FR	**France**	389	122
GB	**United Kingdom**	30	72
GR	**Greece**	217	79
HR	**Croatia**	593	80
HU	**Hungary**	495	61
IE	**Ireland**	93	25
IS	**Iceland**	65	8
IT	**Italy**	419	169
LT	**Lithuania**	127	29
LU	**Luxembourg**	207	117
LV	**Latvia**	95	28
ME	**Montenegro**	350	42
MK	**North Macedonia**	366	41
MT	**Malta**	51	37
NL	**Netherlands**	-53	94
NO	**Norway**	108	30
PL	**Poland**	142	85
PT	**Portugal**	422	62
RO	**Romania**	360	45
RS	**Serbia**	344	73
SE	**Sweden**	102	22
SI	**Slovenia**	521	132
SK	**Slovakia**	400	73
TR	**Turkey**	414	50

Emitter country		Damage over EEA38 + UK (*) - €2019/tonne of pollutant emissions for O_3 precursors	
		NO_X	NMVOC
ATL	**NE Atlantic Ocean**	99	37
BAS	**Baltic Sea**	52	78
BLS	**Black Sea**	272	67
NOS	**North Sea**	26	142
MED	**Mediterranean Sea**	182	124
(*) Missing emitter countries: Liechtenstein, North Macedonia, Kosovo			

In some countries NO_X emission reductions increase ozone levels and thus damage from ozone (e.g. the Netherlands in the previous table, the Netherlands and Belgium in the next table. This can be explained by the titration effect. In the ozone cycle, the so-called NO_X titration effect consists of the removal of O_3 through reaction with nitrogen monoxide (NO), it occurs during night-time in the immediate vicinity of large nitrogen oxides sources. If NO_X ambient concentrations decrease in those areas, the titration process can be neutralised, and ozone concentrations can increase despite NO_X emissions being reduced.

Figure 11 shows the theoretical formation of O_3 as a function of NO_X and VOCs and of the ratio VOC/NO_X.

Figure 11: The theoretical formation of O_3 as a function of NO_X and NMVOCs and of the ratio VOC/NO_X (Source: NRC book "Rethinking the Ozone problem in urban and regional air pollution")



In countries such as Belgium and the Netherlands, the population density implies high NO_X concentrations over a large area of the territory. Also, there are less biogenic VOC emissions than for example in the Mediterranean countries. Therefore, the situation is rather one of VOC limitation. In such a regime (upper left area of the figure), a reduction in NO_X emissions will lead to an increase in O_3 (of which the concentrations are presented by the isopleths). On the contrary, even in a NO_X limited regime, a reduction in VOC emissions will not lead to an increase in ozone.

Table 24 shows the forest damage associated to a tonne of emission from the precursor pollutants to ozone (measured as AOT40) indicated in the columns.

Table 24: Marginal damage costs of major air pollutants – impacts on forests

Emitter country		Damage over EU27 + UK - €$_{2019}$/tonne of pollutant emissions for O_3 precursors	
		NO_X	NMVOC
AT	Austria	172	38
BE	Belgium	-5	48
BG	Bulgaria	94	9
CY	Cyprus	1	0
CZ	Czechia	112	36
DE	Germany	49	48
DK	Denmark	39	19
EE	Estonia	48	8
ES	Spain	128	24
FI	Finland	57	9
FR	France	186	53
GB	United Kingdom	19	36
GR	Greece	17	5
HR	Croatia	241	32
HU	Hungary	154	20
IE	Ireland	65	15
IT	Italy	134	67
LT	Lithuania	66	9
LU	Luxembourg	52	46
LV	Latvia	64	10
MT	Malta	15	16
NL	Netherlands	-26	39
PL	Poland	46	27
PT	Portugal	179	31
RO	Romania	173	18
SE	Sweden	81	11
SI	Slovenia	223	61
SK	Slovakia	142	23

Table 25 shows the building materials damage associated to a tonne of emission from the acidifying pollutants indicated in the columns.

Table 25: Marginal damage costs of major air pollutants – impacts on utilitarian buildings

Emitter country		Damage over EU27+UK - €2019/tonne of pollutant emission	
		NO_X	SO_2
EU27 (*)		102	373
AT	Austria	208	516
BE	Belgium	119	679
BG	Bulgaria	131	301
CY	Cyprus	102	373
CZ	Czechia	183	719
DE	Germany	138	636
DK	Denmark	102	348
EE	Estonia	45	137
ES	Spain	26	64
FI	Finland	29	107
FR	France	103	354
GB	United Kingdom	62	269
GR	Greece	71	128
HR	Croatia	102	373
HU	Hungary	256	681
IE	Ireland	48	105
IT	Italy	82	193
LT	Lithuania	107	270
LU	Luxembourg	150	629
LV	Latvia	67	180
MT	Malta	102	373
NL	Netherlands	120	652
PL	Poland	191	716
PT	Portugal	19	49
RO	Romania	198	539
SE	Sweden	49	162
SI	Slovenia	185	480
SK	Slovakia	235	677
(*) Defined as including UK and excluding Croatia. Cyprus, Croatia, Malta set at EU27 average.			

Table 26 shows the ecosystems damage associated to a tonne of emission from the precursor pollutants to eutrophication indicated in the columns. Estonia shows a comparatively high marginal damage cost for NH_3. This is almost entirely due to damage within Estonia (cf. Table 54). This result is due to two grid cells for which the critical load value lies just between the deposition levels in the reference and ammonia reduction scenarios. Moreover, the Natura 2000 areas in these grids cover most of the grid area. This implies that in these two cases, only limited changes in deposition (between the reference and the ammonia reduction scenarios) have a large impact as almost the whole grid area is counted as going from exceedance to non-exceedance of the critical load level. In most other cases where exceedance changes to non-exceedance of critical loads between two scenarios, the Natura 2000 areas cover a smaller part of the respective grids.

The rather small damage estimates for natural ecosystem results appear a weak reflection of willingness to pay given estimated levels of exceedance of the critical load for nitrogen, and the effects that this could have on European ecosystems.

Table 26: Marginal damage costs of major air pollutants – impacts on ecosystems

Country	Country ISO	Damage over EEA38+UK (*) in $€_{2019}$/t – precursors to eutrophication	
		NH_3	NOx
Albania	**AL**	77	45
Austria	**AT**	403	128
Bosnia and Herzegovina	**BA**	52	28
Belgium	**BE**	44	37
Bulgaria	**BG**	138	25
Belarus	**BY**	52	30
Switzerland	**CH**	315	246
Cyprus	**CY**	0	0
Czechia	**CZ**	102	39
Germany	**DE**	168	77
Denmark	**DK**	95	47
Estonia	**EE**	2 594	170
Spain	**ES**	186	59
Finland	**FI**	155	62
France	**FR**	299	106
United Kingdom	**GB**	174	51
Greece	**GR**	165	30
Croatia	**HR**	148	77
Hungary	**HU**	284	100
Ireland	**IE**	220	75
Iceland	**IS**	0	13
Italy	**IT**	490	150
Lithuania	**LT**	151	65
Luxembourg	**LU**	77	31
Latvia	**LV**	213	87
Republic of Moldova	**MD**	24	14
North Macedonia	**MK**	42	47
Malta	**MT**	0	0
Netherlands	**NL**	62	45
Norway	**NO**	11	22
Poland	**PL**	376	100
Portugal	**PT**	82	31
Romania	**RO**	96	52
Serbia	**RS**	53	23
Sweden	**SE**	89	30
Slovenia	**SI**	115	70
Slovakia	**SK**	296	134

(*) Missing emitter countries: Liechtenstein, Turkey, Kosovo, Montenegro. Additional emitter countries: Belarus, Republic of Moldova.

Note that MDCs for ecosystems effects are not included in Table 27 as they are not used in the calculation of externalities in Part B of the report (they were not available at the time of calculating the externalities).

Table 27 aggregates damage costs of the main air pollutants per precursor pollutant, including damage costs for health, crops and forests and building materials. This includes, thus, damage to health from precursors of $PM_{2.5}$, O_3 and NO_2, impacts on crops and forests from precursors of O_3, and impacts on building materials due to changes in emissions of SO_2 and NO_X. Marginal damage costs for ecosystems are not included in Table 27 but are included in Table 75 in Annex 9.

Note that in EMEP SRMs the precursor PM is PM_{10}. Marginal damage costs are therefore calculated for PM_{10} as a precursor of $PM_{2.5}$. PM emissions reported to E-PRTR are also PM_{10}. In the below Table 27we also present MDCs for $PM_{2.5}$. These are calculated through a multiplication of MDCs for PM_{10} with the average value 1.54. A more sophisticated approach would use country and sector specific approaches to conversion from PM_{10} to $PM_{2.5}$. Country and sector specific PM_{10} to $PM_{2.5}$ ratios can be obtained, for example, from the EMEP internet site([35]).

([35]) *https://www.ceip.at/*, the CEIP (EMEP Centre on Emission Inventories and Projections) site centralises the reported data from each European country.

Table 27: Overall marginal damage costs of major air pollutants

Emitter countries		Aggregate marginal damage costs over EEA38 + UK (*) for major air pollutants including impacts on health, crops & forests and material damage in €$_{2019}$/tonne of pollutant											
		NO_X VOLY	NO_X VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
AL	**Albania**	9 661	23 355	66 949	163 868	43 474	106 408	19 436	50 678	850	2 170	9 456	24 028
AM	**Armenia**	1 688	2 757	4 013	6 596	2 606	4 283	2 979	5 099	257	444	594	998
AT	**Austria**	22 542	75 653	69 268	227 195	44 979	147 529	34 630	113 123	2 659	8 225	22 838	75 210
AZ	**Azerbaijan**	297	530	336	622	218	404	1 286	2 441	95	184	89	170
BA	**Bosnia and Herzegovina**	10 115	30 445	36 312	115 067	23 579	74 719	14 007	44 712	1 022	3 000	17 505	55 647
BE	**Belgium**	19 464	67 390	159 127	512 037	103 329	332 491	49 322	159 275	2 703	7 953	49 903	162 757
BG	**Bulgaria**	12 010	39 745	82 132	309 647	53 333	201 070	15 114	46 368	1 007	2 791	16 472	57 968
BY	**Belarus**	1 215	3 479	3 112	9 760	2 021	6 338	3 778	11 176	283	741	1 782	5 631
CH	**Switzerland**	43 859	142 473	101 182	306 655	65 703	199 126	74 294	231 497	4 042	12 216	20 629	64 689
CY	**Cyprus**	7 239	15 125	22 448	48 390	14 576	31 422	10 526	18 212	562	889	6 621	14 690
CZ	**Czechia**	15 017	49 078	88 092	282 451	57 202	183 409	22 528	71 277	2 713	8 138	41 050	131 597
DE	**Germany**	20 447	74 611	75 797	266 647	49 219	173 147	34 621	116 457	1 990	5 721	26 428	90 380
DK	**Denmark**	7 595	25 273	39 174	124 113	25 437	80 593	17 274	54 274	549	1 483	8 030	25 429
EE	**Estonia**	2 056	6 947	7 941	26 735	5 157	17 360	2 242	6 789	203	508	3 702	12 426
ES	**Spain**	12 586	42 076	63 795	201 671	41 425	130 955	22 548	71 915	1 299	3 611	7 116	22 620
FI	**Finland**	4 101	14 457	20 346	65 365	13 212	42 445	5 393	17 104	241	634	4 185	13 494
FR	**France**	19 396	63 549	65 395	208 191	42 464	135 189	34 580	111 252	2 156	6 209	13 167	42 289
GB	**United Kingdom**	16 537	55 583	86 815	268 250	56 373	174 188	37 714	117 415	1 659	4 721	32 816	102 432
GE	**Georgia**	824	1 448	1 709	3 099	1 110	2 012	2 338	4 307	253	472	419	786
GR	**Greece**	7 321	26 639	41 820	145 705	27 156	94 614	11 901	36 550	1 273	3 480	11 940	40 964
HR	**Croatia**	17 497	59 756	54 289	192 306	35 252	124 874	23 315	79 013	1 736	5 231	17 409	59 766
HU	**Hungary**	20 348	68 822	77 977	261 548	50 635	169 836	24 317	77 634	1 620	4 795	22 556	74 032
IE	**Ireland**	10 510	29 780	19 612	50 219	12 735	32 609	26 844	77 934	636	1 779	5 115	15 412
IT	**Italy**	28 857	108 056	165 372	592 650	107 384	384 838	26 967	93 755	4 803	15 641	25 980	92 536
LT	**Lithuania**	5 158	18 333	17 633	62 144	11 450	40 353	7 845	25 598	263	648	5 888	20 409
LU	**Luxembourg**	21 876	71 925	80 297	247 472	52 141	160 696	45 946	150 220	1 641	4 639	25 404	82 699
LV	**Latvia**	4 965	19 089	26 831	98 627	17 423	64 043	8 276	28 699	262	666	4 742	16 887
MD	**Moldova**	3 738	10 628	10 733	33 341	6 969	21 650	9 970	28 561	532	1 463	5 018	14 927
ME	**Montenegro**	8 089	23 848	13 370	40 341	8 682	26 195	9 550	29 148	715	1 938	11 058	33 796

Emitter countries		Aggregate marginal damage costs over EEA38 + UK (*) for major air pollutants including impacts on health, crops & forests and material damage in €$_{2019}$/tonne of pollutant											
		NO_X VOLY	NO_X VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
MK	**North Macedonia**	5 597	15 297	55 022	152 981	35 729	99 338	13 094	37 938	1 232	3 293	17 857	50 921
MT	**Malta**	2 017	7 159	52 496	150 194	34 088	97 529	5 774	17 077	902	2 487	30 502	87 032
NL	**Netherlands**	23 088	79 355	95 143	294 599	61 781	191 298	42 521	135 753	2 068	6 051	34 773	112 094
NO	**Norway**	5 341	16 706	20 096	56 741	13 049	36 845	5 082	15 339	407	1 102	3 332	9 673
PL	**Poland**	8 457	26 911	42 634	129 265	27 684	83 938	14 289	42 598	1 137	3 070	22 895	70 230
PT	**Portugal**	8 804	31 399	67 543	234 012	43 859	151 956	10 555	35 283	802	2 221	7 339	25 279
RO	**Romania**	15 800	52 360	64 723	217 324	42 028	141 119	20 072	61 831	1 309	3 747	14 949	48 566
RS	**Serbia**	7 366	22 994	57 921	185 863	37 611	120 690	15 725	48 616	1 040	3 043	25 220	81 845
RU	**Russian Federation**	247	598	462	1 256	300	815	751	1 964	152	382	215	599
SE	**Sweden**	5 453	18 595	16 854	53 538	10 944	34 765	6 460	20 188	345	933	5 456	17 332
SI	**Slovenia**	24 889	84 337	112 372	373 078	72 969	242 259	28 225	93 509	3 243	10 127	23 949	80 286
SK	**Slovakia**	16 217	50 172	76 992	233 434	49 995	151 580	19 963	60 571	1 958	5 753	33 896	104 013
TR	**Turkey**	19 634	33 710	61 497	99 897	39 933	64 868	15 484	25 939	1 189	1 935	15 691	25 728
ATL	**NE Atlantic Ocean**	2 340	6 886	9 945	31 273	6 458	20 307	5 900	18 762	924	2 744		
BAS	**Baltic Sea**	2 859	9 011	21 233	68 505	13 788	44 484	7 527	24 155	1 278	3 583		
BLS	**Black Sea**	6 642	12 023	59 595	109 859	38 698	71 337	17 688	32 646	1 773	3 287		
MED	**Mediterranean Sea**	3 303	9 458	44 078	112 472	28 622	73 034	10 945	31 509	2 484	6 547		
NOS	**North Sea**	9 455	30 571	66 407	209 322	43 121	135 923	19 137	61 269	3 830	11 431		

(*) Missing emitter countries relative to EEA38+UK

For health damage for the $PM_{2.5}$ precursors (NO_X, SO_2, $PM_{2.5}$, NMVOC, NH_3): Iceland, Liechtenstein, Kosovo

For health damage for the O_3 precursors (NO_X, NMVOC): Iceland, Liechtenstein, Kosovo

For health damage for the NO_2 precursor (NO_X): Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo

For crop damage for the O_3 precursors (NO_X, NMVOC): Iceland, Liechtenstein, Serbia, Kosovo

For forest damage for the O_3 precursors (NO_X, NMVOC): Albania, Iceland, Bosnia and Herzegovina, Liechtenstein, Montenegro, Norway, North Macedonia, Switzerland, Serbia and Kosovo, Turkey

For building material damage from SO_2 and NO_X: Albania, Iceland, Bosnia and Herzegovina, Liechtenstein, Montenegro, Norway, North Macedonia, Switzerland, Serbia and Kosovo, Turkey

Table 28 presents European average damage costs per tonne of pollutant. These were calculated as weighted average summing the product of country emissions and country specific marginal damage costs, then dividing by total emissions for all countries. For this calculation, emissions reported to EMEP were used. These may be different from the emissions as used in models to derive the Source Receptor Matrices for which gap-filling is sometimes applied. Covering emissions from all sectors and all emission sources, they exceed the emissions reported to E-PRTR (cf. also section 7).

The damage cost set in Table 28 accounts for impacts on health from ozone, fine particulate matter and NO_2, impacts on crops & forests from ozone and impacts on building materials from NO_X and SO_2. The average European damage costs in Table 28 have been calculated for the EEA38+UK countries, excluding Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo.

Table 28: Average European marginal damage costs accounting for impacts on health from ozone, fine particulate matter and nitrogen dioxide, impacts on crops & forests from ozone and impacts on building materials from NO_X and SO_2.

Pollutant	**Average European damage cost (€$_{2019}$ per tonne) - impacts on health, crops, forests & materials**	
	VOLY	**VSL**
NO_X	16 767	54 815
SO_2	19 203	48 809
PM_{10}	45 507	143 703
$PM_{2.5}$	70 081	221 303
NMVOC	1 877	5 400
NH_3	18 620	57 045
EEA 38 + UK: missing emitter countries: Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo		

Health impacts account for 100 % of the overall damage costs for PM and NH_3 (cf. Figure 12 and Figure 13). Health impacts account for 97.3 % (99.2 %), impacts on crops and forests for 2 % (0.6 %) and impacts on building materials for 0.7 % (0.2 %) of the overall damage costs for NO_x in the VOLY (VSL) estimate. Health impacts account for 97.7 % (99.1 %) and impacts on building materials for 2.3 % (0.9 %) of the overall damage costs for SO_2 in the VOLY (VSL) estimate. Health impacts account for 93.5 % (97.7 %) and impacts on crops and forests for 6.5 % (2.3 %) of the overall damage costs for NMVOCs in the VOLY (VSL) estimate.

Figure 12: Relative share of damage to health, crops & forests and building materials in the overall European average damage costs from main air pollutants – VOLY estimate (note: Y-axis cut off at 90 %)

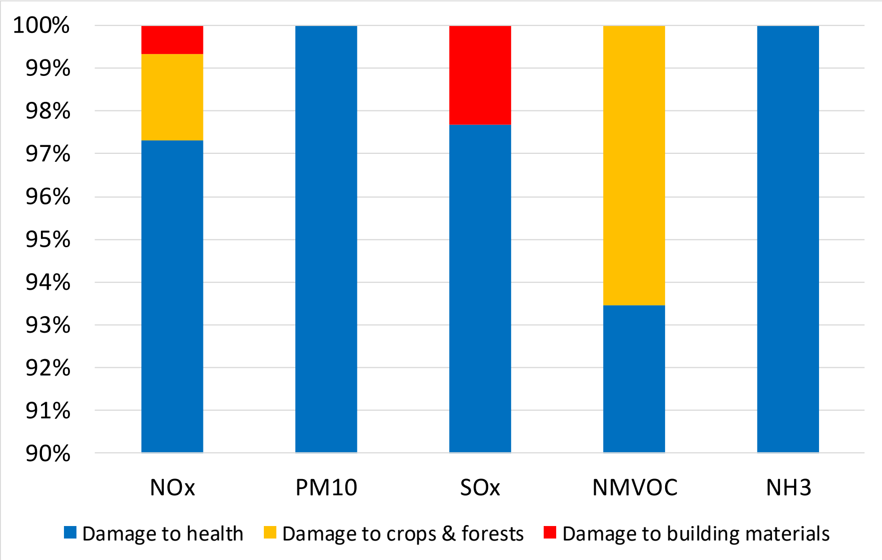
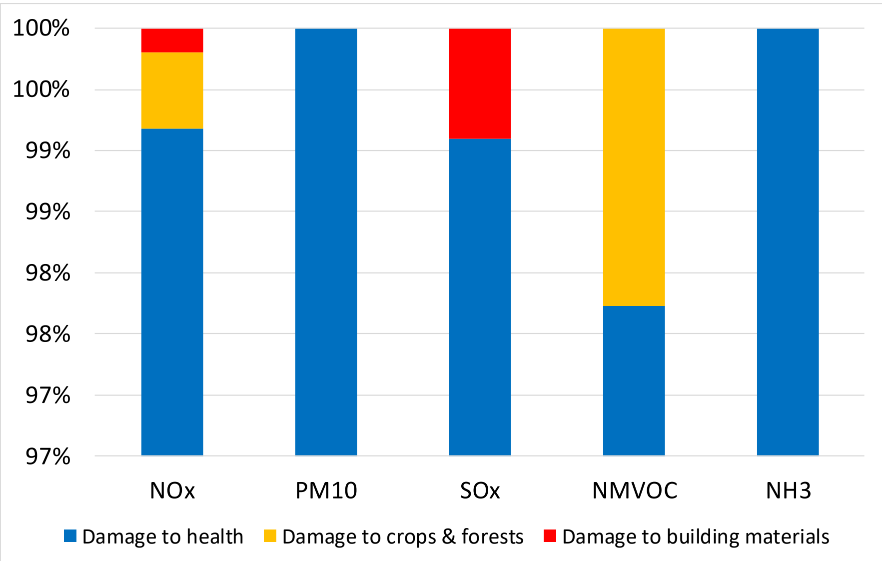


Figure 13: Relative share of damage to health, crops & forests and building materials in the overall European average damage costs from main air pollutants – VSL estimate (note: Y-axis cut off at 97 %)



6.2 Marginal damage costs for toxic metals and organics

The marginal damage costs (€$_{2019}$ per kg pollutant emitted to air) of the heavy metals and organics assessed in this study are summarised in Table 29 to Table 32, while maps of country-specific results are depicted in Figure 14 to Figure 16 for benzo(a)pyrene, hexavalent chromium, and benzene, respectively. Results for pollutants that impact human health only through inhalation dose are distinguished by emitter country. These costs represent the cumulative health burden across the entire European population (including source country) due to an unspecified emission source located in the emitter country.

For all pollutants, marginal damage costs are also calculated at the pan-European scale, that is to say, for an unspecified source located somewhere within Europe. In this context, Europe represents the geographical area covering EU27 (as of 2020) plus United Kingdom, Liechtenstein, Switzerland, Norway and the remaining Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia and Kosovo). For other country groupings, the following adjustment factors should be applied: 0.944 for EU27 plus United Kingdom, 0.970 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, or 1.151 for EU27 plus United Kingdom, Liechtenstein, Switzerland, Norway, other Balkan countries & Turkey. Country-specific values (except for Iceland) should also be updated using these same multipliers when accounting for changes in the population at risk across different geographical areas.

In the table below, the damage costs calculated in this study are compared against previous estimates presented in EEA (2014). The damage costs of arsenic, cadmium lead and mercury are much higher than previous values because the current estimates include a wider range of serious health effects, including premature mortality, as noted in Table 19 (Nedellec and Rabl, 2016a). The large increase in the damage cost for cadmium, as an example, is related to the inclusion of premature mortality (see Table 35), whereas for the EEA (2014) assessment only the cost due to lung cancers was quantified. For hexavalent chromium, estimates for the inhalation URF vary significantly between studies (range: 0.023–1.5×10-1) (Haney et al., 2013; CA OEHHA). In this work, we have used the geometric mean of the range of published values (4.0×10-2), which happens to be similar to the recommended value by WHO (2000) and the estimate by ECHA (2013), meanwhile the U.S. EPA IRIS value (1.2×10-2) was used in the previous EEA (2014) assessment. In addition to the changes reported in the table footnotes, the size of the population at risk has increased, and the parameter η was added to equation (1).

Table 29: Marginal damage costs of heavy metals and organics for European emissions (€$_{2019}$ per kg pollutant emitted to air)

Pollutant	Current study	EEA (2014)†
Arsenic (inorganic)	11 044	445
Cadmium	185 175	37‡
Chromium (hexavalent, VI)	3 129Ᵽ	245‡
Lead	32 531	1 231§
Mercury	16 903	3 649§
Nickel	24Ᵽ	4.8‡
1,3 Butadiene	1.3	0.64‡
Benzene	0.36Ᵽ	0.10‡
Benzo(a)pyrene	6 806Ᵽ	1 632‡
Dioxins/Furans (TCDD equiv.)	60.1 million	34.5 million
Formaldehyde	0.25Ᵽ	0.28‡

† Costs adjusted for inflation to year 2019

‡ Considers inhalation dose only

§ Accounts for IQ loss only

Ᵽ An updated unit risk factor is used

In EEA (2014) the damage cost given for chromium was lower (38 €$_{2005}$) than indicated in Table 29 because it presented chromium at valence state 0. In the present report the cost for chromium is given in the hexavalent state, directly. This avoids having to assume that CrVI corresponds approximately to 20 % of Cr. The reader can pick the fraction that is appropriate for the specific study. The value given in Table 29 is calculated as follows: value given in EEA (2014) = 38 €$_{2005}$ * 5 (20 % of Cr is hexavalent) = 190 €$_{2005}$, which is then adjusted for inflation to the year 2019 (x1.276), or 245 €$_{2019}$. For arsenic, cadmium and lead, the intake dose is mostly from ingestion of contaminated foods (typically, > 98 % of the total contribution). The variability of the inhalation dose by country of emission relative to the total exposure (inhalation plus ingestion) is very small, and consequently no country-specific values were calculated. There would be no adjustment needed for mercury as the intake dose is only from ingestion of methylmercury from contaminated fish.

Low and high marginal damage cost estimates are also presented in Table 30, Table 31 and Table 32. These values indicate the 68 % confidence interval (CI) of the costs, and are calculated using the uncertainty analysis methods discussed in (Rabl, Spadaro & Holland, 2014, Chapter 11). The health cost (equation 10) is the sum of the product of uncorrelated random functions, usually characterised by either a normal or lognormal distribution. The sum extends across all health outcomes of concern associated with a particular pollutant.

$$\begin{matrix}\textit{Health}\\ \textit{cost}\end{matrix} = \sum \begin{pmatrix}\textit{Exposure-Response}\\ \textit{function}\end{pmatrix} \cdot \begin{pmatrix}\textit{Population-weighted}\\ \textit{exposure}\end{pmatrix} \cdot \frac{\textit{Cost}}{\textit{incidence}} \qquad [10]$$

The health cost comprises 3 key components: The exposure-response function (health risk), the population-weighted exposure, and the health outcome cost per incidence. According to the central limit theorem, the natural distribution of a product of many uncorrelated terms is lognormal. Although the health cost involves a finite number of terms, the dominant factors in the product happen to have distributions fairly close to lognormal. For the central estimate of the health cost, one needs the expectation value of the damage cost (μ), and for the confidence interval an estimate of the overall geometric standard deviation (σg) calculated using standard statistical methods with estimates for the geometric standard deviations σg,j for each term in equation (10): exposure calculation, health risk calculation, and economic valuation. The 68 %CI is then calculated with equation (11).

$$\begin{matrix}\textit{low}\\ \textit{bound}\end{matrix} = \frac{\mu}{\sigma_g} \cdot exp\left[-0.5 \cdot ln^2(\sigma_g)\right] \qquad \begin{matrix}\textit{high}\\ \textit{bound}\end{matrix} = \mu \cdot \sigma_g \cdot exp\left[-0.5 \cdot ln^2(\sigma_g)\right] \qquad [11]$$

The confidence interval of each term in the health cost or for the sum itself may be calculated using a Monte Carlo simulation, or approximated using a simple analysis based on the ordinary rules for the sum or product of terms having a normal or lognormal distribution. On the basis of the methodology detailed in (Rabl, Spadaro & Holland, 2014, Chapter 11) we estimate an overall geometric standard deviation of 3 for those pollutants that enter the human body through inhalation only, specifically 1,3 butadiene, benzene, formaldehyde, benzo(a)pyrene, hexavalent chromium and nickel (Spadaro and Rabl, 2008b). For pollutants that pass through the food chain, an additional term must be included to capture the uncertainty of the intake fraction, which leads to a value of 4.1 for the overall σg applied to arsenic, cadmium, lead and mercury (Nedellec and Rabl, 2016a), and 5 for dioxins and furans. For the population exposure, we qualitatively account for atmospheric conditions that might impact concentration estimates and pollutant transfer between environmental compartments. For the health risk calculation, we consider the uncertainty in the exposure-response function by acknowledging the significant variability of the inhalation unit risk factor and the oral slope factor for cancer outcomes (literature estimates for these parameters can vary by an order of magnitude), while for the valuation process we consider the uncertainty of the estimate for the VSL and VCM which influence the mortality cost, as well as other variables that influence the cost of morbidity, including the timing of disease or death (latency period). It is worth pointing out that on a log-scale, the confidence interval is symmetric about the median, but on a linear-scale the probability that the true damage cost is below the mean μ is greater than the probability that is it above this value.

Table 30: European and country-specific marginal damage costs (€$_{2019}$ per kg pollutant emitted to air)

Emitter location	Depletion velocity (cm/s)	Population density† (pers/km²)	1,3 butadiene			Benzene		
			central	low‡	high‡	central	low‡	high‡
Europe*	**0.57**	**112**	**1.32**	***0.24***	**2.16**	**0.36**	***0.065***	***0.59***
Austria	0.56	110	1.31	*0.24*	2.16	0.36	*0.065*	*0.59*
Balkans	0.49	73	1.00	*0.18*	1.64	0.27	*0.049*	*0.44*
Belgium	0.66	214	2.17	*0.40*	*3.56*	0.59	*0.107*	*0.97*
Bulgaria	0.49	53	0.72	*0.13*	*1.19*	0.20	*0.036*	*0.32*
Croatia	0.57	110	1.29	*0.24*	*2.12*	0.35	*0.064*	*0.58*
Cyprus	0.43	56	0.87	*0.16*	*1.43*	0.24	*0.043*	*0.39*
Czechia	0.59	116	1.32	*0.24*	*2.16*	0.36	*0.065*	*0.59*
Denmark	0.86	83	0.65	*0.12*	*1.06*	0.18	*0.032*	*0.29*
Estonia	0.62	33	0.36	*0.065*	*0.58*	0.10	*0.018*	*0.16*
Finland	0.62	33	0.36	*0.065*	*0.58*	0.10	*0.018*	*0.16*
France	0.45	105	1.56	*0.28*	*2.56*	0.42	*0.077*	*0.70*
Germany	0.52	152	1.96	*0.36*	*3.21*	0.53	*0.097*	*0.87*
Greece	0.49	55	0.75	*0.14*	*1.23*	0.20	*0.037*	*0.33*
Hungary	0.57	106	1.24	*0.23*	*2.04*	0.34	*0.062*	*0.55*
Ireland	0.59	59	0.67	*0.12*	*1.10*	0.18	*0.033*	*0.30*
Italy	0.71	150	1.41	*0.26*	*2.32*	0.38	*0.070*	*0.63*
Latvia	0.62	40	0.43	*0.08*	*0.71*	0.12	*0.021*	*0.19*
Lithuania	0.62	52	0.56	*0.10*	*0.92*	0.15	*0.028*	*0.25*
Luxembourg	0.59	138	1.57	*0.29*	*2.57*	0.43	*0.077*	*0.70*
Malta	0.45	33	0.49	*0.089*	*0.81*	0.13	*0.024*	*0.22*
Netherlands	0.66	228	2.31	*0.42*	*3.79*	0.63	*0.114*	*1.03*
Norway	0.89	43	0.32	*0.059*	*0.53*	0.088	*0.016*	*0.14*
Poland	0.57	97	1.14	*0.21*	*1.87*	0.31	*0.056*	*0.51*
Portugal	0.54	62	0.77	*0.14*	*1.26*	0.21	*0.038*	*0.34*
Romania	0.57	73	0.86	*0.16*	*1.41*	0.23	*0.042*	*0.38*
Slovakia	0.58	106	1.22	*0.22*	*2.01*	0.33	*0.061*	*0.54*
Slovenia	0.57	110	1.29	*0.24*	*2.12*	0.35	*0.064*	*0.58*
Spain	0.50	55	0.74	*0.13*	*1.21*	0.20	*0.036*	*0.33*
Sweden	0.86	75	0.58	*0.11*	*0.96*	0.16	*0.029*	*0.26*
Switzerland	0.55	139	1.69	*0.31*	*2.78*	0.46	*0.084*	*0.75*
UK	0.59	122	1.38	*0.25*	*2.27*	0.38	*0.068*	*0.62*
Iceland§	0.44	24	0.0042	*0.00077*	*0.0070*	0.0012	*0.00021*	*0.0019*
Turkey	0.57	60	0.81	*0.15*	*1.34*	0.22	*0.040*	*0.36*

* Europe consists of EU27 (as of 2020) plus United Kingdom, Liechtenstein, Switzerland, Norway and other Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia and Kosovo); for other regional combinations, use the adjustment factors: 0.944 for EU27 plus United Kingdom, 0.970 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, or 1.151 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, other Balkan countries & Turkey. These same factors should be applied to the country-specific damage cost estimates, except for Iceland, to account for changes in the population at risk for different geographical areas.

† Population density for a circular area with radius 1000 km cantered in the middle of the emitter country. This information is used to improve estimates of population-weighted air concentration (see text).

‡ 68 % confidence interval for a lognormal distribution with geometric standard deviation of 3.

§ Damage cost considering only the Icelandic population.

Table 31: European and country-specific marginal damage costs (€$_{2019}$ per kg pollutant emitted to air)

Emitter location	Depletion velocity (cm/s)	Population density† (pers/km²)	Formaldehyde⊕			Benzo[a]Pyreneᵽ		
			central	low‡	high‡	central	low‡	high‡
Europe*	**0.57**	**112**	**0.25**	***0.046***	***0.41***	**6 806**	***1 241***	***11 166***
Austria	0.56	110	0.25	*0.046*	*0.41*	6 804	*1 240*	*11 163*
Balkans	0.49	73	0.19	*0.035*	*0.31*	5 160	*941*	*8 466*
Belgium	0.66	214	0.42	*0.076*	*0.68*	11 231	*2 047*	*18 426*
Bulgaria	0.49	53	0.14	*0.025*	*0.23*	3 746	*683*	*6 147*
Croatia	0.57	110	0.25	*0.045*	*0.41*	6 684	*1 219*	*10 967*
Cyprus	0.43	56	0.17	*0.030*	*0.27*	4 511	*822*	*7 401*
Czechia	0.59	116	0.25	*0.046*	*0.41*	6 810	*1 241*	*11 173*
Denmark	0.86	83	0.12	*0.023*	*0.20*	3 343	*609*	*5 485*
Estonia	0.62	33	0.068	*0.012*	*0.11*	1 844	*336*	*3 025*
Finland	0.62	33	0.068	*0.012*	*0.11*	1 844	*336*	*3 025*
France	0.45	105	0.30	*0.055*	*0.49*	8 082	*1 473*	*13 260*
Germany	0.52	152	0.38	*0.068*	*0.62*	10 124	*1 846*	*16 611*
Greece	0.49	55	0.14	*0.026*	*0.24*	3 888	*709*	*6 379*
Hungary	0.57	106	0.24	*0.043*	*0.39*	6 441	*1 174*	*10 568*
Ireland	0.59	59	0.13	*0.023*	*0.21*	3 464	*631*	*5 683*
Italy	0.71	150	0.27	*0.049*	*0.44*	7 318	*1 334*	*12 006*
Latvia	0.62	40	0.083	*0.015*	*0.14*	2 235	*407*	*3 666*
Lithuania	0.62	52	0.11	*0.020*	*0.18*	2 905	*530*	*4 766*
Luxembourg	0.59	138	0.30	*0.055*	*0.49*	8 101	*1 477*	*13 292*
Malta	0.45	33	0.09	*0.017*	*0.15*	2 540	*463*	*4 167*
Netherlands	0.66	228	0.44	*0.081*	*0.73*	11 965	*2 181*	*19 632*
Norway	0.89	43	0.062	*0.011*	*0.10*	1 673	*305*	*2 746*
Poland	0.57	97	0.22	*0.040*	*0.36*	5 894	*1 075*	*9 671*
Portugal	0.54	62	0.15	*0.027*	*0.24*	3 977	*725*	*6 525*
Romania	0.57	73	0.16	*0.030*	*0.27*	4 436	*809*	*7 278*
Slovakia	0.58	106	0.23	*0.043*	*0.38*	6 330	*1 154*	*10 386*
Slovenia	0.57	110	0.25	*0.045*	*0.41*	6 684	*1 219*	*10 967*
Spain	0.50	55	0.14	*0.026*	*0.23*	3 810	*695*	*6 251*
Sweden	0.86	75	0.11	*0.020*	*0.18*	3 021	*551*	*4 956*
Switzerland	0.55	139	0.32	*0.059*	*0.53*	8 754	*1 596*	*14 362*
UK	0.59	122	0.27	*0.048*	*0.44*	7 162	*1 306*	*11 751*
Iceland§	0.44	24	0.00081	*0.00015*	*0.0013*	22	*4.0*	*36*
Turkey	0.57	60	0.16	*0.028*	*0.26*	4 214	*768*	*6 914*

* Europe consists of EU27 (as of 2020) plus United Kingdom, Liechtenstein, Switzerland, and Norway and other Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia and Kosovo); for other regional combinations, use the adjustment factors: 0.944 for EU27 plus United Kingdom, 0.970 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, or 1.151 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, other Balkan countries & Turkey. These same factors should be applied to the country-specific damage cost estimates, except for Iceland, to account for changes in the population at risk for different geographical areas.

† Population density for a circular area with radius 1000 km centred in the middle of the emitter country. This information is used to improve estimates of population-weighted air concentration (see text).

‡ 68 % confidence interval for a lognormal distribution with geometric standard deviation of 3.

ᵽ In this study, it is assumed that 30 % of the total quantity of PAH emitted to air has an equivalent BaP mass toxicity.

§ Damage cost considering only the Icelandic population.

⊕ Although IARC has classified formaldehyde as a carcinogen, the relevance of this endpoint at the typical exposure levels that would be experienced by the general public is now being debated by the scientific community. Other adverse health endpoints of greater concern might be the impact of this pollutant to eyes and upper airway irritation. It is likely that the damage cost estimate shown here represents an upper bound estimate.

Table 32: European and country-specific marginal damage costs (€$_{2019}$ per kg pollutant emitted to air)

Emitter location	Depletion velocity (cm/s)	Population density† (pers/km²)	Hexavalent Chromiumᵽ			Nickel		
			central	low‡	high‡	central	low‡	high‡
Europe*	**0.57**	**112**	**3 129**	***570***	***5 134***	**24.3**	***4.4***	***39.8***
Austria	0.56	110	3 128	*570*	*5 132*	24.3	*4.4*	*39.8*
Balkans	0.49	73	2 372	*433*	*3 893*	18.4	*3.4*	*30.2*
Belgium	0.66	214	5 163	*941*	*8 472*	40.1	*7.3*	*65.7*
Bulgaria	0.49	53	1 722	*314*	*2 826*	13.4	*2.4*	*21.9*
Croatia	0.57	110	3 073	*560*	*5 042*	23.8	*4.3*	*39.1*
Cyprus	0.43	56	2 074	*378*	*3 403*	16.1	*2.9*	*26.4*
Czechia	0.59	116	3 131	*571*	*5 137*	24.3	*4.4*	*39.8*
Denmark	0.86	83	1 537	*280*	*2 522*	11.9	*2.2*	*19.6*
Estonia	0.62	33	848	*155*	*1 391*	6.6	*1.2*	*10.8*
Finland	0.62	33	848	*155*	*1 391*	6.6	*1.2*	*10.8*
France	0.45	105	3 716	*677*	*6 097*	28.8	*5.3*	*47.3*
Germany	0.52	152	4 655	*849*	*7 637*	36.1	*6.6*	*59.2*
Greece	0.49	55	1 787	*326*	*2 933*	13.9	*2.5*	*22.7*
Hungary	0.57	106	2 961	*540*	*4 859*	23.0	*4.2*	*37.7*
Ireland	0.59	59	1 592	*290*	*2 613*	12.4	*2.3*	*20.3*
Italy	0.71	150	3 364	*613*	*5 520*	26.1	*4.8*	*42.8*
Latvia	0.62	40	1 027	*187*	*1 686*	8.0	*1.5*	*13.1*
Lithuania	0.62	52	1 336	*243*	*2 191*	10.4	*1.9*	*17.0*
Luxembourg	0.59	138	3 725	*679*	*6 111*	28.9	*5.3*	*47.4*
Malta	0.45	33	1 168	*213*	*1 916*	9.1	*1.7*	*14.9*
Netherlands	0.66	228	5 501	*1 003*	*9 026*	42.7	*7.8*	*70.0*
Norway	0.89	43	769	*140*	*1 262*	6.0	*1.1*	*9.8*
Poland	0.57	97	2 710	*494*	*4 446*	21.0	*3.8*	*34.5*
Portugal	0.54	62	1 828	*333*	*3 000*	14.2	*2.6*	*23.3*
Romania	0.57	73	2 039	*372*	*3 346*	15.8	*2.9*	*26.0*
Slovakia	0.58	106	2 910	*531*	*4 775*	22.6	*4.1*	*37.0*
Slovenia	0.57	110	3 073	*560*	*5 042*	23.8	*4.3*	*39.1*
Spain	0.50	55	1 752	*319*	*2 874*	13.6	*2.5*	*22.3*
Sweden	0.86	75	1 389	*253*	*2 279*	10.8	*2.0*	*17.7*
Switzerland	0.55	139	4 025	*734*	*6 603*	31.2	*5.7*	*51.2*
UK	0.59	122	3 293	*600*	*5 403*	25.5	*4.7*	*41.9*
Iceland§	0.44	24	10	*1.8*	*17*	0.078	*0.014*	*0.13*
Turkey	0.57	60	1 937	*353*	*3 179*	15.0	*2.7*	*24.7*

* Europe consists of EU27 (as of 2020) plus United Kingdom, Liechtenstein, Switzerland, and Norway and other Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia and Kosovo); for other regional combinations, use the adjustment factors: 0.944 for EU27 plus United Kingdom, 0.970 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, or 1.151 for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, other Balkan countries & Turkey. These same factors should be applied to the country-specific damage cost estimates, except for Iceland, to account for changes in the population at risk for different geographical areas.

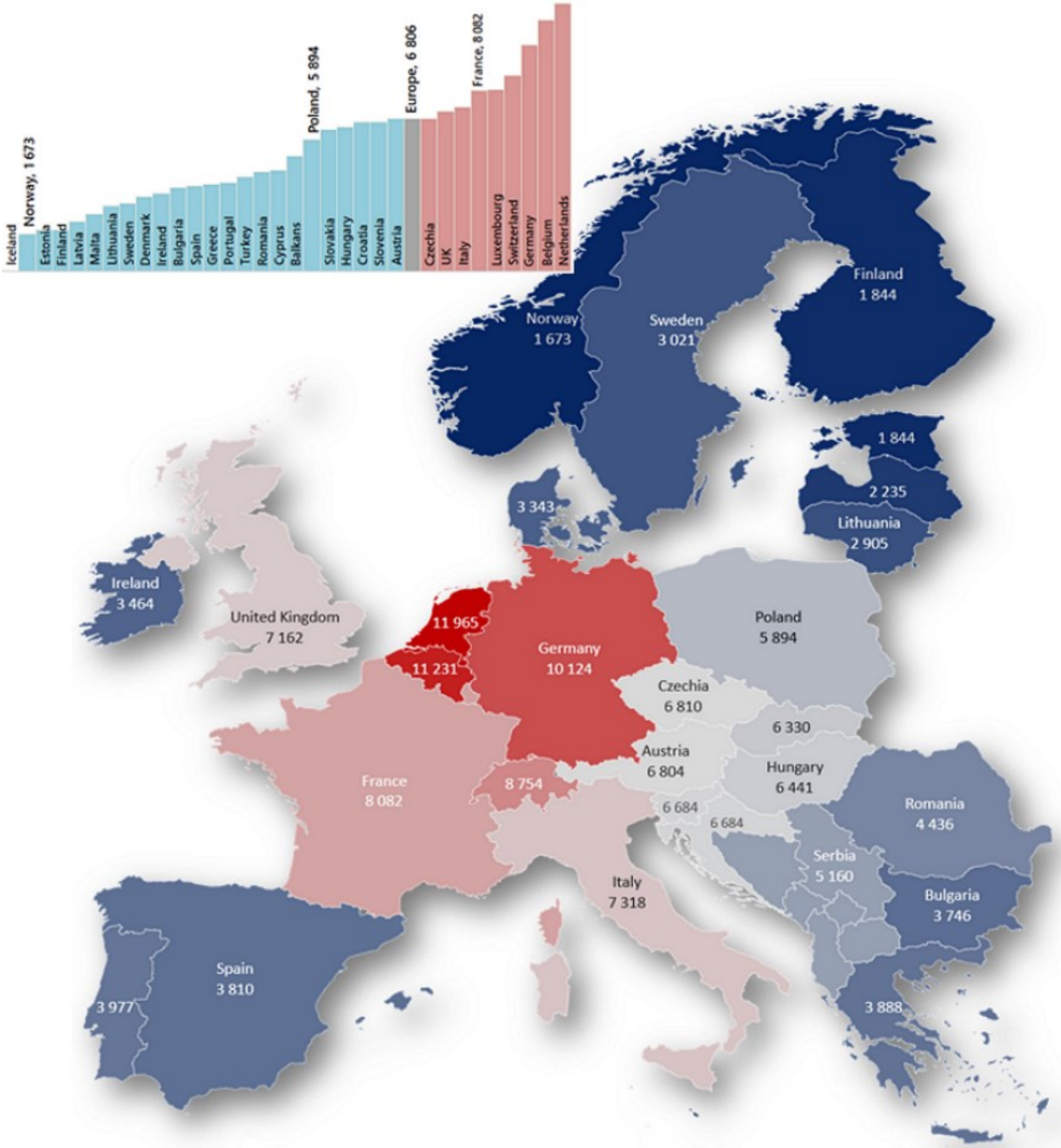
† Population density for a circular area with radius 1000 km centred in the middle of the emitter country. This information is used to improve estimates of population-weighted air concentration (see text).

‡ 68 % confidence interval for a lognormal distribution with geometric standard deviation of 3.

ᵽ Hexavalent chromium (or Chromium VI) typically accounts for 20 % of the total chromium mass emission to air.

§ Damage cost considering only the Icelandic population.

Figure 14: BaP marginal damage cost map by emitter country (€$_{2019}$ per kg emission to air)



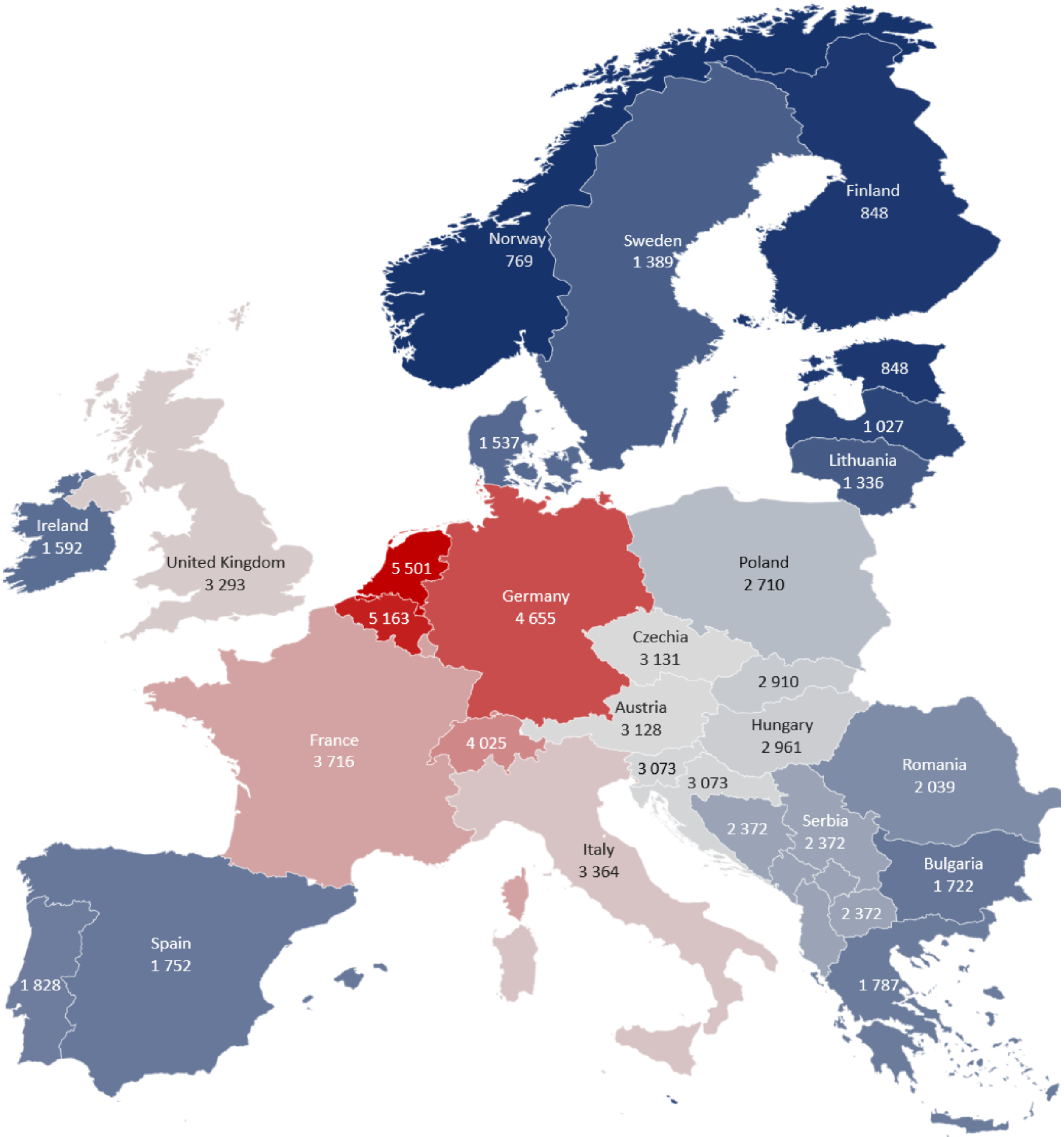
Note:

(i) The European marginal damage cost is 6 806 € per kg emission.

(ii) Estimates for Iceland and Turkey are 22 and 4 214 € per kg emission, respectively.

(iii) Interpretation: An emission of 1 kg BaP per year in Germany contributes a damage cost of 10 124 € across Europe (EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway and other Balkan countries). For EU27 plus United Kingdom, multiply costs by 0.944, and for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, scale by 0.970. For Liechtenstein, take the mean of Austria & Switzerland, and for Andorra, assume the mean value of Spain and France.

Figure 15: Chromium VI marginal damage cost map by emitter country (€$_{2019}$ per kg emission to air)



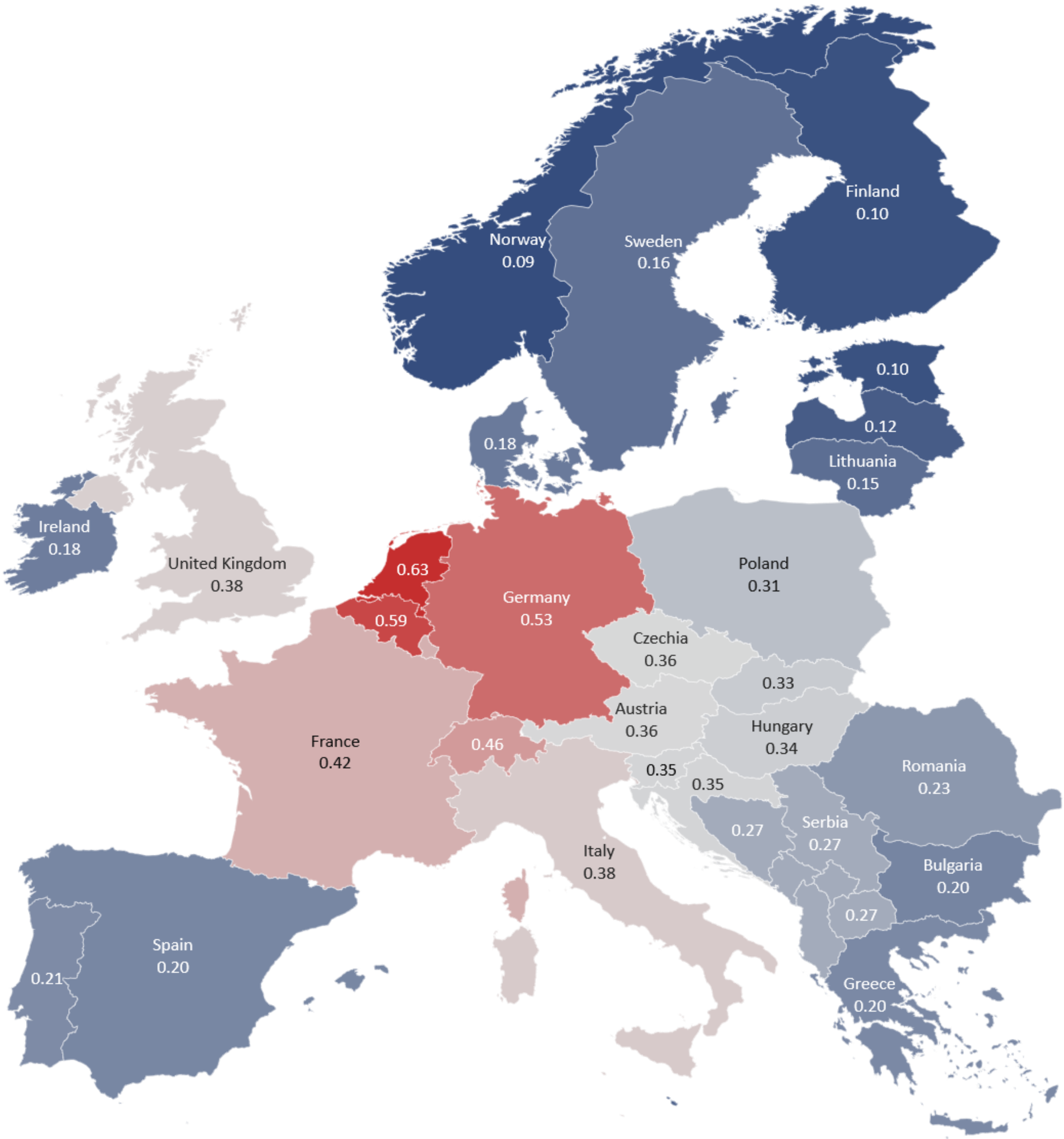
Note:

(i) The European marginal damage cost is 3 129 € per kg emission.

(ii) Estimates for Iceland and Turkey are 10 and 1 937 € per kg emission, respectively.

(iii) Interpretation: An emission of 1 kg chromium VI per year in Germany contributes a damage cost of 4 655 € across Europe (EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway and other Balkan countries). For EU27 plus United Kingdom, multiply costs by 0.944, and for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, scale by 0.970. For Liechtenstein, take the mean of Austria & Switzerland, and for Andorra, assume the mean value of Spain & France.

Figure 16: Benzene marginal damage cost map by emitter country (€$_{2019}$ per kg emission to air)



Note:

(i) The European marginal damage cost is 0.36 € per kg emission (357 € per tonne of pollutant).

(ii) Estimates for Iceland and Turkey are 0.0012 and 0.22 € per kg emission, respectively.

(iii) Interpretation: An emission of 1 kg benzene per year in Germany contributes a damage cost of 0.53 € across Europe (EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway and other Balkan countries). For EU27 plus United Kingdom, multiply costs by 0.944, and for EU27 plus United Kingdom, Liechtenstein, Switzerland, and Norway, scale by 0.970. For Liechtenstein, take the mean of Austria & Switzerland, and for Andorra, assume the mean value of Spain & France.

6.3 Values for carbon valuation

The DG Move Handbook on the External Costs of Transport (EC, 2019) provides estimates of the marginal costs of GHG mitigation as the basis for valuing GHG emissions. The Paris Agreement is intended to prevent temperature rises above 1.5-2 degrees Celsius, a level above which substantial climate damage is foreseen. The DG Move Handbook reviews a wide range of studies in providing the estimates shown in Table 33. These costs are the average of the values found in the literature, calculated for the minimum, maximum and central estimates. The preferred value for EC (2019) is the central estimate.

Table 33: Climate change avoidance costs in €/tCO_2 equivalent (€$_{2019}$)

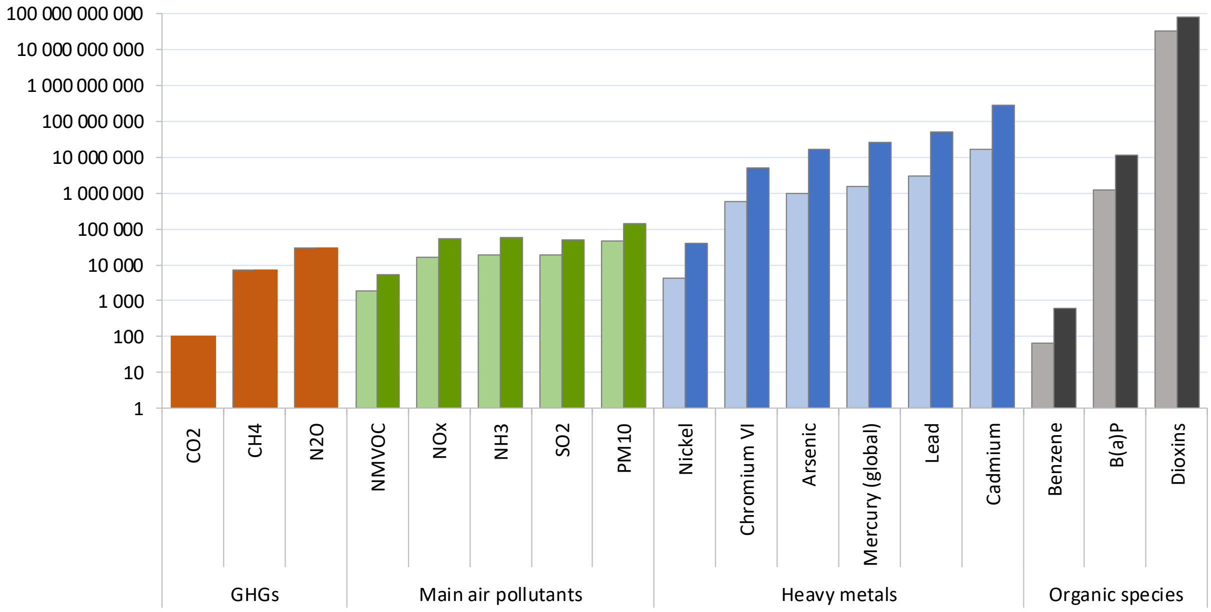
	Low	Central	High
Short and medium term, to 2030	63	105	199
Longer term (2040 to 2060)	164	283	524

The use of the DG MOVE approach in the present report follows a review of literature carried out in 2019 (Schucht et al., 2019b) and EEA's request to be as far as possible consistent with other DG services.

6.4 Average marginal damage costs for all selected pollutants

Figure 17 summarises the MDCs for all the pollutants considered. It shows the variation in the updated damage costs per unit of emission between pollutants, averaged across countries. These are averages across Europe, except for mercury and CO2 for which global estimates are shown. While for the other pollutants EEA38+UK impacts will be dominant, mercury is a properly global issue, like climate change, and similarly is regulated at global level. For main air pollutants, heavy metals and organic pollutants, Figure 17 presents lower and upper bounds. It is important to stress that the "low" and "high" damage cost estimates for the main air pollutants do not refer to a confidence interval, but rather reflect the different choices of VSL & VOLY. For heavy metals and organic species, however, the low and high damage costs do refer to confidence intervals.

Figure 17: Estimates of average damage cost per tonne emitted all air pollutants considered in € (€$_{2019}$)



6.5 Comparison with previous results

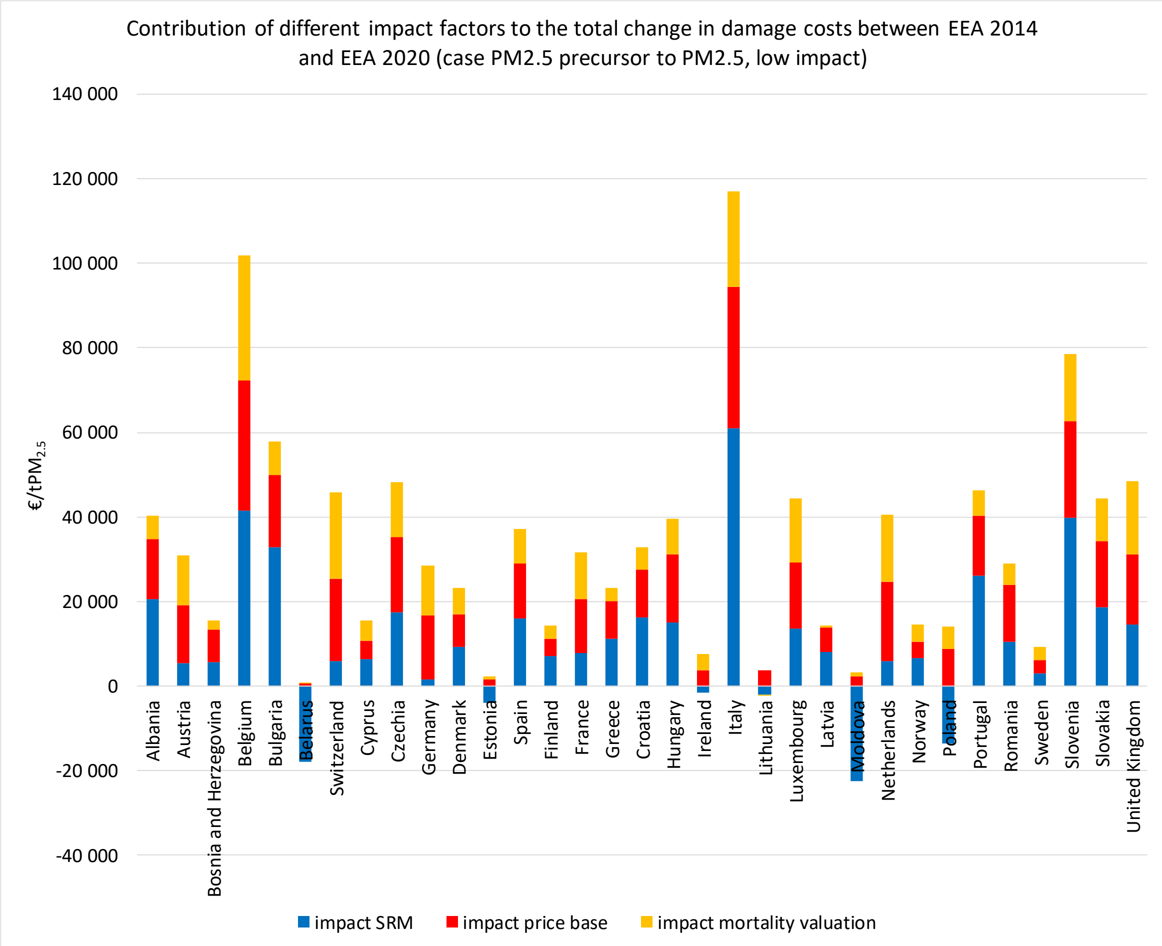
As illustrated in this section, damage costs per tonne of emission change significantly between the previous (EEA, 2014) and the current report. Therefore, externalities presented in part B of the report are calculated also for the period covered in the EEA (2014) report.

Comparisons are presented for the major air pollutants and impacts on health and on crops, and for toxic metals and organic pollutants and their impacts on health. Impacts of major air pollutants on forests are assessed for the first time in the present report. Also, MDCs for ecosystems damage have been calculated for the first time (but are not included in the externality assessment in Part B). Material building damage is updated by inflation, the increase in prices between 2005 and 2019 is 28 %.

6.5.1 Major air pollutants

The following two figures show the results of a decomposition analysis that illustrates reasons for changes in the current damage costs compared to those calculated in EEA (2014) for the $PM_{2.5}$ precursor $PM_{2.5}$ and the damage costs only referring to health impacts. As the figures indicate, the major difference comes from the source receptor matrices (blue part of the bars). Prices increased by 28 % between 2005 (price base used in EEA, 2014) and 2019 (price base used in the current report). This contribution to absolute changes in damage costs is indicated by the red parts of the bars. The remaining variation is due to the update of the monetary unit values for mortality.

Figure 18: Decomposition of factors explaining the change in marginal damage costs for $PM_{2.5}$ precursor emissions due to health effects between the EEA (2014) edition and the current values – low VOLY

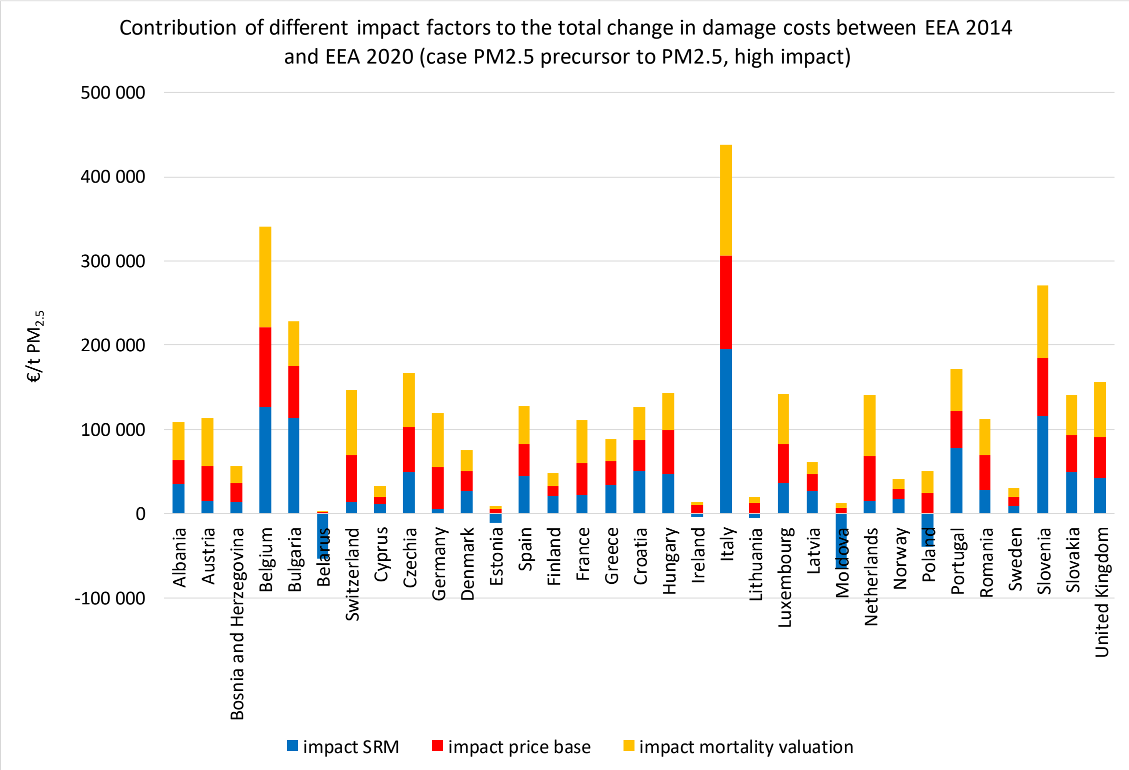


It is difficult to isolate the exact reasons that explain changes in SRMs between different years. Amongst the possible reasons for SRM changes between 2010 and 2017 are:

- changes in emission data (which are updated regularly also for historical years),
- update of ship traffic emissions,
- changes in model formulations (in particular, new parametrisations have been included for secondary organic aerosols, improving their modelling),
- changes in meteorology,
- changes in model resolution (both in the meteorology and the EMEP model).

The importance of each of these factors depends on the species and the source-receptor pair in question and cannot easily be judged in general terms. For this reason, the decomposition analysis is presented only for $PM_{2.5}$ and not for the other precursor pollutants.

Figure 19: Decomposition of factors explaining the change in marginal damage costs for $PM_{2.5}$ precursor emissions due to health effects between the EEA (2014) edition and the current values – high VSL



Analyses of trajectories of externalities from industrial facilities over time should be based on a single set of the marginal damage costs (not on combinations of different ones).

Table 34 compares the damage costs per tonne of pollutant for impacts on crops between the EEA (2014) and the present report. The damage values from EEA (2014) are expressed both in their original price base ($€_{2005}$) and converted to the price base used in the present report ($€_{2019}$), through multiplication with the factor 1.2758 from HICP (Eurostat) for EU28.

Table 34: Evolution of marginal damage costs between EEA (2014) and the present report – impacts on crops

	Damage in €/tonne of pollutant					
	EEA (2014), €2005		EEA (2014), €2019		Current assessment, €2019	
	NO_X	NMVOCs	NO_X	NMVOCs	NO_X	NMVOCs
Austria	405	86	517	110	485	94
Belgium	-15	345	-19	440	12	121
Bulgaria	381	36	486	46	398	47
Croatia	401	57	512	73	593	80
Cyprus	-	-	0	0	273	38
Czechia	345	112	440	143	337	108
Denmark	179	190	228	242	56	35
Estonia	155	39	198	50	75	22
Finland	119	39	152	50	78	22
France	595	167	759	213	389	122
Germany	393	214	501	273	162	132
Greece	369	32	471	41	217	79
Hungary	428	52	546	66	495	61
Ireland	250	118	319	151	93	25
Italy	321	119	410	152	419	169
Latvia	238	56	304	71	95	28
Lithuania	250	40	319	51	127	29
Luxembourg	381	309	486	394	207	117
Malta	179	100	228	128	51	37
Netherlands	-113	333	-144	425	-53	94
Poland	274	83	350	106	142	85
Portugal	190	60	242	77	422	62
Romania	405	42	517	54	360	45
Slovakia	417	64	532	82	400	73
Slovenia	405	100	517	128	521	132
Spain	369	80	471	102	533	91
Sweden	214	73	273	93	102	22
United Kingdom	58	214	74	273	30	72
Baltic Sea	131	155	167	198	52	78
Mediterranean Sea	83	70	106	89	182	124
NE Atlantic Ocean	179	60	228	77	99	37
North Sea	31	286	40	365	26	142

Several factors may explain that current damage costs are not higher than the earlier (EEA, 2014) ones. For example, damage costs are calculated based on crop production, and this was updated from 2010 (EEA, 2014) to 2016 in the current study. While the current study includes 120 crop species, the 20 crops included in EEA (2014) account for approximately 80 % of the overall production value. It is thus normal that the higher crop number does not lead to proportional increases in damage.

6.5.2 Toxic metals and organic pollutants

Table 35 indicates the key changes in the current study versus Nedellec et al. (2016 & 2019) and the previous EEA (2014) assessment.

Table 35: Changes in marginal damage costs for arsenic, cadmium, lead, mercury and dioxins

Pollutant	Marginal damage cost (€$_{2019}$ per kg emitted to air)				Differences vs. Nedellec and Rabl (2016a,b,c)
	Current study		Previous results[*] (Total only)		
Arsenic (European[§] estimate)	**Total: 11 044** (995–16 734)†		Nedellec et al. (2016c)	6 061	French-specific inputs used in Nedellec et al. were replaced with updated European statistics on demographics and illness-specific information, including cancer data on mortality rate, survival probability and latency period by organ site, and EU incidence data for diabetes. Life table calculations on loss of life expectancy were revised, and an updated estimate of the share of inorganic arsenic in food was used. Illness and mortality costs were revised and adjusted for inflation & income growth to 2019.
	Non-cancer mortality	2 887	EEA (2014)	445‡	
	Cancer mortality	2 950			
	Chronic bronchitis	126			
	IQ loss	983			
	Diabetes	4 098			
	Mortality share	53 %			
Cadmium (European[§] estimate)	**Total: 185 175** (16 691–280 576)†		Nedellec et al. (2016c)	147 446	In addition to updates already mentioned for arsenic, European-specific incidence (by gender) and cost data for hip fractures were used in lieu of French statistics.
	Mortality	182 457	EEA (2014)	37‡	
	Non-fatal cancers	611			
	Non-fatal hip fractures	2 106			
	Mortality share	99 %			
Lead (European[§] estimate)	**Total: 32 531** (2 932–49 290)†		Nedellec et al. (2016b)	31 781	In addition to updates already mentioned for arsenic, the DALY score per year lived with moderate anaemia in Nedellec et al. (0.058) was replaced with the Global Burden of Disease (GBD, 2017) recommended value of 0.052 (http://ghdx.healthdata.org/record/ihme-data/gbd-2017-disability-weights).
	Mortality	26 844	EEA (2014)	1 231‡	
	IQ loss	5 627			
	Anaemia	60			
	Mortality share	83 %			
Mercury (Global estimate)	**Total: 16 903** (1 524–25 612)†,Ᵽ		Nedellec et al. (2016b)	24 336	Assumptions and input data were revised and updated to 2019 statistics. In particular, international costs per case are expressed in nominal terms, instead of purchasing power parity prices.
	Cardiovascular mortality	15 099	EEA (2014)	3 649‡	
	IQ loss	1 805			
	Mortality share	89 %			
Dioxins and furans, as TCDD equivalent (European[§] estimate)	**Total: 61 M** (33 M–83 M)†		Nedellec et al. (2019)	171 M€	Nedellec et al. (2016a) don't report a marginal damage cost for dioxins and furans, while Nedellec et al. (2019) have proposed 171 million € (inflation adjusted to 2019). The damage cost in this study was calculated using equations (7) through (9) with ω = 37.3 to account for the combined contribution of inhalation and ingested dose.
	Fatal liver cancers	60.3 M€	EEA (2014)	34 M‡	
	Non-fatal liver cancers	0.24 M€			
	Mortality share	99.6 %			

* Costs adjusted for inflation to year 2019.
† 68 % confidence interval for a lognormal distribution with geometric standard deviation of 4.1 for arsenic, cadmium, lead and mercury, and 5 for dioxins/furans.

‡ Marginal damage cost estimates for arsenic, cadmium and dioxins/furans account for lung cancers (fatal and non-fatal incidences) due to combined ingestion and inhalation dose for arsenic and dioxins/furans, and inhalation only for cadmium. For lead and mercury, cost estimates cover the IQ loss. For mercury emissions, the EEA (2014) European estimate is about 32 % of 3 649 €, or 1 161 €/kg.

§ Europe includes EU27 (as of 2020) plus United Kingdom, Liechtenstein, Switzerland and Norway and other Balkan countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia and Kosovo); for other regional configurations, use the adjustment factors: 0.944 for EU27 plus United Kingdom, 0.970 for EU27 plus United Kingdom, Liechtenstein, Switzerland and Norway, or 1.151 for EU27 plus United Kingdom, Liechtenstein, Switzerland and Norway, other Balkan countries & Turkey. For Iceland, the damage costs for the inhalation dose only are: 0.34 (68 % Confidence Interval, CI: 0.062–0.56) € per kg arsenic; 0.47 (68 % CI: 0.086–0.59) € per kg cadmium; and 4.0 (68 % CI: 0.74–6.6) € per kg lead. For dioxins/furans, the inhalation dose damage cost is 8 400 (68 % CI: 460–11 500) € per kg dioxins/furans (as TCDD equivalent).

‽ Following the methodology in Spadaro and Rabl (2008a), about two-thirds of European emissions fall back on European soil (impacting around 550 million people), while the remaining mass is globally dispersed (affecting nearly 7 billion people). The European share of the global damage cost is about 42 %, or 7 060 (68 % CI: 640–10 700) € per kg mercury emitted to air (human exposure occurs through ingestion of methyl-mercury in food).

Key input data sources: Abrahamsen et al. (2020); Cubadda et al. (2017); European Cancer Information System (ECIS) database (https://ecis.jrc.ec.europa.eu); European Commission Eurostat database (https://ec.europa.eu/eurostat/data/database); Huette et al. (2020); Svedbom et al. (2013); Spadaro and Rabl (2004); Tellez-Plaza et al. (2012).

Part B Calculation of externalities – results

Results presented in Chapters 8 to 10 use the sectoral adjustment factors in Annex 4. In this Annex, a split between "internal" damage (damage from pollutant emissions perceived in the emitter country only) and "external" damage (damage from pollutant emissions perceived across Europe but excluding the damage perceived in the emitter country) is presented for illustrative reasons. The use of the marginal damage costs including transboundary effects (as presented in part A of this report) is recommended.

7 The E-PRTR emission data

The damage costs (or externalities) determined in the following chapters are based upon the atmospheric emissions of selected pollutants reported by individual facilities to the E-PRTR pollutant register for the years 2008 to 2017.

Table 36 indicates the number of facilities reporting emissions of the selected pollutants:

- main air pollutants ammonia (NH3), nitrogen oxides (NO_x), non-methane volatile organic compounds (NMVOCs), particulate matter (PM_{10})([36]) and sulphur oxides (SO_2),
- heavy metals arsenic, cadmium, chromium, lead, mercury and nickel,
- organic pollutants: benzene, dioxins and furans, and polycyclic aromatic hydrocarbons (PAHs);
- greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O).

Table 36: Number of reporting facilities when accounting for all pollutant groups

Number of facilities reporting the selected air pollutant emissions									
2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
11 137	11 040	11 077	11 208	11 137	11 375	11 561	11 764	11 768	11 893

The E-PRTR register contains information on releases to air for 32 countries: the EU27 Member States, Iceland, Norway, Serbia, Switzerland and the UK.

The dataset is not complete for all countries:

- For Croatia, data on emissions of main air pollutants, greenhouse gases and heavy metals is available from 2014 onwards, organic pollutants were reported only in 2014 and 2015.
- For Serbia, data on emissions of main air pollutants is available from 2009 onwards. Greenhouse gases are reported from 2009 to 2014. The country does not report any emissions of the selected heavy metals and organic pollutants.
- Iceland reports greenhouse gases only in 2008.
- Malta reports organic pollutants only in 2013.
- Cyprus does not report the selected organic pollutants.

For the years they have reported data, these countries are included when aggregate results over all countries are presented below. In the presentation of country-specific results below they are excluded when their reporting is incomplete. Iceland is excluded from all country specific results because no MDCs for health effects from the main air pollutants are available for this country. Note also that no emission data is available for Kosovo.

([36]) $PM_{2.5}$ emissions are not reported in E-PRTR. Cf. section (cf. footnote 8 and section 6.1 for information on conversion from PM_{10} to $PM_{2.5}$).

In some instances, reported data may be incomplete. This is obviously the case for Serbia and Iceland as far as greenhouse gases are concerned. It may also be the case for individual facilities. Where reporting is incomplete, damage costs are underestimated for the facility or country concerned. While reporting for NO_X and SO_2 emissions is complete in the period from 2013 to 2017 for the 30 installations with the highest aggregate damage costs in 2017 (Chapter 10), some of these facilities have not reported PM_{10} emissions (or only in 2017), and others have not reported any CO_2 emissions (Annex 6).

Prior to the estimation of damage costs, several E-PRTR data points were revised to correct apparent errors in the reported emissions (cf. Annex 1). Potential anomalies were identified using the following criteria:

- Emission value represents >1 % of European total and has changed by more than 50 % between years; or
- Emission value represents >20 % of national total and has changed by more than 50 % between years.

If either of these criteria were met, then outlying values were examined individually in more detail, by plotting the time series of emissions of all pollutants for the relevant facilities. Outlying values were then corrected where values were clearly reported incorrectly by 1 or more orders of magnitude, indicating a unit error in reporting. Similarly, if the reported value was a significant outlier while other pollutants reported from the same facility were consistent with the magnitude of emissions reported from other years in the time series, then the outlying value was replaced with the previous year’s value.

If neither of these methods of correction were appropriate, the values were left unchanged and remained in the dataset.

A detailed list of the corrections made is provided in Annex 1.

The following table compares the reporting of emissions to E-PRTR and EMEP in 2017.

Table 37: Emissions reported to E-PRTR and EMEP by EEA sector in 2017 (tonnes)

	Emissions reported to E-PRTR (tonnes)	Aggregated national total emissions reported to EMEP (tonnes)	% E-PRTR emissions of national totals
NO_X	1 743 599	8 124 469	21 %
SO_2	1 627 493	2 675 551	61 %
PM_{10}	83 143	2 193 133	4 %
NMVOC	429 143	7 673 940	6 %
NH_3	234 447	4 236 339	6 %
As	23	142	16 %
Cd	9	67	14 %
Cr	57	388	15 %
Hg	26	55	47 %
Ni	141	639	22 %
Pb	287	1 482	19 %
Dioxins + furans	0.0010	0.0020	50 %
PAHs	48	1 256	4 %

The table indicates that the E-PRTR emissions only cover a part of the overall emissions. The EMEP totals include emissions for sectors not included in the 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 37 shows that for most pollutants, other sources not included in E-PRTR, produce the majority of emissions. **Therefore, the damage costs estimated in this study clearly do not represent the total damage costs caused by air pollution across Europe.**

Figure 20: Emissions reported to E-PRTR in 2017 (note logarithmic scale)

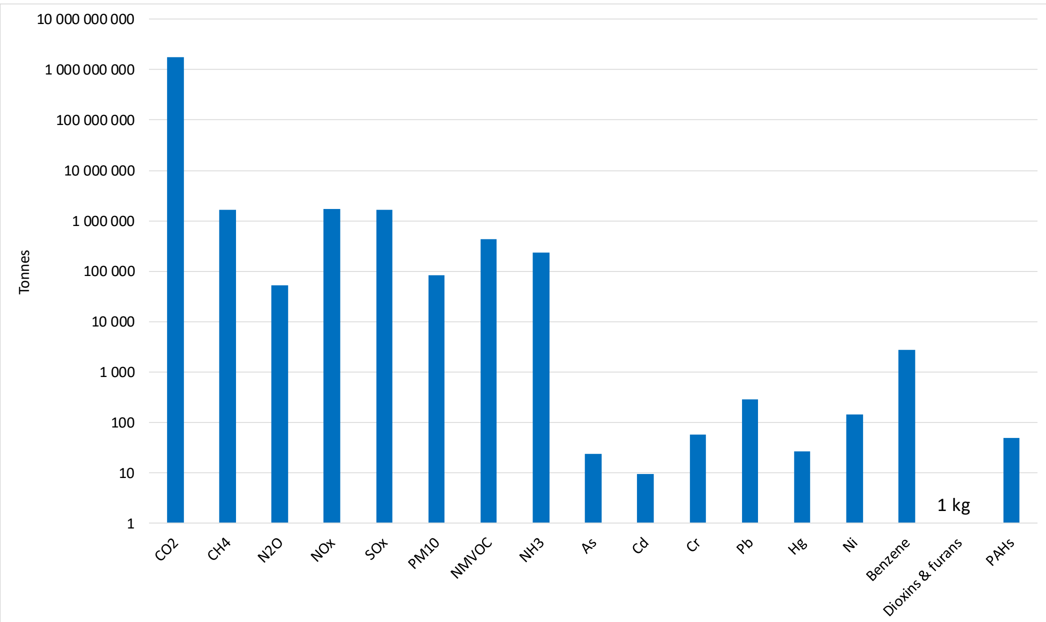


Figure 20 illustrates how much total emissions of each pollutant reported to E-PRTR in 2017 vary in scale. Emissions are dominated by CO_2, followed by methane and the main air pollutants and heavy metals. Reported emissions of dioxins and furans are so small they are not visible in the graph. The ordering of pollutants by damage cost per tonne is very different, with dioxins & furans having the highest marginal damage cost (cf. Table 29).

8 Calculation of externalities

Quantification of externalities is straightforward as it consists of multiplying pollutant releases reported in E-PRTR with the marginal country-specific damage costs per tonne of each pollutant presented in Part A of this report.

There are two exceptions.

- Marginal damage costs were assessed for BaP, whereas in E-PRTR, the PAH emissions are not reported in terms of BaP equivalent. Annex II of the E-PRTR gives guidance on the list of species included: "Polycyclic aromatic hydrocarbons (PAHs) are to be measured for reporting of releases to air as benzo(a)pyrene (50-32-8), benzo(b)fluoranthene (205-99-2), benzo(k)fluoranthene (207-08-9), indeno(1,2,3-cd)pyrene (193-39-5) (derived from Regulation (EC) No 850/2004 of the European Parliament and of the Council of 29 April 2004 on persistent organic pollutants". After reviewing several sources on ambient air emissions and concentrations for the four pollutants (incl. WHO, IARC and others), it is considered here that the toxicity of BaP is 10x higher than any of the other three components in the list, and that BaP constitutes around 20 % of air releases. This implies that the PAH mixture has a mass equivalent toxicity of 30 % BaP emissions. The damage costs for BaP are therefore scaled by 30 % when calculating the externalities of PAH emissions reported in E-PRTR.
- Marginal damage costs were assessed for hexavalent chromium (CrVI), whereas in E-PRTR chromium and compounds are reported. It is here assumed that the fraction of Cr emitted as CrVI is 20 % (this is the assumption made in ExternE and also mentioned by the U.S. EPA). Therefore, the costs for CrVI are scaled by 20 % before multiplying them with the Cr emissions reported in E-PRTR.

For the greenhouse gases nitrous oxide and methane, the damage costs per tonne of emission are calculated as the marginal abatement cost for CO_2 multiplied by the Global Temperature Change Potentials of N_2O and CH_4, respectively (Table 20).

In the results presented hereafter, the core set of marginal damage costs (Chapter 6) is used, including damage not only in the emitter country but over the European region.

9 Aggregated damage cost

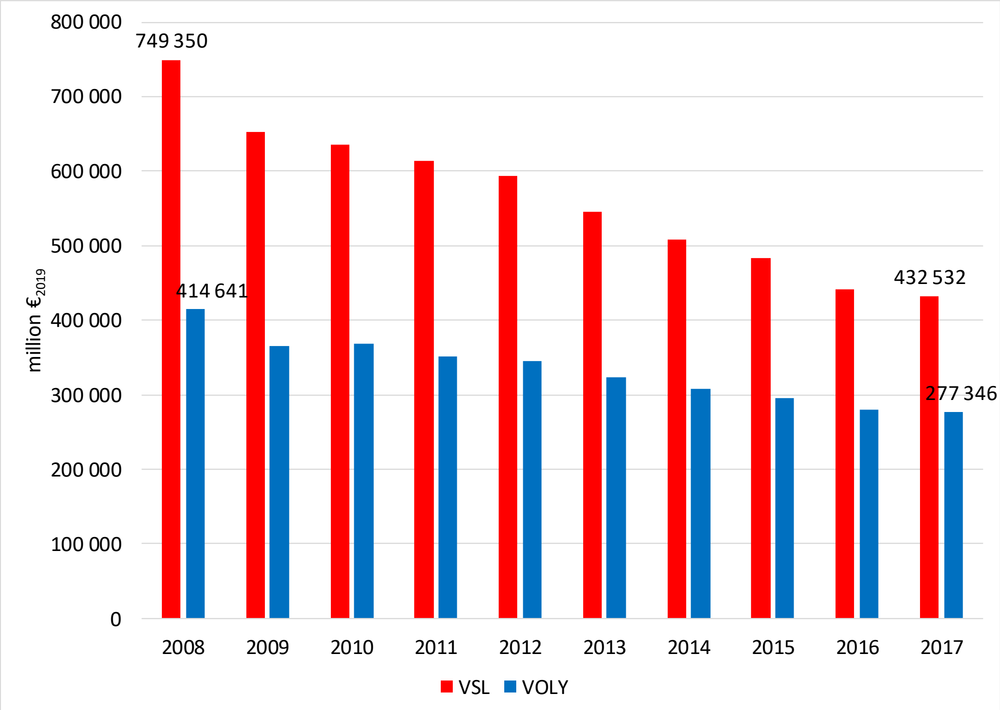
In the following, results are calculated with the complete damage cost set (excluding ecosystems) and using sector adjustment factors (cf. Annex 7).

9.1 Damage costs aggregated over Europe

9.1.1 Damage cost aggregated over all four pollutant groups

Aggregated damage costs for 2008 to 2017 are provided in Figure 21. The lower value of the range provided corresponds to the valuation of mortality from main air pollutants, calculated using the VOLY approach, whilst the upper value corresponds to the case when the VSL approach has been applied to mortality valuation. Damage costs caused by emissions from E-PRTR facilities declined over the period studied.

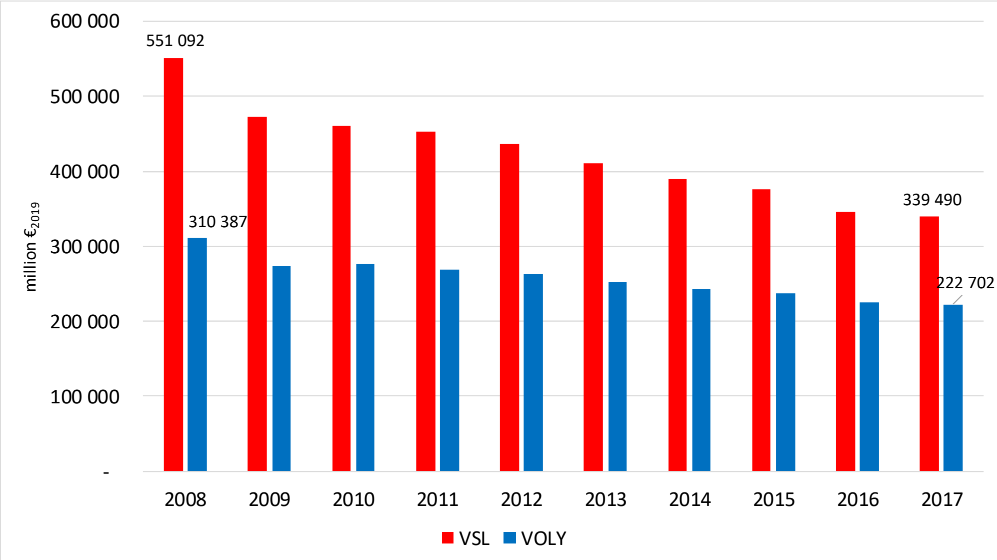
Figure 21: Damage costs aggregated over the four pollutant groups from 2008 to 2017 (million €$_{2019}$)



In Figure 21, we have not cleaned the data set for facilities that have not reported emissions in every year, or that were not present over the whole period. This figure therefore includes everything reported for each year. In Figure 22 the same results are presented for the set of facilities reporting over the entire time period 2008-17. While in the previous figure approximately 19,700 facilities reported, the data set in Figure 22 only contains about 5,040 installations. However, this figure confirms that overall, facilities have reduced emissions over time.

A more detailed analysis of these trends is presented in Chapter 10.

Figure 22: Damage costs aggregated over the four pollutant groups from 2008 to 2017 (million €$_{2019}$) – identical facilities reporting over the whole period



9.1.2 Damage costs by pollutant group and year

Table 38 illustrates aggregated cost between 2008 and 2017 of damage caused by emissions from E-PRTR industrial facilities by pollutant group. They are dominated by costs from main air pollutants and greenhouse gases. Damage costs from the main air pollutants are reduced by 54 % in 2017 relative to 2008. The reductions for damage from greenhouse gases, heavy metals and organic pollutants, respectively, are 19 %, 43 % and 60 %.

Table 38: Aggregated damage costs by pollutant groups from 2008 to 2017 (million €$_{2019}$)

	Aggregated damage costs (million €$_{2019}$)									
	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Main air pollutants (NH_3, NO_x, PM_{10}, SO_2, NMVOCs)	148 983-483 692	127 559-413 532	118 781-385 673	117 029-379 726	111 144-360 979	98 069-319 434	88 629-288 937	82 838-270 272	70 896-232 313	68 165-223 350
Greenhouse gases (CO_2, CH_4, N_2O)	244 550	224 766	233 786	221 439	220 081	212 972	206 588	202 595	196 725	197 269
Heavy metals (As, Cd, Cr, Hg, Ni, Pb)	20 770	13 414	16 447	13 090	13 133	12 127	12 068	10 547	11 989	11 775
Organic pollutants (benzene, dioxins and furans, PAHs)	338.51	163.48	191.23	191.03	111.89	133.36	129.26	144.38	143.86	136.69
Sum	**414 641-749 350**	**365 904-651 876**	**369 205-636 098**	**351 750-614 446**	**344 469-594 304**	**323 302-544 667**	**307 415-507 723**	**296 125-483 559**	**279 753-441 170**	**277 346-432 532**

9.1.3 Damage costs by pollutant and year

Figure 23 shows the damage cost by main air pollutant, for the period from 2008 to 2017 for the lower mortality valuation approach (VOLY). Damage costs were reduced for all main air pollutants, except for ammonia. In 2017 relative to 2008, the reduction (in %) was most important for SO_2 and PM_{10}, followed by NO_X and NMVOCs. Damage related to NH_3 increased.

Figure 23: Damage costs for main air pollutants from 2008 to 2017 (million €$_{2019}$) – indicator VOLY for mortality

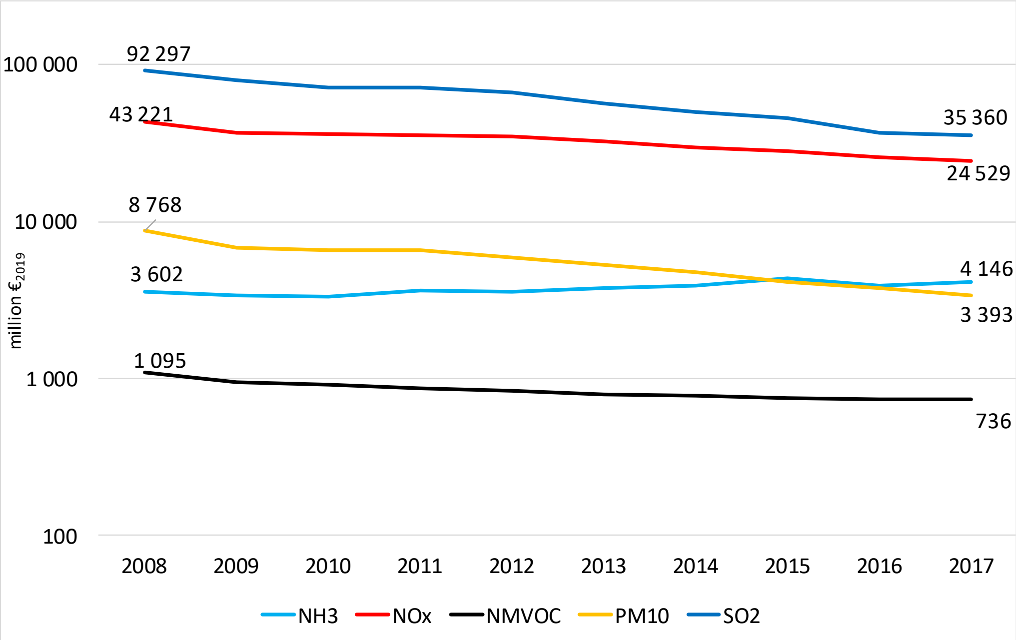


Figure 24 presents the damage cost by the main air pollutants in 2017 for the two alternative estimates (VOLY & VSL). The wide range in the estimated damage costs illustrates the large sensitivity of results in terms of both the values and methods used to calculate the pollutant-specific damage costs.

Figure 24: Damage costs for main air pollutants in 2017 (million €$_{2019}$) – indicators VOLY and VSL for mortality

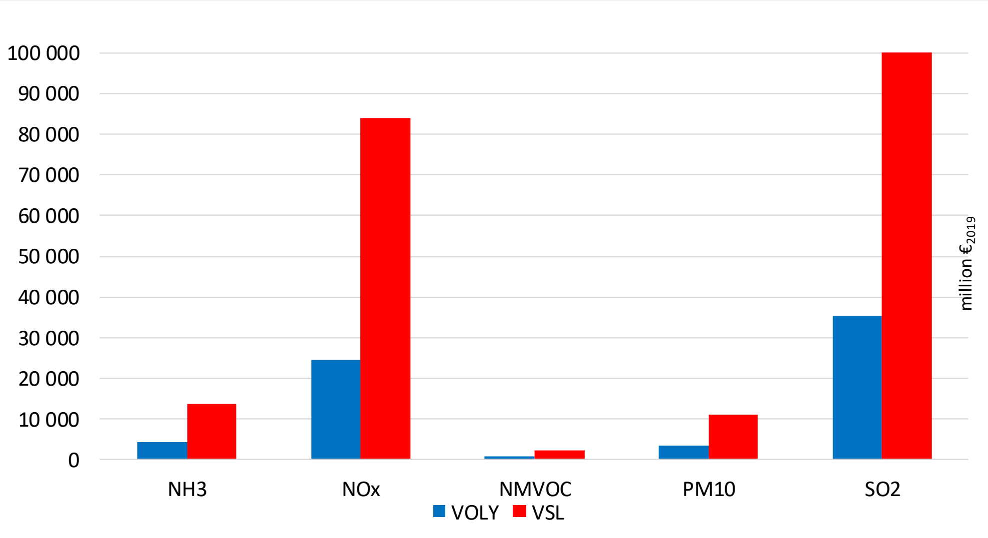
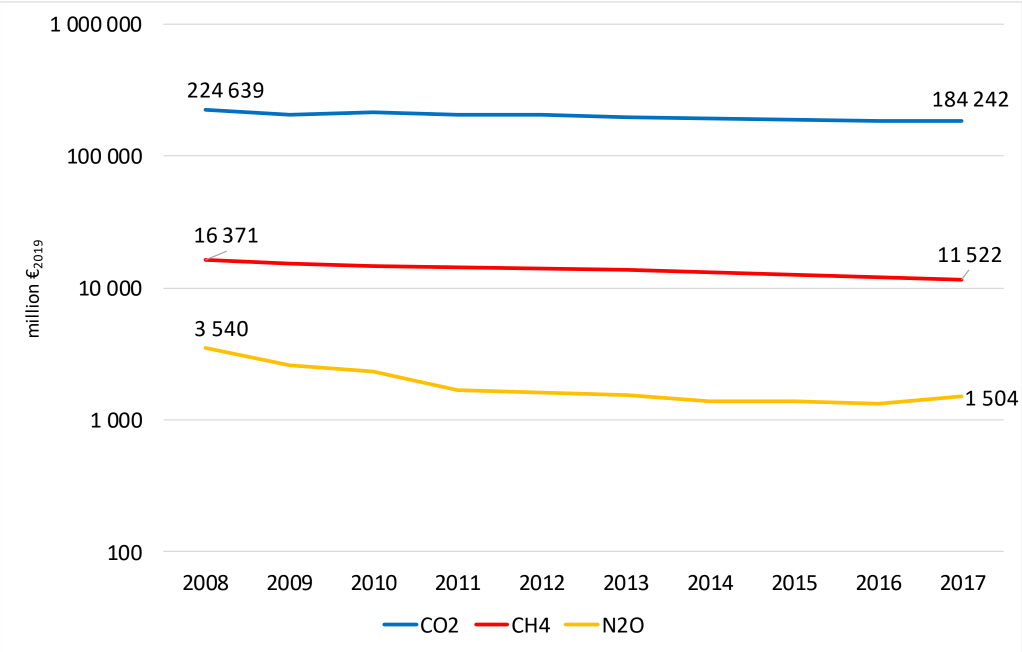


Figure 25 shows the damage costs by greenhouse gas considered, for the period 2008 to 2017. Damage from the 3 greenhouse-gases considered was reduced over the period. In 2017 relative to 2008, the percentage reduction was most important for N_2O, followed by CH_4 and CO_2.

Figure 25: Damage costs for greenhouse gases from 2008 to 2017 (million €$_{2019}$)

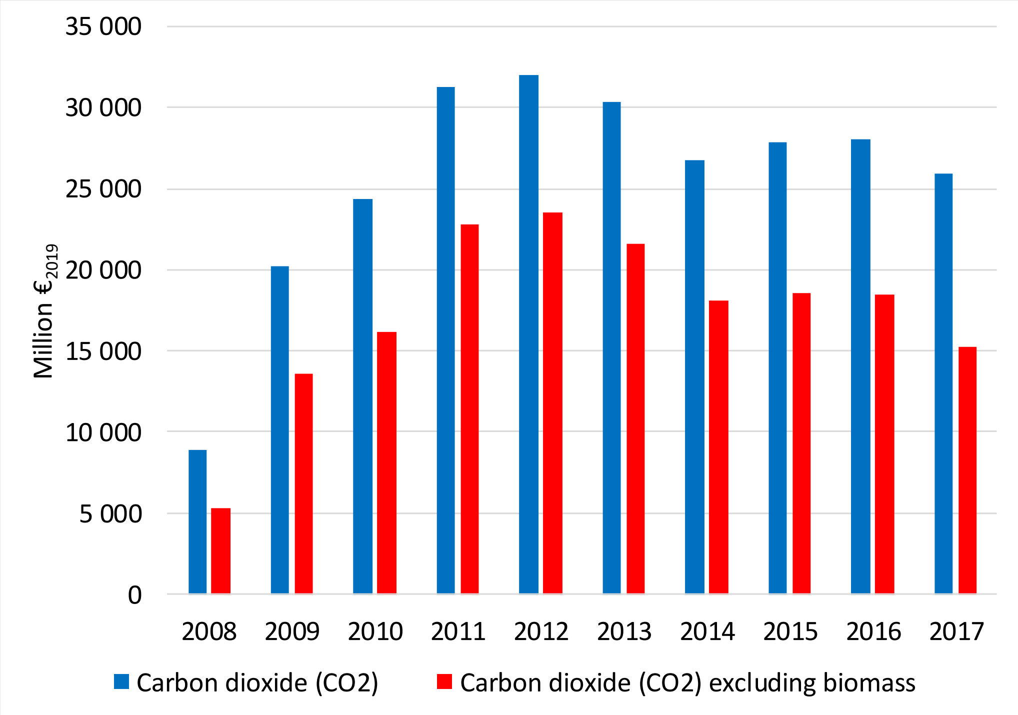


A question arises regarding the inclusion or exclusion, in the damage cost assessment, of CO_2 from biomass combustion: the assumption often applied is that biomass would decay, releasing CO_2 and so its sustainable use is contained within the natural carbon cycle. There are at least two further issues to consider, however. The first is that promotion of renewable energy technologies has led to a high level of industrialisation of biomass burning. Some old coal-fired power stations (e.g. in Belgium, Poland and the UK) have been converted to burn biomass in large quantities, in the order of several million tonnes each year. In the case of the Drax plant in the UK, wood is imported from the Southern US States. Further debate is needed on the sustainability of these activities. A second issue concerns the timescales for release. Natural decay of wood will occur over perhaps many years, whilst combustion releases the CO_2 instantaneously (Johnson, 2009; Cherubini et al., 2011). A further issue is the short-term impact of black carbon. While most experts agree that biomass use is not necessarily carbon neutral, the scientific debate on what assumptions to use with respect to the CO_2 emissions of biomass combustion is unresolved.

It would have been interesting to present, in the two previous figures, the difference in damage from carbon emissions depending on whether or not CO_2 emissions from biomass are accounted for. This has not been possible because only a subset of facilities reporting to E-PRTR report explicitly total carbon emissions and carbon emissions excluding biomass.

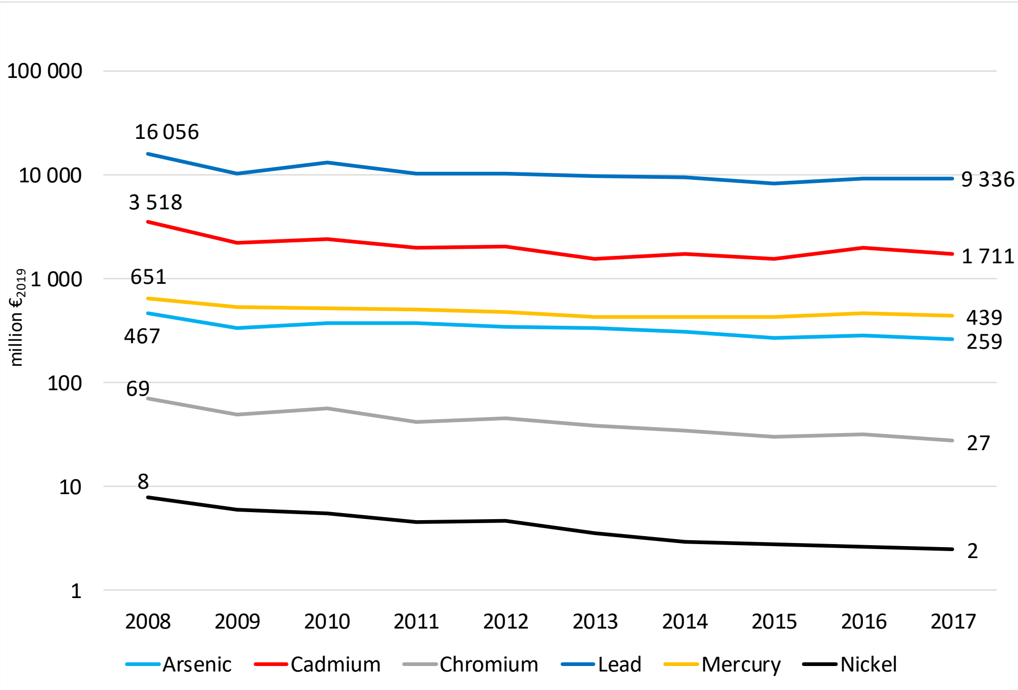
For those who do, Figure 26 compares the damage from total CO_2 emissions and from CO_2 emissions excluding biomass combustion. Depending on the year, the latter are between 26 % and 41 % lower.

Figure 26: Comparison of damage costs from total CO2 emissions and CO2 emissions excluding biomass combustion reported – selected facilities



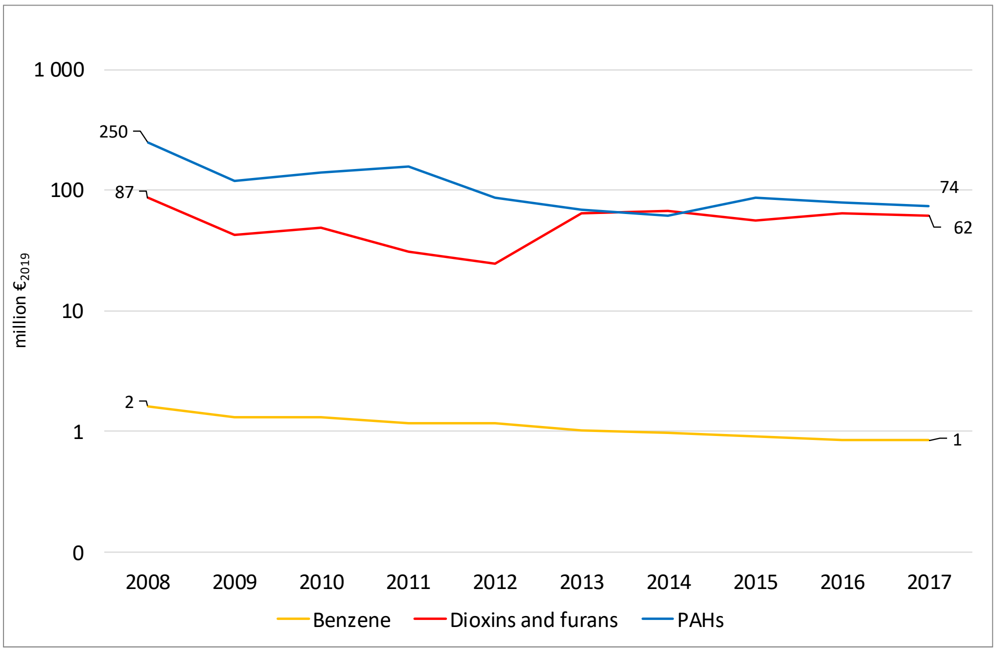
Between 2008 and 2017, estimated damage costs also decreased from all toxic metals considered (Figure 27). In 2017 relative to 2008, the decrease was most prominent for nickel, followed by chromium and cadmium, before arsenic, lead and mercury. As a reminder, the mercury burden is for the global population, of which around 40 % affects Europe directly.

Figure 27: Damage costs for heavy metals from 2008 to 2017 (million €$_{2019}$)



The evolution of estimated damage costs from organic pollutants over the period from 2008 to 2017 is presented in Figure 28.

Figure 28: Damage costs for organic pollutants from 2008 to 2017 (million €$_{2019}$)



When comparing 2017 to 2008, estimated damage was reduced most for PAHs and least for dioxins and furans, although there is a significant year-to-year variability.

9.2 Damage costs aggregated over Europe by sector

9.2.1 Damage cost aggregated over all four pollutant groups

Estimated damage aggregated over Europe and over all pollutants by EEA sub-sector is dominated by emissions from energy production and heavy industry, followed by fuel production and processing (Table 39). Estimated damage from waste management and light industry is in the same order of magnitude. Lowest contributions to the estimated damage come from the sectors livestock and wastewater treatment.

Table 39: Damage costs by EEA sector from 2008 to 2017 – aggregate over all pollutants (million €$_{2019}$) – VOLY valuation

VOLY, million €$_{2019}$	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Energy production	232 767	217 097	212 238	199 984	199 360	185 436	169 699	163 648	149 671	146 711
Heavy industry	112 656	84 921	93 012	90 062	84 232	81 760	82 676	77 880	76 461	74 454
Fuel production and processing	37 317	33 341	31 782	30 181	27 534	24 695	23 614	22 801	22 976	23 476
Waste management	15 964	15 699	15 166	16 037	17 698	15 722	15 388	15 335	15 115	15 783
Light industry	12 230	11 824	14 135	12 433	12 516	12 124	12 147	12 097	12 077	13 314
Livestock	2 914	2 703	2 616	2 864	2 780	3 195	3 462	3 890	3 276	3 423
Wastewater treatment	792	319	256	188	349	370	428	473	177	184
Sum	**414 641**	**365 904**	**369 205**	**351 750**	**344 469**	**323 302**	**307 415**	**296 125**	**279 753**	**277 346**

This order has not changed over the period 2008 to 2017. Consequently, damage cumulated over the reporting years 2008 to 2012 (Figure 29) and 2013 to 2017 (Figure 30) and damage in 2017 (Figure 31) show similar patterns.

Figure 29: Damage costs by EEA sector aggregated over 2008 to 2012 and over all pollutants, in million €2019

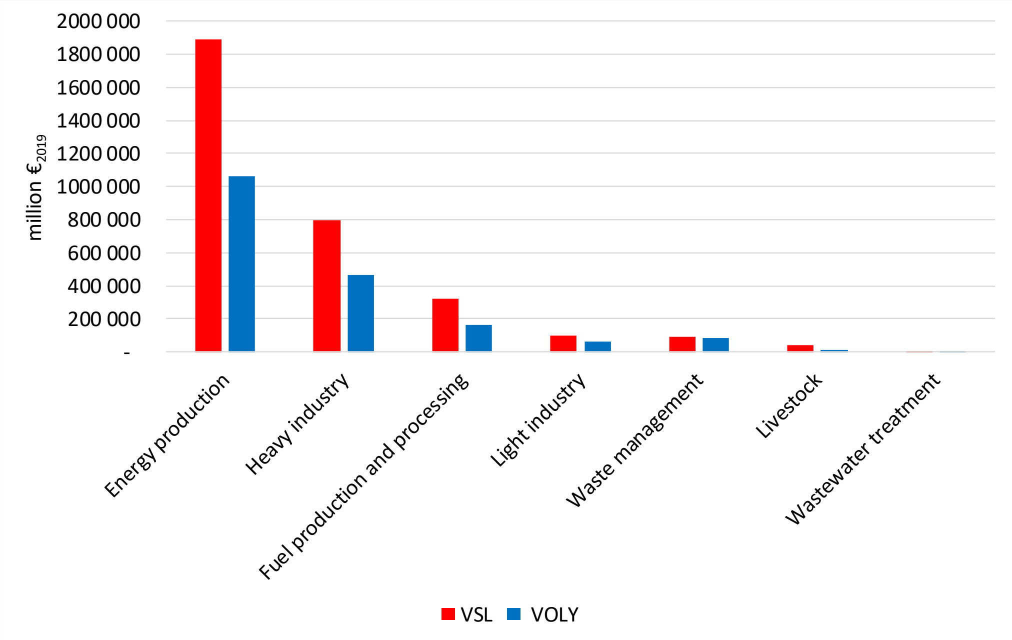


Figure 30: Damage costs by EEA sector aggregated over 2013 to 2017 and over all pollutants, in million €2019

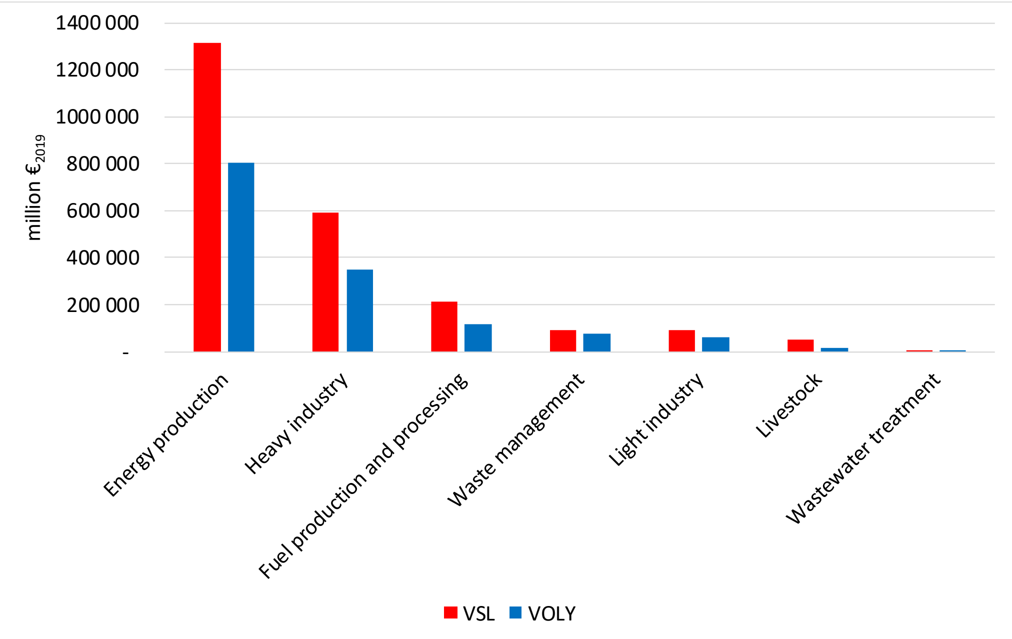
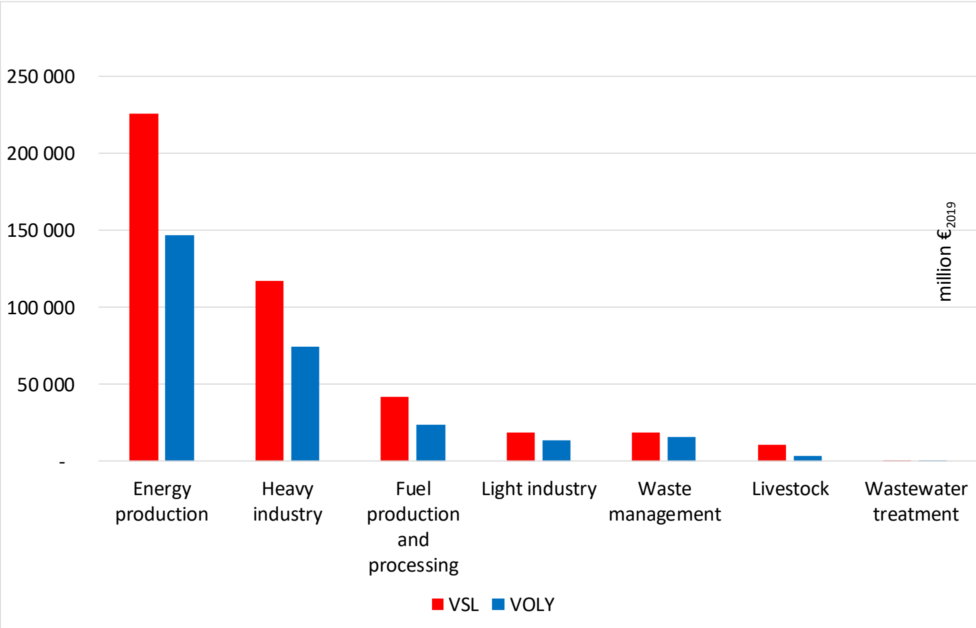


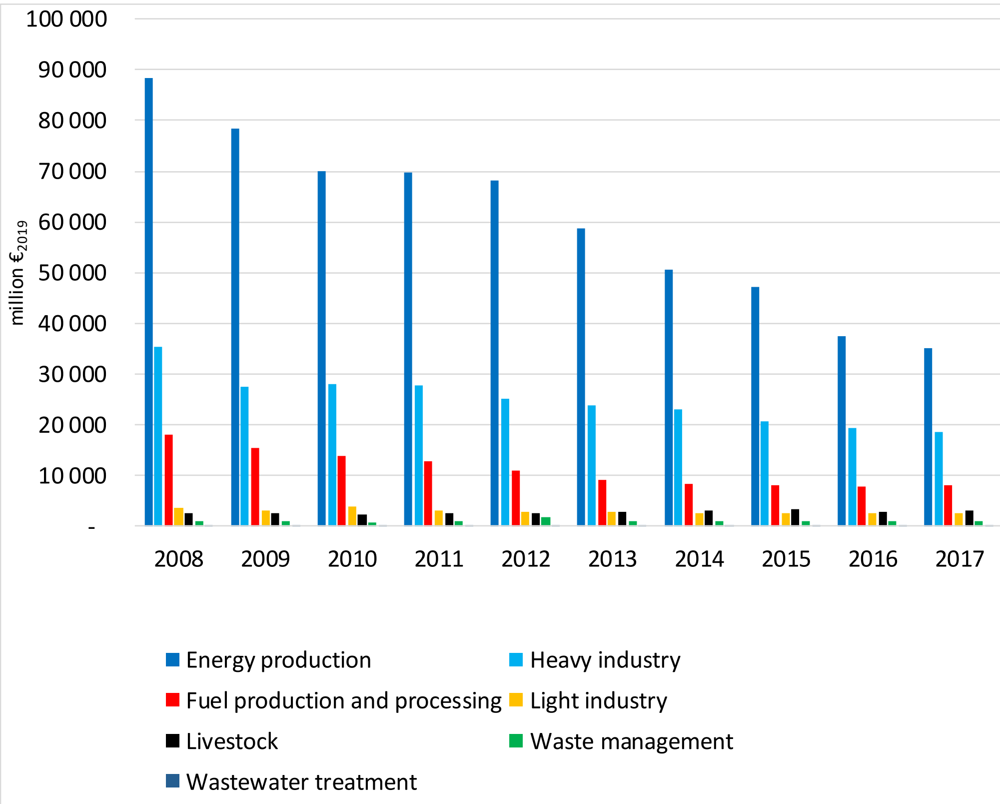
Figure 31: Damage costs by EEA sector in 2017 aggregated over all pollutants, in million €$_{2019}$



9.2.2 Damage cost aggregated by pollutant group

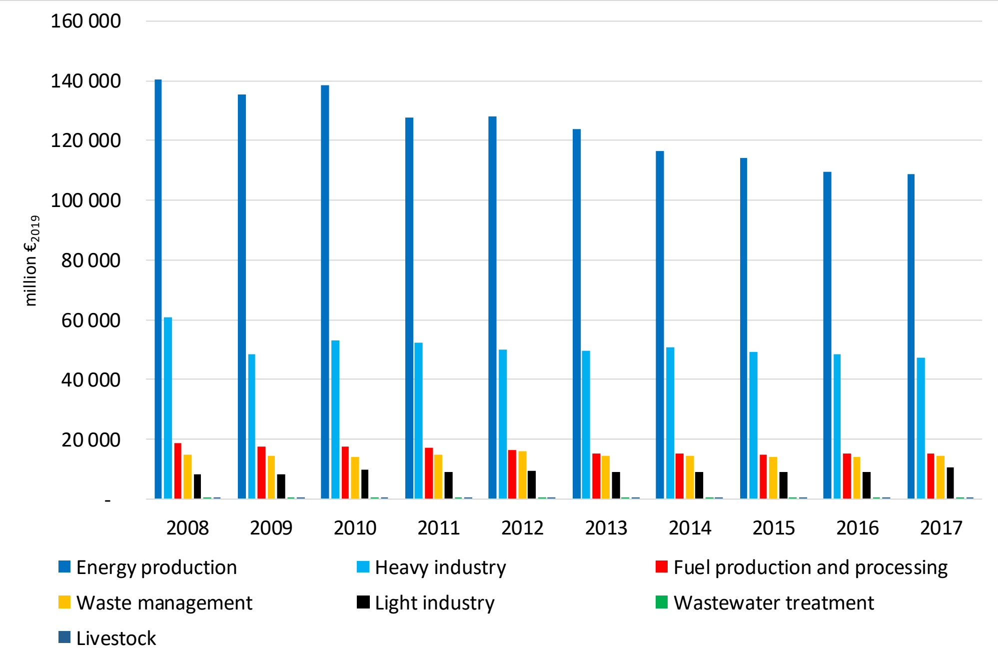
The ranking is slightly different when looking at the main air pollutants specifically. Again, estimated damage is highest from energy production and heavy industry, followed by fuel production and processing, then light industry and livestock and finally waste management and wastewater treatment (Figure 32).

Figure 32: Damage costs of main air pollutants by EEA sector 2008 - 2017, in million €$_{2019}$



When considering greenhouse gases, estimated damage is dominated by emissions from the sector energy production, followed by heavy industry, fuel production and processing, waste management and light industry. Contributions of livestock and wastewater treatment to overall damage are low (Figure 33).

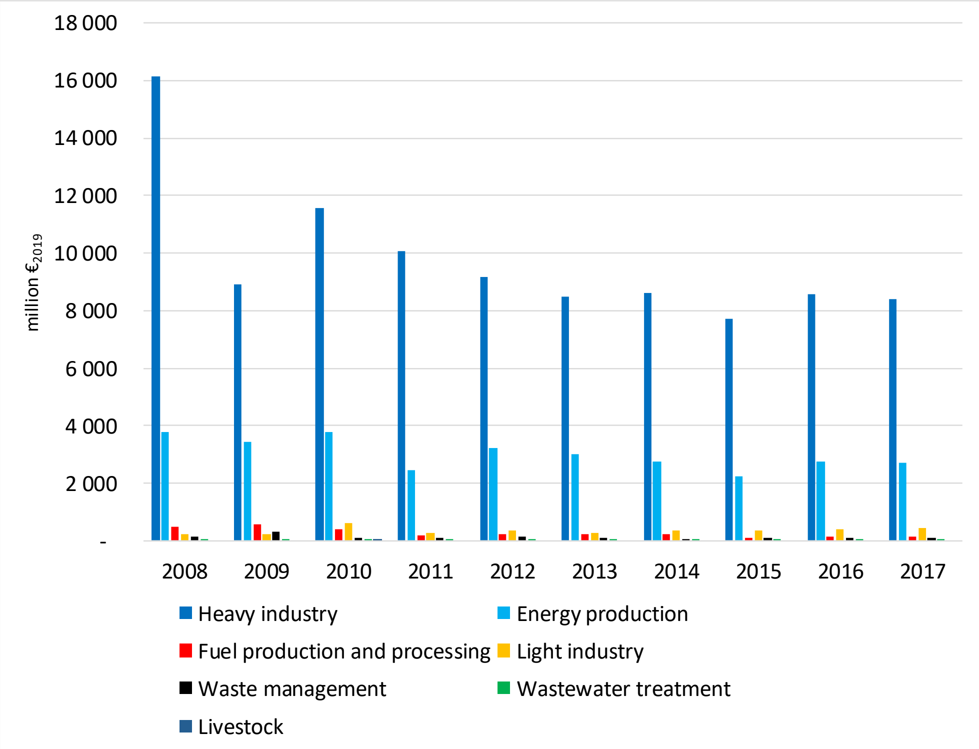
Figure 33: Damage costs of greenhouse gases by EEA sector 2008 - 2017, in million €$_{2019}$



In 2008, damage estimated from heavy metals is dominated by heavy industry and energy production. This is followed by the sectors fuel production, light industry and waste management (Figure 34). Over time, the relative position of fuel production and processing, light industry and waste management changes.

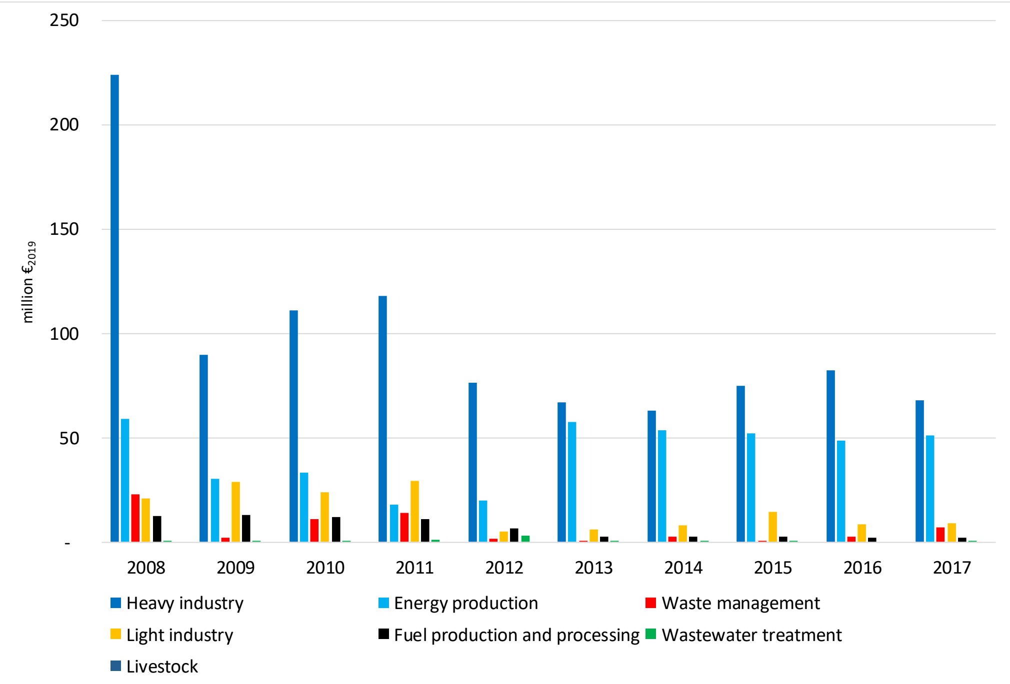
A decrease in damage from 2008 to 2009, followed by a slight increase for several sectors is visible in this figure, and in the following figure showing damage estimated from organic pollutants. This might be explained by the economic crisis to some extent.

Figure 34: Damage costs of heavy metals by EEA sector 2008 - 2017, in million €$_{2019}$



In 2008, damage estimated from organic pollutants is dominated by the sector heavy industry. Other contributors are energy production, waste management, light industry and fuel production and processing (Figure 35). As was the case for heavy metals, the exact order of some sectors changes between years. In the case of organic pollutants this concerns energy production, waste management and light industry.

Figure 35: Damage costs of organic pollutants by EEA sector 2008 - 2017, in million €$_{2019}$



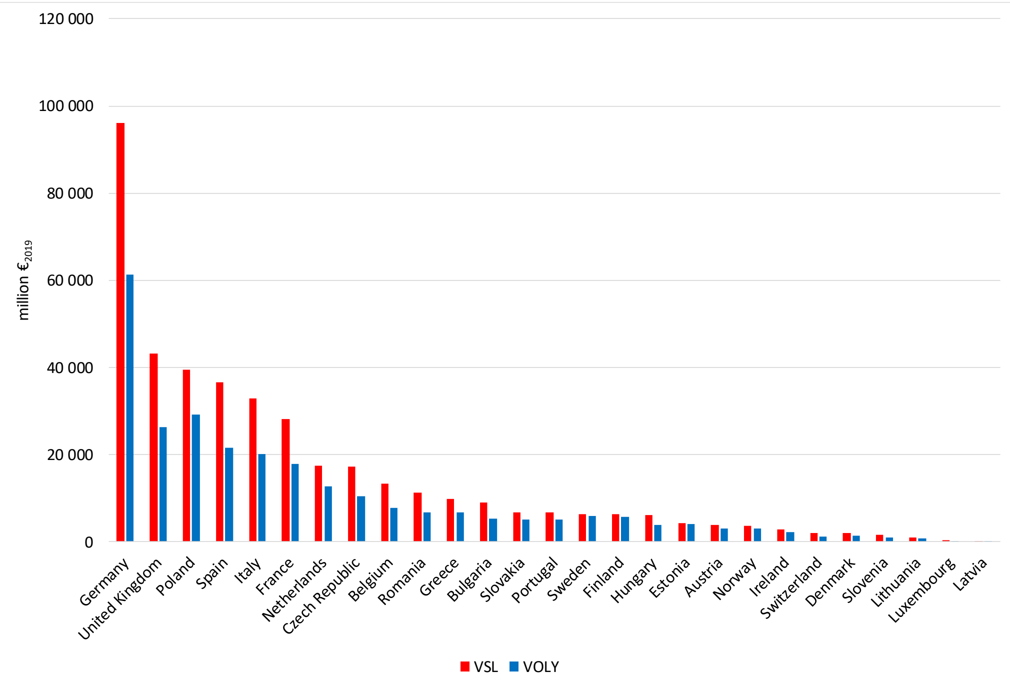
9.3 Damage costs aggregated over Europe by country

In this section, the analysis focuses on the year 2017.

9.3.1 Damage cost aggregated over all four pollutant groups

In Figure 36 damage costs aggregated over all pollutants and impacts (health, crops & forests, building materials) are presented, for the two indicators for mortality. For the VSL estimate, estimated damage is highest in Germany, the UK, Poland, Spain, Italy and France, all countries with many industrial facilities. In this figure, Croatia, Serbia, Malta and Cyprus were excluded because their reporting was incomplete for some pollutant groups. Iceland is excluded because we lack marginal damage costs for health effects from main air pollutants for this country.

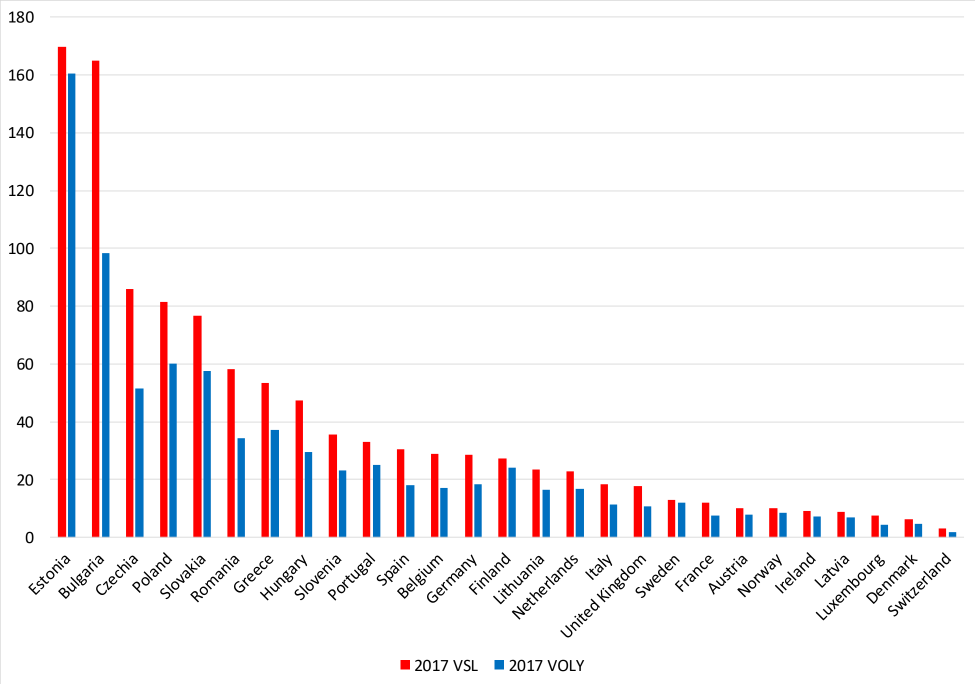
Figure 36: Damage costs by country in 2017 aggregated over all pollutant groups (million €$_{2019}$)



In Figure 37, GDP[37] is used as an indicator of national production to normalise the national damage costs against the respective level of services generated by the national economies. When applying this measure, certain countries previously shown as having the highest damage costs — Germany, the United Kingdom, Spain, Italy or France — drop significantly down the ranking, while Estonia, Bulgaria and Czechia rise to the top. Poland remains toward the top of the ranking, indicating high amounts of pollutants relative to GDP emitted at Polish facilities. In this figure, again, Croatia, Serbia, Malta and Cyprus were excluded because their reporting was incomplete for some pollutant groups. Iceland is excluded because we lack marginal damage costs for health effects from main air pollutants for this country.

[37] Gross domestic product at market prices [TEC00001], https://ec.europa.eu/eurostat/databrowser/view/tec00001/default/table?lang=en. GDP for 2017 at market prices was converted to €$_{2019}$ price base using the HICP coefficient (Eurostat) of 1.03393 for EU28.

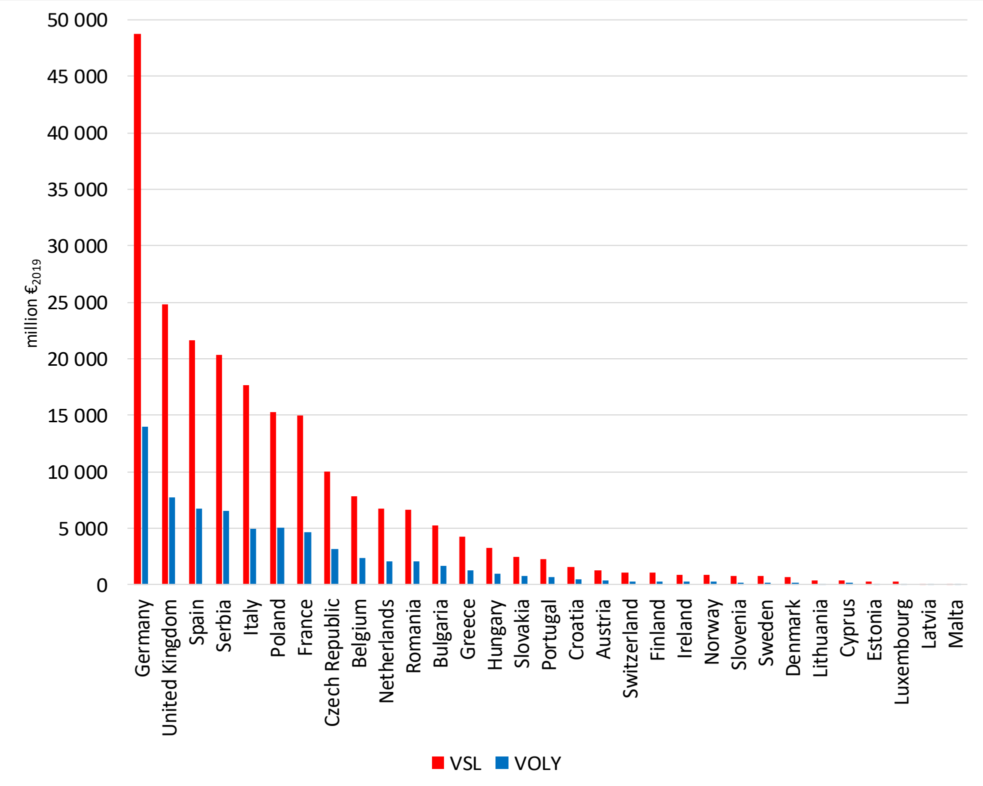
Figure 37: Damage costs by country in 2017 aggregated over all pollutant groups normalised against GDP, 2017



9.3.2 Damage cost by pollutant group

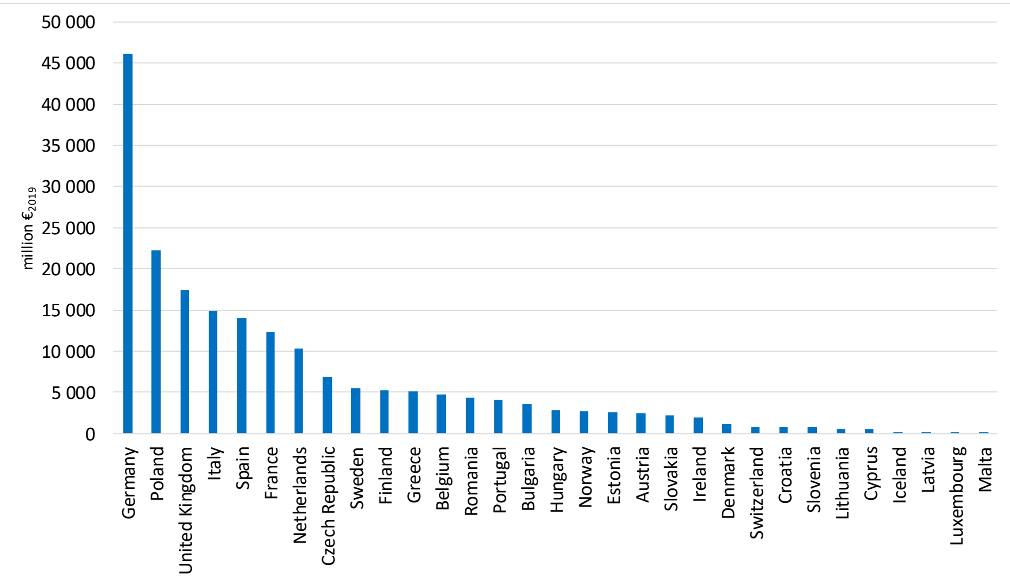
When considering damage from the main air pollutants only (Figure 38), the countries for which estimates are the highest change. Serbia appears in the fourth position. This country was excluded in the previous two figures because in 2017 the only pollutants for which it reported emissions were the main air pollutants. Iceland is excluded from this presentation as we lack MDCs for this country.

Figure 38: Damage costs by country for the main air pollutants in 2017 (million €$_{2019}$)



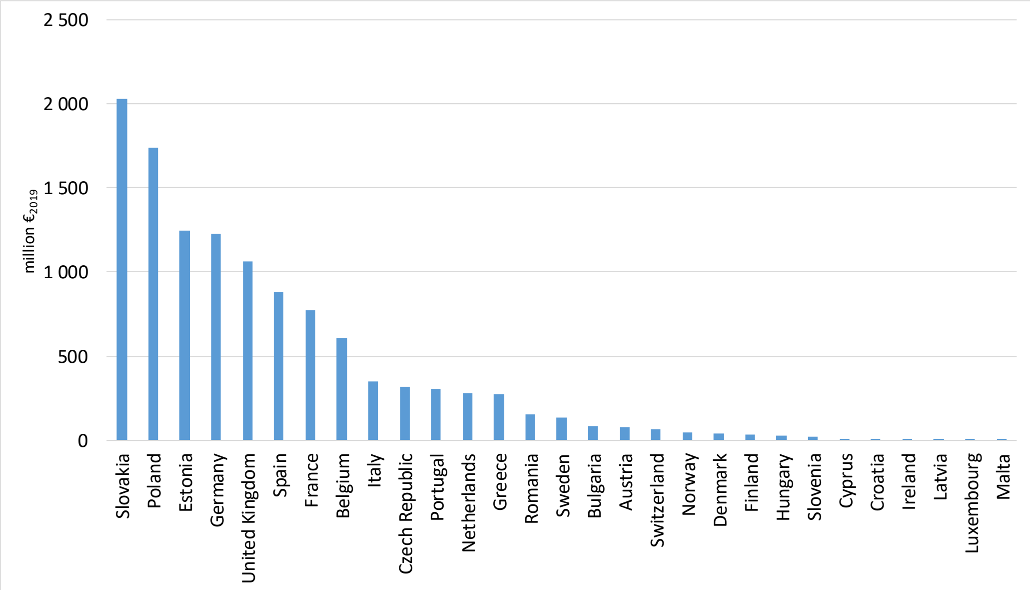
For greenhouse gases the pattern is similar to that for the aggregate over all pollutants, with highest estimated damage for the countries with the highest number of facilities: Germany, Poland, the UK, Italy, Spain and France (Figure 39). In this figure Serbia is excluded, not having reported any greenhouse gases.

Figure 39: Damage costs by country for greenhouse gases in 2017 (million €$_{2019}$)



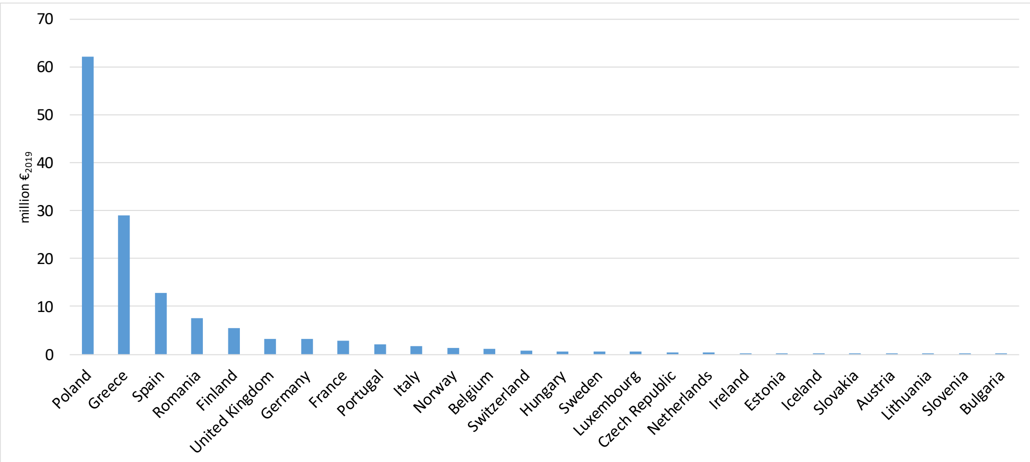
Estimated damage from heavy metals brings different countries to the highest positions: estimated health damage in Slovakia and Estonia exceeds that of Germany, the UK, Spain, Italy and France (Figure 40). Lithuania and Iceland have not reported any emissions of heavy metals.

Figure 40: Damage costs by country for heavy metals in 2017 (million €$_{2019}$)



Estimated damage for organic pollutants brings Romania to the fourth position (Figure 41). Denmark, Cyprus, Malta, Latvia and Croatia have not reported organic pollutants in 2017.

Figure 41: Damage costs by country for organic pollutants in 2017 (million €$_{2019}$)

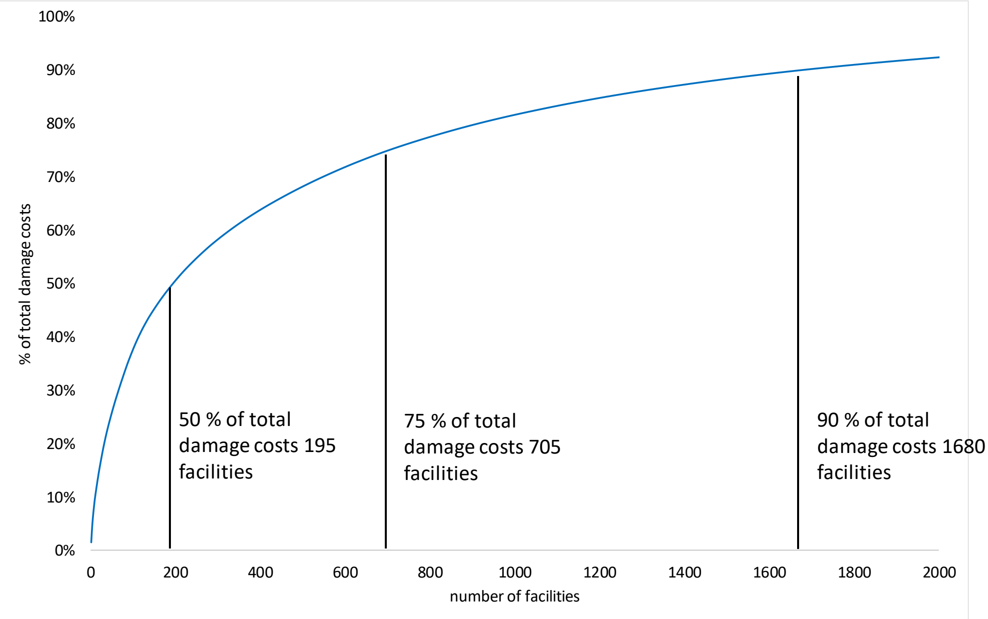


10 Damage costs for individual facilities

10.1 Cumulative distribution of damage costs associated with emissions of selected pollutants

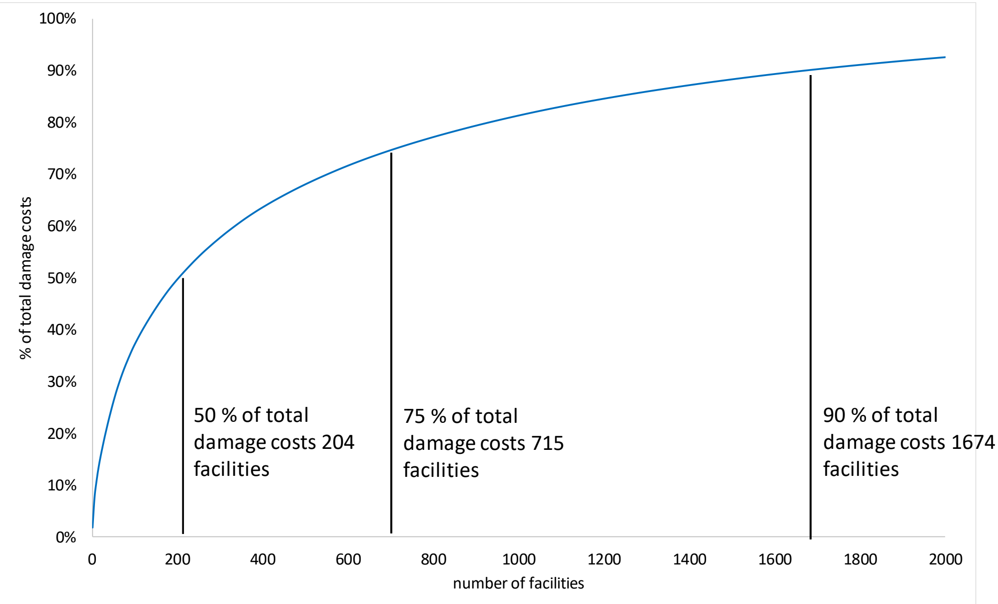
The following three figures present the cumulative distribution of estimated damage for the first 2000 facilities in terms of damage. Estimated damage here accounts for health impacts from main air pollutants (using the lower estimate relying on mortality valuation with VOLY) and damage from greenhouse gases. In Figure 42 damage is cumulated over the years 2008 to 2012, in Figure 43 it is cumulated over the years 2013 to 2017, and in Figure 44 estimated damage is presented for the last reporting year (2017).

Figure 42: Cumulative distribution of the estimated damage costs from main air pollutants and greenhouse gases, 2008–2012 – mortality valued using the VOLY indicator



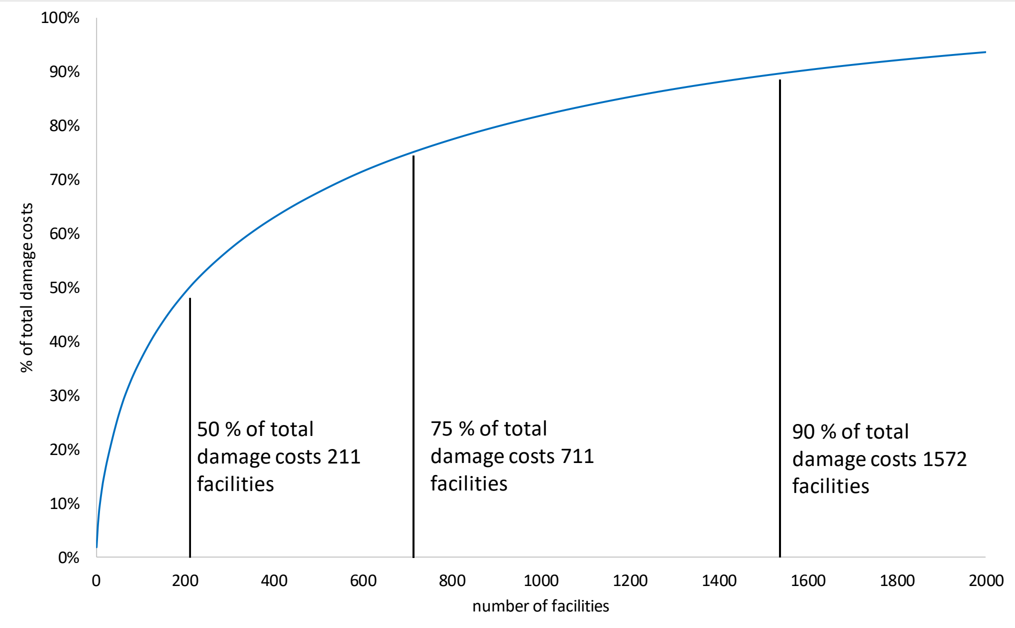
The figures show that it is a small fraction of the facilities that accounts for the highest share of estimated damage. In the period 2008-2012 195 facilities accounted for 50 % of estimated damage, 705 for 75 % and 1680 for 90 % (Figure 42).

Figure 43: Cumulative distribution of the estimated damage costs from main air pollutants and greenhouse gases, 2013–2017 – mortality valued using the VOLY indicator



In the period 2013-2017 204 facilities accounted for 50 % of estimated damage, 715 for 75 % and 1674 for 90 % (Figure 43).

Figure 44: Cumulative distribution of the estimated damage costs from main air pollutants and greenhouse gases, 2017 – mortality valued using the VOLY indicator



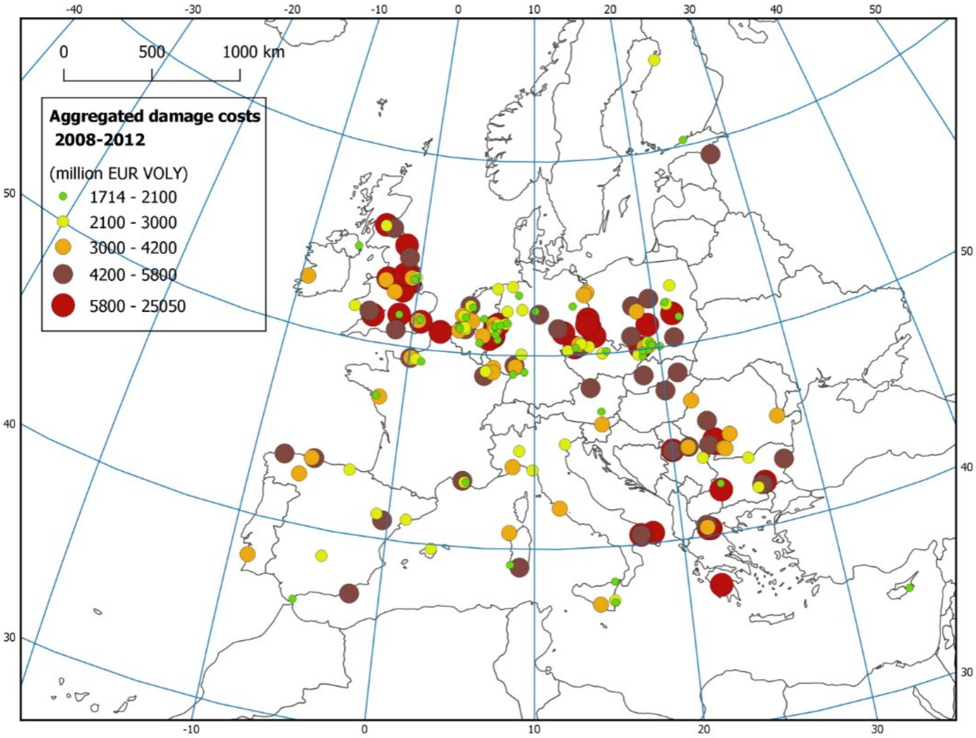
In 2017 211 facilities accounted for 50 % of estimated damage, 711 for 75 % and 1572 for 90 % (Figure 44). This corresponds to 1.8 %, 6.1 % and 13.5 %, respectively, in the total number of facilities (11655[38]) having reported emissions from main air pollutants and greenhouse gases in 2017.

The cumulative distribution changes slightly when choosing the higher VSL estimate. In 2017, for example, 192 facilities account for 50 % of the damage when choosing the VSL indicator, 713 account for 75 % and 1673 account for 90 % of the overall damage.

Figure 45, Figure 46 and Figure 47 present the location of the top 50 % polluters for the 3 periods considered (2008-2012, 2013-2017, and 2017), again accounting for damage from main air pollutants and greenhouse gases. Colour code and size of circles indicate the size range of estimated damage.

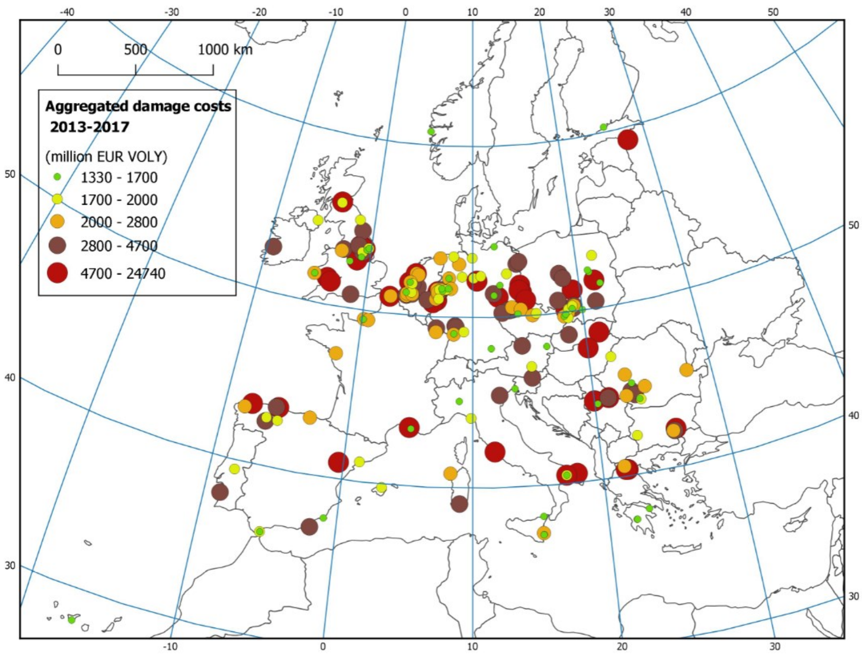
[38] 11 893 facilities reported emissions from main air pollutants, organic pollutants, heavy metals and greenhouse gases in 2017.

Figure 45: Localisation of the 195 installations accounting for 50 % of the aggregate damage costs from main air pollutants (VOLY) and greenhouse gases in 2008-2012



Countries in which the top polluters are situated were in the period from 2008 to 2012 above all the UK, Bulgaria, Poland, Germany, Greece and Romania, and amongst others also Slovakia, Serbia, Czechia and Estonia (cf. also Table 40).

Figure 46: Localisation of the 204 installations accounting for 50 % of the aggregate damage costs from main air pollutants (VOLY) and greenhouse gases in 2013-2017



In the period from 2013 to 2017 the top polluters came from Poland, Germany, the UK, Bulgaria, France, Serbia, Greece and Italy. Highly polluting fcailities are, amiongst others, also situated in Slovakia, Spain and Estonia (cf. also Table 41).

And in 2017 the most polluting facilities were situated in Poland, Germany, the UK, Serbia, Bulgaria, France, and Italy. Highly polluting facilities were also found, amongst others, in Greece, Spain, the Netherlands, Hungary, Portugal, Estonia and Slocakia (cf. also Table 42).

Figure 47: Localisation of the 211 installations accounting for 50 % of the aggregate damage costs from main air pollutants (VOLY) and greenhouse gases in 2017

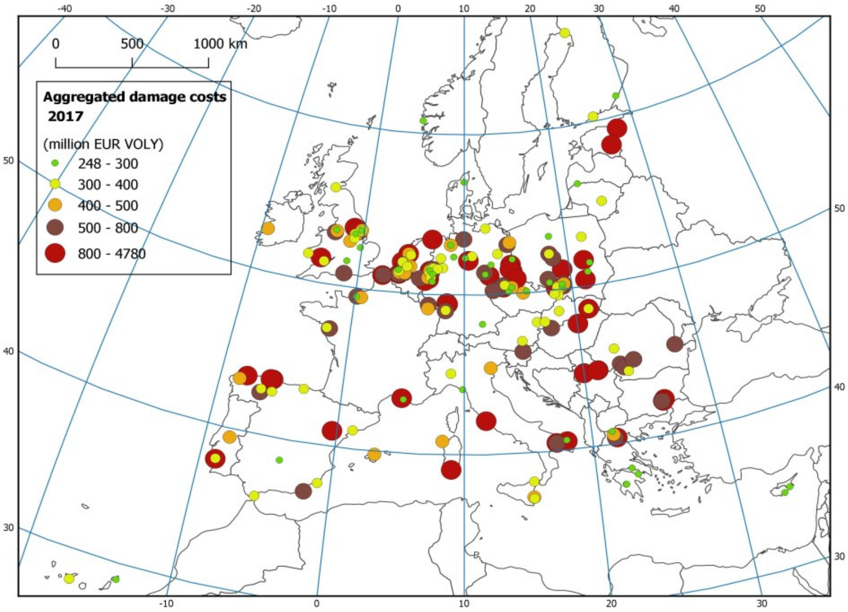
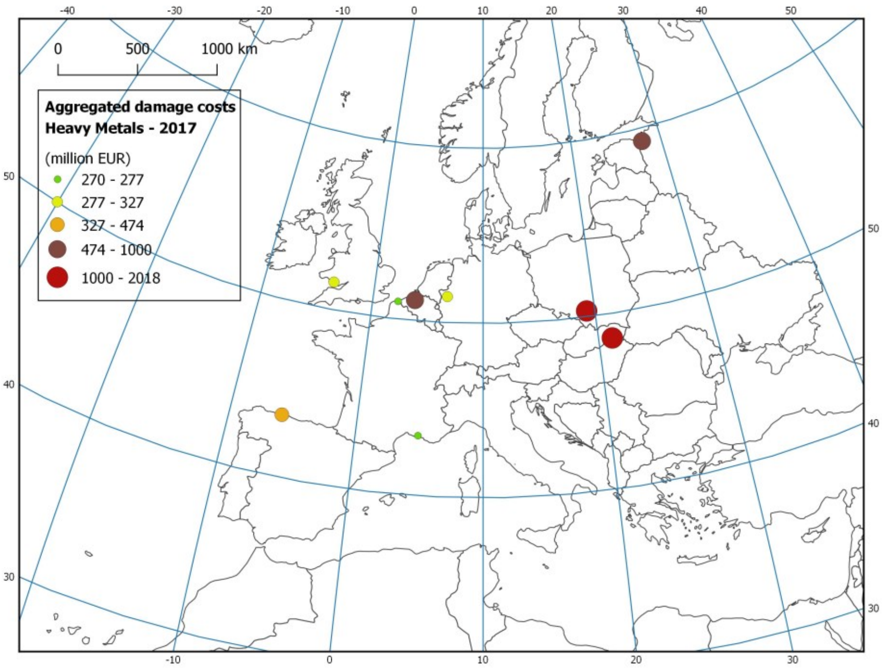


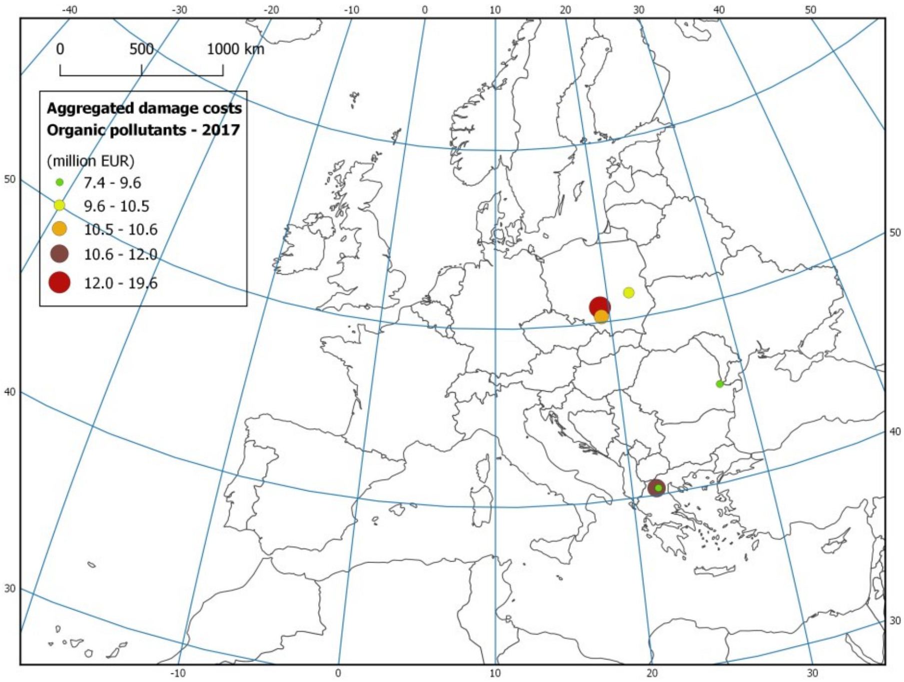
Figure 48 and Figure 49 present the location of the top 50 % polluters in 2017, accounting for damage from heavy metals and from organic species, respectively. Damage from these pollutants is even more concentrated in a few facilities.

Figure 48: Localisation of the 9 installations accounting for 50 % of the aggregate damage costs from heavy metals in 2017



With respect to heavy metals, the facilities responsible for the highest damage in 2017 are situated in Slovakia and Poland, followed by Estonia and Belgium.

Figure 49: Localisation of the 6 installations accounting for 50 % of the aggregate damage costs from organic pollutants in 2017



With respect to organic pollutants, the facilities responsible for the highest damage are situated in Poland and Greece.

10.2 The top 30 E-PRTR facilities having the highest absolute damage costs from emissions of selected pollutants – complete set of facilities

The tables below show the top 30 E-PRTR facilities having the highest absolute damage costs from main air pollutants and greenhouse gases. Table 40 shows the results cumulated over the period 2008-2012, Table 41 cumulated over the period 2013-2017, and Table 42 for the latest reporting year, 2017. Ordering is based on the VOLY estimate. Ordering by the VSL estimate would lead to slightly diverging results as obvious when considering column 7 of the tables. In these estimates all facilities were included, also those that have not reported emissions in every year or shut within the period.

Most of the facilities accounting for the highest absolute damage are thermal power stations and other combustion plants. In the period 2008-2012 one iron and steel plant was amongst the top 30 polluters and one installation for the processing of ferrous metals. In the period 2013 to 2017 there were 4 iron and steel plants, one metal ore roasting or sintering installation and one installation for the processing of ferrous metals. And in 2017 there were 3 iron and steel plants, one facility for the processing of ferrous metals, one metal ore roasting or sintering installation and one chemical installation for the production of basic organic chemicals amongst the top 30 polluters.

Table 40: The top 30 E-PRTR facilities having the highest absolute damage costs from emissions of the main air pollutants and greenhouse gases, aggregated over the 5-year period 2008–2012– ranking based on the VOLY estimate

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$	Aggregate damage cost (VSL) in million €$_{2019}$
1	Drax Power Limited; Drax Power Ltd	SELBY	United Kingdom	Thermal power stations and other combustion installations	25 046	44 990
2	TETs Maritsa iztok 2 EAD	Kovachevo	Bulgaria	Thermal power stations and other combustion installations	24 896	65 076
3	PGE Elektrownia Belchatów S.A.	Rogowiec	Poland	Thermal power stations and other combustion installations	23 598	37 397
4	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Peitz	Germany	Thermal power stations and other combustion installations	18 552	33 107
5	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Thermal power stations and other combustion installations	17 159	24 543
6	Longannet Power Station	Kincardine	United Kingdom	Thermal power stations and other combustion installations	14 553	31 723
7	COMPLEXUL ENERGETIC TURCENI	TURCENI	Romania	Thermal power stations and other combustion installations	13 762	35 557
8	RWE Power AG Kraftwerk Neurath	Grevenbroich	Germany	Thermal power stations and other combustion installations	12 991	18 416
9	RWE Power AG	Eschweiler	Germany	Thermal power stations and other combustion installations	12 601	17 921
10	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Thermal power stations and other combustion installations	11 011	17 971
11	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS; ELLISPONTOS	Greece	Thermal power stations and other combustion installations	10 214	16 849
12	EDF Energy (Cottam Power) Ltd; Cottam Power Station	Retford	United Kingdom	Thermal power stations and other combustion installations	9 706	16 483
13	RWE Power AG Kraftwerk Frimmersdorf	Grevenbroich	Germany	Thermal power stations and other combustion installations	9 672	14 453
14	COMPLEXUL ENERGETIC ROVINARI	ROVINARI	Romania	Thermal power stations and other	9 497	23 737

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €2019	Aggregate damage cost (VSL) in million €2019
				combustion installations		
15	PGE Elektrownia Turów S.A.	Bogatynia	Poland	Thermal power stations and other combustion installations	9 338	16 105
16	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	Thermal power stations and other combustion installations	9 214	16 700
17	Elektrownia KOZIENICE S.A.	Swierze Górne	Poland	Thermal power stations and other combustion installations	8 910	15 629
18	CENTRALE TERMOELETTRICA Federico II (BR SUD)	BRINDISI	Italy	Thermal power stations and other combustion installations	8 894	14 906
19	ILVA S.P.A. Stabilimento di Taranto	TARANTO	Italy	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	8 664	18 813
20	Kraftwerk Schwarze Pumpe GmbH	Spremberg	Germany	Thermal power stations and other combustion installations	8 131	12 847
21	PD Termoelektrane Nikola Tesla; TENT A	Beograd; Obrenovac	Serbia	Thermal power stations and other combustion installations	8 014	24 895
22	EDF Energy (West Burton Power) Ltd; West Burton Power Station	RETFORD	United Kingdom	Thermal power stations and other combustion installations	7 983	13 735
23	E.ON UK plc; Ratcliffe-on-Soar Power Station	NOTTINGHAM	United Kingdom	Thermal power stations and other combustion installations	7 765	14 757
24	Elektrárny Prunérov	Kadan	Czech Republic	Thermal power stations and other combustion installations	7 642	14 381
25	PPC S.A. SES MEGALOPOLIS A’	MEGALOPOLI	Greece	Thermal power stations and other combustion installations	7 639	19 376
26	Eggborough Power Ltd; Eggborough Power Station	Goole	United Kingdom	Thermal power stations and other combustion installations	7 540	13 996
27	Keadby Generations LTD; FIDDLERS FERRY POWER STATION	WARRINGTON	United Kingdom	Thermal power stations and other combustion installations	7 416	13 518

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$	Aggregate damage cost (VSL) in million €$_{2019}$
28	ARCELORMITTAL SITE DE DUNKERQUE	GRANDE-SYNTHE	France	Installations for the processing of ferrous metals	7 323	11 017
29	Keadby Generations LTD; Ferrybridge 'C' Power Station	Knottingley	United Kingdom	Thermal power stations and other combustion installations	7 256	14 265
30	RWE npower plc; Aberthaw Power Station	Barry	United Kingdom	Thermal power stations and other combustion installations	6 947	13 192

Table 41: The top 30 E-PRTR facilities having the highest absolute damage costs from emissions of the main air pollutants and greenhouse gases, aggregated over the 5-year period 2013–2017 - ranking based on the VOLY estimate

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €2019	Aggregate damage cost (VSL) in million €2019
1	PGE Elektrownia Belchatów S.A.	Rogowiec	Poland	Thermal power stations and other combustion installations	24 737	35 837
2	RWE Power AG Kraftwerk Neurath	Grevenbroich	Germany	Thermal power stations and other combustion installations	20 124	28 913
3	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Peitz	Germany	Thermal power stations and other combustion installations	18 215	31 498
4	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Thermal power stations and other combustion installations	17 933	27 128
5	Drax Power Limited; Drax Power Ltd	SELBY	United Kingdom	Thermal power stations and other combustion installations	17 237	30 627
6	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Thermal power stations and other combustion installations	13 717	22 890
7	RWE Power AG	Eschweiler	Germany	Thermal power stations and other combustion installations	11 925	17 200
8	TETs Maritsa iztok 2 EAD	Kovachevo	Bulgaria	Thermal power stations and other combustion installations	9 138	17 051
9	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	Thermal power stations and other combustion installations	8 748	15 688
10	Elektrownia KOZIENICE S.A.	Swierze Górne	Poland	Thermal power stations and other combustion installations	8 471	13 366
11	ARCELORMITTAL SITE DE DUNKERQUE	GRANDE-SYNTHE	France	Installations for the processing of ferrous metals	8 314	12 333
12	Kraftwerk Schwarze Pumpe GmbH	Spremberg	Germany	Thermal power stations and other combustion installations	8 252	13 195
13	PD Termoelektrane Nikola Tesla; TENT A	Beograd; Obrenovac	Serbia	Thermal power stations and other combustion installations	8 186	25 397
14	PD Termoelektrane i kopovi Kostolac; Termoelektrana Kostolac B	Kostolac	Serbia	Thermal power stations and other combustion installations	7 282	22 561
15	PD Termoelektrane Nikola Tesla; TENT B	Beograd; Obrenovac	Serbia	Thermal power stations and other combustion installations	7 147	22 140
16	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS; ELLISPONTOS	Greece	Thermal power stations and other combustion installations	6 888	9 645

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$	Aggregate damage cost (VSL) in million €$_{2019}$
17	CENTRALE TERMOELETTRICA Federico II (BR SUD)	BRINDISI	Italy	Thermal power stations and other combustion installations	6 780	10 286
18	Corus UK Limited; PORT TALBOT STEEL WORKS	PORT TALBOT	United Kingdom	Metal ore (including sulphide ore) roasting or sintering installations	6 231	11 119
19	Longannet Power Station	Kincardine	United Kingdom	Thermal power stations and other combustion installations	6 112	13 054
20	Enel Produzione SpA - Centrale di Torrevaldaliga Nord	CIVITAVECCHIA	Italy	Thermal power stations and other combustion installations	6 078	7 871
21	ArcelorMittal FOS	FOS-SUR-MER	France	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	5 932	9 935
22	CENTRAL TERMICA DE ANDORRA	ANDORRA	Spain	Thermal power stations and other combustion installations	5 754	13 510
23	RWE npower plc; Aberthaw Power Station	Barry	United Kingdom	Thermal power stations and other combustion installations	5 742	11 672
24	Scunthorpe Intergrated Iron and Steel Works	Scunthorpe	United Kingdom	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	5 573	10 903
25	PGE Elektrownia Turów S.A.	Bogatynia	Poland	Thermal power stations and other combustion installations	5 571	8 128
26	U.S.Steel s.r.o.	Košice	Slovakia	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	5 536	8 097
27	Salzgitter Flachstahl GmbH	Salzgitter	Germany	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	5 508	8 582
28	UNIDAD DE PRODUCCION TERMICA AS PONTES	PONTES DE GARCIA RODRIGUEZ (AS)	Spain	Thermal power stations and other combustion installations	5 426	9 061
29	Elektrownia RYBNIK S.A.	Rybnik	Poland	Thermal power stations and other combustion installations	5 351	8 566
30	Eggborough Power Ltd; Eggborough Power Station	Goole	United Kingdom	Thermal power stations and other combustion installations	5 302	10 625

Since the carbon cost is a dominant contribution to the combined cost of main air pollutants and greenhouse gases, Table 42 presents, additionally to the combined damage from main air pollutants and greenhouse gases, separately the damage linked to the main air pollutants.

For the lower (VOLY) estimate, the share of damage from air pollutants in the combined damage from air pollutants and greenhouse gases varies between 8 % and 100 % (facilities not having reported any greenhouse gas emissions). The mean is 32 %. For the higher (VSL) estimate, the share varies between 21 % and 100 %, with a mean of 55 %.

Table 42: The top 30 E-PRTR facilities having the highest absolute damage costs from emissions of the main air pollutants and greenhouse gases, 2017 – ranking based on the VOLY estimate

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$				Position when normalised by CO_2 emissions
					Main air pollutants and greenhouse gases		Main air pollutants		
					VOLY	VSL	VOLY	VSL	
1	PGE Elektrownia Bełchatów S.A.	Rogowiec	Poland	Thermal power stations and other combustion installations	4 772	6 449	824	2 501	861
2	RWE Power AG Kraftwerk Neurath	Grevenbroich	Germany	Thermal power stations and other combustion installations	3 775	5 405	636	2 265	883
3	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Thermal power stations and other combustion installations	3 615	5 521	759	2 665	711
4	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Peitz	Germany	Thermal power stations and other combustion installations	3 471	5 817	942	3 289	539
5	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Thermal power stations and other combustion installations	2 710	4 444	698	2 433	582
6	Drax Power Limited; Drax Power Ltd	SELBY	United Kingdom	Thermal power stations and other combustion installations	2 601	4 150	704	2 254	543
7	RWE Power AG	Eschweiler	Germany	Thermal power stations and other combustion installations	2 410	3 446	404	1 441	886
8	PD Termoelektrane i kopovi Kostolac; Termoelektrana Kostolac B	Kostolac	Serbia	Thermal power stations and other combustion installations	1 840	5 697	1 840	5 697	No CO_2 emissions reported
9	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	Thermal power stations and other combustion installations	1 758	3 125	557	1 924	425
10	TETs Maritsa iztok 2 EAD	Kovachevo	Bulgaria	Thermal power stations and other combustion installations	1 708	2 979	606	1 877	357
11	ARCELORMITTAL SITE DE DUNKERQUE	GRANDE-SYNTHE	France	Installations for the processing of ferrous metals	1 641	2 336	311	1 006	766

Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$				Position when normalised by CO_2 emissions
					Main air pollutants and greenhouse gases		Main air pollutants		
					VOLY	VSL	VOLY	VSL	
12	Kraftwerk Schwarze Pumpe GmbH	Spremberg	Germany	Thermal power stations and other combustion installations	1 583	2 498	372	1 288	639
13	Elektrownia KOZIENICE S.A.	Swierze Górne	Poland	Thermal power stations and other combustion installations	1 517	2 024	246	752	910
14	PD Termoelektrane Nikola Tesla; TENT A	Beograd; Obrenovac	Serbia	Thermal power stations and other combustion installations	1 485	4 607	1 485	4 607	No CO_2 emissions reported
15	PD Termoelektrane Nikola Tesla; TENT B	Beograd; Obrenovac	Serbia	Thermal power stations and other combustion installations	1 470	4 556	1 470	4 556	No CO_2 emissions reported
16	UNIDAD DE PRODUCCION TERMICA AS PONTES	PONTES DE GARCIA RODRIGUEZ (AS)	Spain	Thermal power stations and other combustion installations	1 247	2 122	395	1 270	431
17	Corus UK Limited; PORT TALBOT STEEL WORKS	PORT TALBOT	United Kingdom	Metal ore (including sulphide ore) roasting or sintering installations	1 179	2 189	470	1 480	287
18	ArcelorMittal FOS	FOS-SUR-MER	France	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	1 168	1 895	328	1 055	504
19	Enel Produzione SpA - Centrale di Torrevaldaliga Nord	CIVITAVECCHIA	Italy	Thermal power stations and other combustion installations	1 146	1 460	120	435	1244
20	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS; ELLISPONTOS	Greece	Thermal power stations and other combustion installations	1 144	1 588	203	647	831
21	Salzgitter Flachstahl GmbH	Salzgitter	Germany	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	1 123	1 833	290	999	591

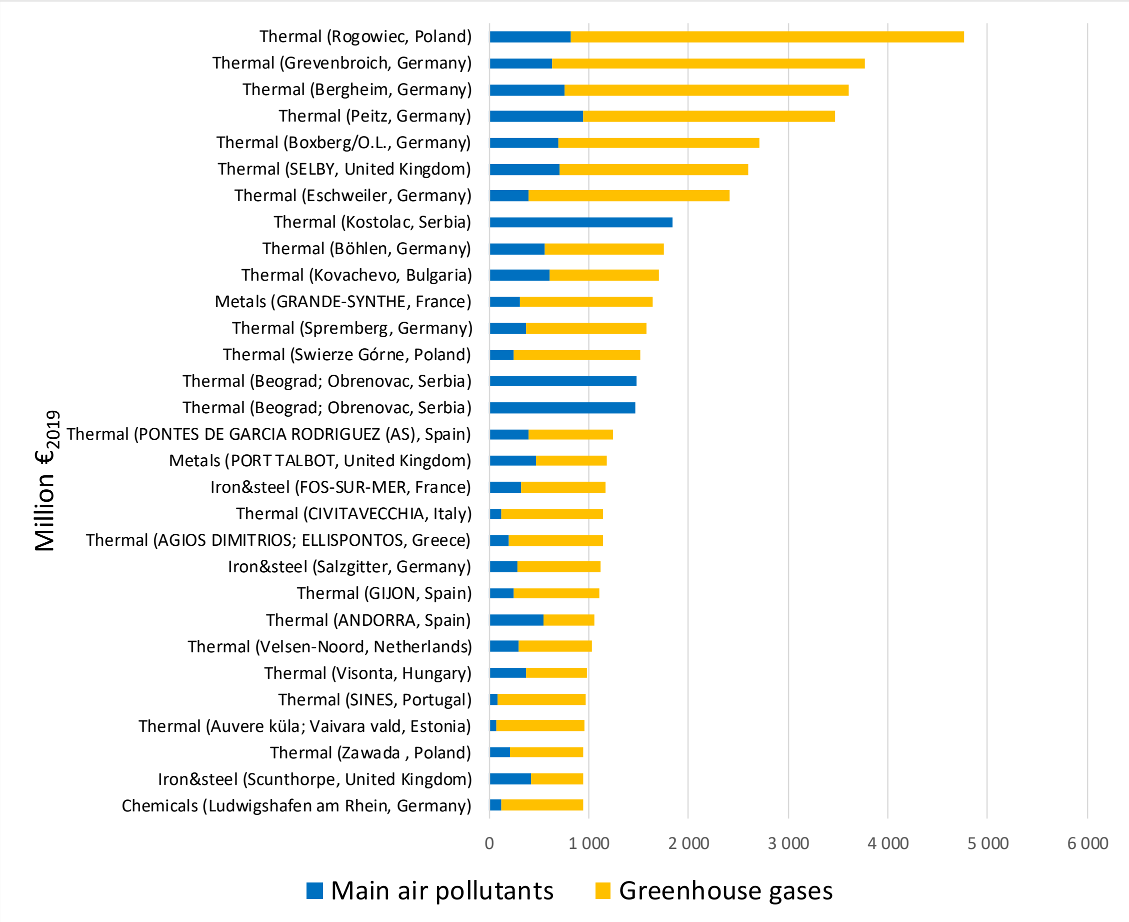
Number	Facility	City	Country	Activity	Aggregate damage cost (VOLY) in million €$_{2019}$				Position when normalised by CO_2 emissions
					Main air pollutants and greenhouse gases		Main air pollutants		
					VOLY	VSL	VOLY	VSL	
22	CENTRAL TÉRMICA DE ABOÑO	GIJON	Spain	Thermal power stations and other combustion installations	1 110	1 662	250	802	670
23	CENTRAL TERMICA DE ANDORRA	ANDORRA	Spain	Thermal power stations and other combustion installations	1 057	2 272	552	1 767	145
24	Tata Steel IJmuiden BV[39]	Velsen-Noord	Netherlands	Thermal power stations and other combustion installations	1 032	1 720	302	990	482
25	Mátrai Eromu Zrt.	Visonta	Hungary	Thermal power stations and other combustion installations	979	1 824	373	1 219	320
26	Central Termoeléctrica Sines	SINES	Portugal	Thermal power stations and other combustion installations	975	1 191	89	305	1316
27	Eesti Energia Narva Elektrijaamad AS; Eesti soojuselektrijaam	Auvere küla; Vaivara vald	Estonia	Thermal power stations and other combustion installations	955	1 116	77	239	1420
28	Elektrownia Polaniec Spólka Akcyjna - Grupa Electrabel Polska	Zawada	Poland	Thermal power stations and other combustion installations	952	1 395	214	657	675
29	Scunthorpe Integrated Iron and Steel Works	Scunthorpe	United Kingdom	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	947	1 859	423	1 335	220
30	BASF SE	Ludwigshafen am Rhein	Germany	Chemical installations for the production on an industrial scale of basic organic chemicals	942	1 271	129	457	824

[39] The E-PRTR classification category ‘thermal power stations and other combustion installations’ includes a variety of plant that complicates certain analyses.

Amongst the thermal power plants that are part of the top 30 E-PRTR facilities accounting for the highest absolute damage in 2017, according to information available on the internet, almost all use coal (facilities 1, 6, 8, 13, 16, 19, 20, 22, 26, 28) and/or lignite (2, 3, 4, 5, 7, 9, 10, 12, 14 & 15, 16, 23). Facility 16 uses additionally natural gas, facility 22 blast furnace gas and facility 28 uses biomass. Facility 24 uses only blast furnace gas and facility 27 only oil shale.

Figure 50 presents the same results as Table 42 but highlighting the contribution of damage from main air pollutants versus that from greenhouse gases. This indicates that the ranking is different when only the main air pollutants are considered. The figure furthermore highlights high emissions of main air pollutants from several Serbian power plants.

Figure 50: Top 30 E-PRTR facilities by quantifiable damage cost in 2017 – valuation with VOLY for main air pollutants



In the previous three tables and in Figure 50, the ranking of facilities was based on the lower, VOLY damage estimate. As can be seen in Table 42, in 2017, five facilities would not be part of the top 30 if damage was ranked based on the VSL estimate. The Italian power station situated in Civitavecchia would switch from the 19th to the 31st position, the Portuguese Power station situated in Sines would switch from position 26 to position 46, the Estonian power station in Auvere küla from position 27 to position 54, the Polish power station in Zawada from position 28 to 36 and the German chemical company situated in Ludwigshafen from position 30 to 40.

10.3 The top 30 E-PRTR facilities having the highest absolute damage costs from emissions of selected pollutants – sub-set of facilities reporting over the whole period

In order to investigate further the trends indicated in Figure 21 and Figure 22 above, we have assessed how the ranking of facilities changes when the ranking is based on 2008 or 2017, on the complete set of facilities (including those that have shut within or reported irregularly over the period) or on the subset of facilities that have reported emissions in all years from 2008 to 2017 (excluding those that have shut within or reported irregularly over the period). Ranking is based on the VOLY estimate.
In Table 43 we capture damage from the top 30 most damaging plant in the starting year (2008) that have operated throughout the period, excluding those that have shut (ranking in column 1). The table also indicates what their position would be if all plants operating in the starting year were considered (column 12). Their relative position in 2017 amongst plants operated throughout the period (columns 11) and amongst all plants (column 13) are also presented.

The table additionally indicates the damage results for the VOLY and VSL estimates in both years (columns 7-10), indicating that ranking changes with the choice of the valuation indicator.

The comparison between columns 1 (ranking in 2008) and 11 (ranking in 2017) amongst the facilities that have operated throughout the period shows important differences. Various of the top 30 facilities in 2008 would not be part of the ranking in 2017. Based on the E-PRTR dataset it is impossible to know whether these facilities have reduced emissions through abatement measures or improvements in efficiency or whether they have reduced their production. Or whether their position has only been improved relatively, e.g. due to other facilities having increased production. The comparison also shows that for several facilities their position amongst the top 30 polluters is higher in 2017 than in 2008. This may be either due to lack in abatement measures relative to other facilities, or to increased production over time again relative to other facilities.

Differences in ranking in 2008 are limited when comparing the set of facilities that have operated throughout the period (column 1) to the complete set of facilities (column 12). Differences in ranking are slightly more important when comparing the two sets of 2017 facilities (columns 11 and 13).

Results for the top 30 polluters have changed in the following ways:

1. Some of the installations that were in the top 30 polluters in 2008 when including all facilities (Table 40) have been closed permanently. Some others may not have reported in every year and hence have been excluded from Table 43.
2. Damage from 20 of the 30 plant listed in the worst polluters in 2008 (Table 43) fell significantly by 2017. In most cases it is likely that this is a result of plant being upgraded. It is also possible that plant were only operating for part of the year in 2017, or at a lower load or only at peak demand.
3. Damage results for seven plant are broadly similar in 2008 and 2017 (2 in Poland, 4 in Germany and 1 in France), suggesting that modernisation was carried out prior to 2008 or has yet to be carried out.
4. Damage results for 3 plant, all German, have increased by 20 % or more between 2008 and 2017. (in places 7, 12 and 14 in Table 43). These may have been expanded over the period, or results for 2008 may have been artificially low through plant being unavailable for part of the year as a result of e.g. upgrading works.

The listing of the 30 most polluting plant that have operated throughout the period is likely to contain a mix of plant that are all large but contains some that operate very efficiently and some that are inefficient. As the E-PRTR does not include data on production in any year this cannot be accounted for directly. This indicates some bias against large plant: those that operate efficiently may release significantly less pollution than a collection of smaller plant that combined provide the same level of production. An attempt is made to address this bias in the next section.

Table 43: Top 30 Polluters in 2008 amongst facilities reporting in all years and how the ranking changes in 2017 and when accounting for all facilities in 2008 and 2017 – ranking based on the VOLY estimate

Position in 2008 amongst facilities reporting emissions in all years	Facility ID	Facility	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2017 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
1	15875	TETs Maritsa iztok 2 EAD	Kovachevo	Bulgaria	Thermal power stations and other combustion installations	7 120	1 708	19 887	2 979	9	1	10
2	1298	PGE Górnictwo i Energetyka Konwencjonalna S.A.; Oddzial Elektrownia Belchatów	Rogowiec	Poland	Thermal power stations and other combustion installations	4 507	4 772	7 074	6 449	1	2	1
3	13777	Drax Power Station	SELBY	United Kingdom	Thermal power stations and other combustion installations	4 022	2 601	7 554	4 150	6	3	6
4	167389	SUCURSALA ELECTROCENTRALE TURCENI	TURCENI	Romania	Thermal power stations and other combustion installations	3 867	668	10 382	1 116	50	4	60
5	46361	LEAG; Kraftwerk Jänschwalde	Peitz	Germany	Thermal power stations and other combustion installations	3 619	3 471	6 438	5 817	4	5	4
6	14192	PPC S.A. SES MEGALOPOLIS A'	MEGALOPOLI	Greece	Thermal power stations and other combustion installations	3 076	295	8 346	338	145	6	171
7	44073	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Thermal power stations and other combustion installations	3 072	3 615	4 241	5 521	3	7	3
8	44118	RWE Power AG	Eschweiler	Germany	Thermal power stations and other	2 709	2 410	3 836	3 446	7	8	7

Position in 2008 amongst facilities reporting emissions in all years	Facility ID	Facility	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2017 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					combustion installations							
9	167390	SC COMPLEXUL ENERGETIC ROVINARI SA (SUCURSALA ELECTROCENTRALE ROVINARI)	ROVINARI	Romania	Thermal power stations and other combustion installations	2 615	771	6 858	1 131	41	9	49
10	43783	RWE Power AG Kraftwerk Frimmersdorf	Grevenbroich	Germany	Thermal power stations and other combustion installations	2 443	455	3 678	657	77	10	91
11	7019	ILVA S.P.A. Stabilmento di Taranto	TARANTO	Italy	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2 426	918	5 770	1 560	27	11	32
12	43843	RWE Power AG	Grevenbroich	Germany	Thermal power stations and other combustion installations	2 248	3 775	3 173	5 405	2	13	2
13	7027	CENTRALE TERMOELETTRICA FEDERICO II	BRINDISI	Italy	Thermal power stations and other combustion installations	2 158	818	3 684	1 175	38	14	45
14	74662	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Thermal power stations and other combustion installations	2 126	2 710	3 377	4 444	5	15	5
15	6995	Zespól Elektrowni Patnów-Adamów -Konin S.A.; Elektrownia Patnów	Konin	Poland	Thermal power stations and other combustion installations	2 074	600	4 727	806	54	16	64

Position in 2008 amongst facilities reporting emissions in all years	Facility ID	Facility	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2017 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
16	198	PGE Górnictwo i Energetyka Konwencjonalna S.A.; Oddzial Elektrownia Turów	Bogatynia	Poland	Thermal power stations and other combustion installations	2 041	897	3 422	1 204	29	17	35
17	14245	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS; ELLISPONTOS	Greece	Thermal power stations and other combustion installations	1 927	1 144	3 404	1 588	16	18	20
18	15796	Gorivna instalatsia s nominalna toplinna moshtnost 510 MWt	Galabovo	Bulgaria	Thermal power stations and other combustion installations	1 843	98	5 278	152	476	19	580
19	74740	LEAG Lausitz Energie Kraftwerke AG Kraftwerk Lippendorf	Böhlen	Germany	Thermal power stations and other combustion installations	1 828	1 758	3 361	3 125	8	20	9
20	4951	Elektrownia KOZIENICE S.A.	Swierze Górne	Poland	Thermal power stations and other combustion installations	1 739	1 517	3 121	2 024	12	23	13
21	46366	LEAG; Kraftwerk Schwarze Pumpe	Spremberg	Germany	Thermal power stations and other combustion installations	1 720	1 583	2 709	2 498	11	24	12
22	12992	Uniper UK Limited	NOTTINGHAM	United Kingdom	Thermal power stations and other combustion installations	1 702	414	3 169	758	95	25	110
23	167410	Societatea Complexul Energetic Hunedoara S.A. Sucursala Electrocentrale Deva S.A.	MINTIA	Romania	Thermal power stations and other combustion installations	1 646	394	4 425	1 051	103	26	118
24	31723	Eggborough Power Ltd; Eggborough Power Station	Goole	United Kingdom	Thermal power stations and other	1 627	177	3 288	330	259	28	311

Position in 2008 amongst facilities reporting emissions in all years	Facility ID	Facility	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2017 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					combustion installations							
25	12825	Elektrárny Prunérov	Kadan	Czech Republic	Thermal power stations and other combustion installations	1 597	660	2 983	968	51	30	61
26	4797	ARCELORMITTAL ATLANTIQUE et LORRAINE SITE DE DUNKERQUE	GRANDE-SYNTHE	France	Installations for the processing of ferrous metals	1 579	1 641	2 382	2 336	10	31	11
27	15872	TETs Bobov dol	Golemo selo	Bulgaria	Thermal power stations and other combustion installations	1 557	76	4 363	263	579	32	710
28	8971	UPT COMPOSTILLA	CUBILLOS DEL SIL	Spain	Thermal power stations and other combustion installations	1 534	527	3 553	1 043	66	33	79
29	13368	RWE Generation UK plc; Aberthaw Power Station EPR/RP3133LD	Barry	United Kingdom	Thermal power stations and other combustion installations	1 515	396	3 238	745	102	34	117
30	44290	Uniper Kraftwerke GmbH Kraftwerk Scholven	Gelsenkirchen	Germany	Thermal power stations and other combustion installations	1 445	580	2 308	902	55	37	66

Table 44: Top 30 Polluters in 2017 amongst facilities reporting in all years and how the ranking changes in 2008 and when accounting for all facilities in 2008 and 2017 – ranking based on the VOLY estimate

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
1	1298	PGE Górnictwo i Energetyka Konwencjonalna S.A.; Oddzial Elektrownia Belchatów	Rogowiec	Poland	Thermal power stations and other combustion installations	4 507	4 772	7 074	6 449	2	2	1
2	43843	RWE Power AG	Grevenbroich	Germany	Thermal power stations and other combustion installations	2 248	3 775	3 173	5 405	12	13	2
3	44073	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Thermal power stations and other combustion installations	3 072	3 615	4 241	5 521	7	7	3
4	46361	LEAG; Kraftwerk Jänschwalde	Peitz	Germany	Thermal power stations and other combustion installations	3 619	3 471	6 438	5 817	5	5	4
5	74662	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Thermal power stations and other combustion installations	2 126	2 710	3 377	4 444	14	15	5
6	13777	Drax Power Station	SELBY	United Kingdom	Thermal power	4 022	2 601	7 554	4 150	3	3	6

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					stations and other combustion installations							
7	44118	RWE Power AG	Eschweiler	Germany	Thermal power stations and other combustion installations	2 709	2 410	3 836	3 446	8	8	7
8	74740	LEAG Lausitz Energie Kraftwerke AG Kraftwerk Lippendorf	Böhlen	Germany	Thermal power stations and other combustion installations	1 828	1 758	3 361	3 125	19	20	9
9	15875	TETs Maritsa iztok 2 EAD	Kovachevo	Bulgaria	Thermal power stations and other combustion installations	7 120	1 708	19 887	2 979	1	1	10
10	4797	ARCELORMITTAL ATLANTIQUE et LORRAINE SITE DE DUNKERQUE	GRANDE-SYNTHE	France	Installations for the processing of ferrous metals	1 579	1 641	2 382	2 336	26	31	11
11	46366	LEAG; Kraftwerk Schwarze Pumpe	Spremberg	Germany	Thermal power stations and other combustion installations	1 720	1 583	2 709	2 498	21	24	12
12	4951	Elektrownia KOZIENICE S.A.	Swierze Górne	Poland	Thermal power	1 739	1 517	3 121	2 024	20	23	13

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					stations and other combustion installations							
13	8972	UNIDAD DE PRODUCCION TERMICA AS PONTES	PONTES DE GARCIA RODRIGUEZ (AS)	Spain	Thermal power stations and other combustion installations	1 065	1 247	1 792	2 122	40	51	16
14	13829	Port Talbot Steel Works	PORT TALBOT	United Kingdom	Metal ore (including sulphide ore) roasting or sintering installations	1 117	1 179	1 954	2 189	38	49	17
15	4273	ArcelorMittal FOS	FOS-SUR-MER	France	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	1 044	1 168	1 838	1 895	42	53	18
16	14245	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS; ELLISPONTOS	Greece	Thermal power stations and other combustion installations	1 927	1 144	3 404	1 588	17	18	20

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
17	43283	Salzgitter Flachstahl GmbH	Salzgitter	Germany	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	1 027	1 123	1 623	1 833	44	56	21
18	8521	CENTRAL TÉRMICA DE ABOÑO	GIJON	Spain	Thermal power stations and other combustion installations	1 007	1 110	1 690	1 662	53	66	22
19	8966	CENTRAL TERMICA DE ANDORRA	ANDORRA	Spain	Thermal power stations and other combustion installations	1 104	1 057	2 462	2 272	39	50	23
20	7974	Tata Steel IJmuiden BV	Velsen-Noord	Netherlands	Thermal power stations and other combustion installations	1 004	1 032	1 741	1 720	55	69	24
21	5791	Mátrai Eromu Zrt.	Visonta	Hungary	Thermal power stations and other combustion installations	971	979	1 533	1 824	58	73	25

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
22	5485	Central Termoeléctrica Sines	SINES	Portugal	Thermal power stations and other combustion installations	963	975	1 718	1 191	60	75	26
23	5952	Eesti Energia Narva Elektrijaamad AS; Eesti elektrijaam	Auvere küla; Vaivara vald	Estonia	Thermal power stations and other combustion installations	1 008	955	1 298	1 116	51	64	27
24	6672	ENGIE Energia Polska Spólka Akcyjna	Zawada	Poland	Thermal power stations and other combustion installations	952	952	1 784	1 395	61	76	28
25	109453	BASF SE	Ludwigshafen am Rhein	Germany	Chemical installations for the production on an industrial scale of basic organic chemicals; such as:	735	942	1 084	1 271	80	99	30
26	43818	thyssenkrupp Steel Europe AG Werk Schwelgern	Duisburg	Germany	Installations for the production of pig iron or steel (primary or	1 226	923	2 876	1 979	33	42	31

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					secondary melting) including continuous casting							
27	7019	ILVA S.P.A. Stabilmento di Taranto	TARANTO	Italy	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2 426	918	5 770	1 560	11	11	32
28	6306	Uniper Benelux NV (Maasvlakte)	Maasvlakte Rotterdam	Netherlands	Thermal power stations and other combustion installations	841	908	1 083	1 164	73	90	34
29	198	PGE Górnictwo i Energetyka Konwencjonalna S.A.; Oddzial Elektrownia Turów	Bogatynia	Poland	Thermal power stations and other combustion installations	2 041	897	3 422	1 204	16	17	35
30	14567	ARCELORMITTAL BELGIUM - GENT	Gent	Belgium	Installations for the production of pig iron or steel (primary or secondary	882	891	1 751	1 922	68	85	36

Position in 2017 amongst facilities reporting emissions in all years	Facility ID	Facility Name	City	Country	Activity	VOLY 2008	VOLY 2017	VSL 2008	VSL 2017	Position in 2008 amongst facilities reporting in all years	Position in 2008 amongst all facilities	Position in 2017 amongst all facilities
					melting) including continuous casting							

In Table 44 we capture damage from the top 30 most damaging plant in the most recent year (2017) that have operated throughout the period, excluding those that have shut (ranking in column 1) and what their position would be if all plants operating in 2017 were considered (column 13). Their relative position in 2008 amongst plants operated throughout the period (columns 11) and amongst all plants (column 12) are also presented.

The table shows an inversed picture to that in the previous one. The comparison between columns 1 (ranking in 2017) and 11 (ranking in 2008) amongst the facilities that have operated throughout the period shows that some of the top 30 facilities in 2017 would not have been be part of the top 30 ranking in 2008.

Differences in ranking in 2017 are limited when comparing the set of facilities that have operated throughout the period (column 1) to the complete set of facilities (column 13).

10.4 Normalisation of damage against CO_2 emissions

With respect to the listing of plant by total damage unadjusted for production leading to potential bias against larger but efficient facilities, damage would ideally be weighted by plant output for facilities of the same sector, or output in economic terms (e.g. value added) for cross-sector comparisons, but this is currently not required to be reported to E-PRTR. As an alternative option, we have here normalised damage against CO_2 emissions. This is only a second-best solution for several reasons:

1. The efficiency of facilities in terms of production vs CO_2 emissions varies, given the difference in energy use and efficiency between sectors, and even within sectors.
2. The E-PRTR lists plant providing a variety of outputs that are not directly comparable (e.g. electricity, heat, glass, waste management, and metals)
3. Some of the 30 most damaging facilities identified in section 10.2 do not report CO_2 emissions and therefore fall out of the normalised set of facilities (e.g. the Serbian plants).

Two separate analyses normalising damage have been carried out. The first one assesses for the top 30 polluters in 2017 (within the complete set of facilities) what their position is when damage is normalised against CO_2 emissions (cf. the first and last column in Table 42 above). With normalisation, none of these facilities would be amongst the top 100 polluters and most would take positions exceeding the first 500 facilities. This suggests that the top polluters are not necessarily the least efficient ones and that their position in the overall listing is explained by the size of their production.

The second analysis identified the top 30 facilities after normalisation by CO_2 emissions of damage from all facilities. The result is presented in Table 45 below. Again, none of the top 30 polluters based on normalised damage coincides with the top 30 polluters when damage is not normalised by CO_2 emissions (cf. column 1 and 7).

Table 45: The top 30 E-PRTR facilities when damage costs from emissions of the main air pollutants and greenhouse gases are normalised by CO_2 emissions, 2017

Position when normalised by CO_2 emissions	Facility ID	Facility	City	Country	Activity	Position when not normalised by CO_2 emissions
1	7059	DEPOSITO CONTROLADO DE RESIDUOS URBANOS DE PINTO	PINTO	Spain	Landfills (see note in Guidance Document)	637
2	13410	Waste Recycling Group (Central) Limited; Calvert Landfill Site	BUCKINGHAM	United Kingdom	Landfills (see note in Guidance Document)	624
3	7003	Kotkan Energia Oy; Hovinsaaren voimalaitos	KOTKA	Finland	Thermal power stations and other combustion installations	503
4	12957	Triton (Guillemot West) FPSO	--	United Kingdom	Thermal power stations and other combustion installations	662
5	73883	Aurubis AG	HAMBURG	Germany	Installations for the production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes	592
6	5049	Cabot Italiana SpA	RAVENNA	Italy	Chemical installations for the production on an industrial scale of basic inorganic chemicals	436
7	14726	TESSENDERLO CHEMIE HAM	Ham	Belgium	Chemical installations for the production on an industrial scale of basic inorganic chemicals	874
8	565	STABILIMENTO DI GAZZO VERONESE	GAZZO VERONESE	Italy	Installations for the manufacture of glass; including glass fibre	709
9	211452	Guardian Industries UK Ltd	Goole	United Kingdom	Installations for the manufacture of glass; including glass fibre	672
10	12926	Leman 49/27a	--	United Kingdom	Thermal power stations and	784

Position when normalised by CO_2 emissions	Facility ID	Facility	City	Country	Activity	Position when not normalised by CO_2 emissions
					other combustion installations	
11	24576	CENTRAL DIESEL CEUTA	CEUTA	Spain	Thermal power stations and other combustion installations	720
12	5042	ORION ENGINEERED CARBONS S.r.l.	RAVENNA	Italy	Chemical installations for the production on an industrial scale of basic inorganic chemicals	630
13	284724	INDUSTRIAS DEL TABLERO S.A. (INTASA)	BIDUEIRO (O)	Spain	Industrial plants for the production of paper and board and other primary wood products	821
14	167410	Societatea Complexul Energetic Hunedoara S.A. Sucursala Electrocentrale Deva S.A.	MINTIA	Romania	Thermal power stations and other combustion installations	116
15	8920	PLANTA DE COGENERACIÓN DE GRELVA	Granada	Spain	Thermal power stations and other combustion installations	962
16	157889	ArcelorMittal Bremen GmbH Kokerei Prosper	Bottrop	Germany	Coke ovens	371
17	32920	Quinn Glass Ltd	DERRYLIN	United Kingdom	Installations for the manufacture of glass; including glass fibre	1002
18	7432	CENTRAL DIESEL PUNTA GRANDE	ARRECIFE	Spain	Thermal power stations and other combustion installations	209
19	7421	CENTRAL DIESEL LOS GUINCHOS	BREÑA	Spain	Thermal power stations and other combustion installations	768
20	167411	SUCURSALA ELECTROCENTRALE PAROSENI S.A.	VULCAN	Romania	Thermal power stations and other combustion installations	395
21	14767	AGC GLASS EUROPE VESTIGING MOL	Mol	Belgium	Installations for the manufacture of	1202

Position when normalised by CO_2 emissions	Facility ID	Facility	City	Country	Activity	Position when not normalised by CO_2 emissions
					glass; including glass fibre	
22	6554	Pilkington Italia S.p.A	SAN SALVO	Italy	Installations for the manufacture of glass; including glass fibre	1120
23	579	STABILIMENTO DI LONIGO	LONIGO	Italy	Installations for the manufacture of glass; including glass fibre	1170
24	14373	Guardian Luxguard II	Dudelange	Luxembourg	Installations for the manufacture of glass; including glass fibre	1094
25	74941	GRECIAN MAGNESITE S.A. - YERAKINI MINES	POLIGIROS	Greece	Opencast mining and quarrying	680
26	7398	PLANTA DE GENERACIÓN DE ENERGÍA ELÉCTRICA; AGUA CALIENTE Y VAPOR	NAVIA	Spain	Thermal power stations and other combustion installations	966
27	10912	FORESTAL DEL ATLANTICO; SA	MUGARDOS	Spain	Chemical installations for the production on an industrial scale of basic organic chemicals	995
28	24711	FINANCIERA MADERERA; S.A. - COGENERACION DEL NOROESTE S.L.	SANTIAGO DE COMPOSTELA	Spain	Industrial plants for the production of paper and board and other primary wood products	1015
29	12909	Foinaven FPSO	--	United Kingdom	Thermal power stations and other combustion installations	851
30	8867	CENTRAL TÉRMICA DE ANLLARES	PARAMO DEL SIL	Spain	Thermal power stations and other combustion installations	131

Part C Discussion

This report is an update of the EEA (2014) report describing the damage costs of industrial facilities in Europe based on emissions reported to the E-PRTR. Its main objectives were to:

- describe the methods for determination of human health impacts and associated damage costs arising from emissions to air reported by industrial facilities to the E-PRTR,
- calculate an updated set of marginal damage costs that covers damage to health, crops and forests, building material and ecosystems,
- calculate the externalities from European industrial facilities over the period from 2008 to 2017.

A major update of the marginal damage costs for main air pollutants, heavy metals, organic pollutants and greenhouse gases has been carried out, taking into account up to date scientific knowledge of emissions, pollutant dispersion, stock at risk (people, buildings, ecosystems, etc.), response to pollution and valuation. For the first time, a comprehensive set of sectoral adjustment factors has been calculated for individual emitter sectors and countries([40]). The marginal damage costs have been combined with information of emissions reported to E-PRTR to calculate externalities caused by E-PRTR facilities across Europe.

In updating the marginal damage costs an attempt has been made to ensure consistency in methods and parameters chosen between this study and other ongoing and recent studies to the extent that this represents current knowledge. Full consistency with the analysis for the recent DG ENV Second Clean Air Outlook (Amann et al., 2020) has been reached in the use of exposure-response functions and monetisation of health impacts from the main air pollutants. There is consistency in the updated approaches used here for valuation of mortality and greenhouse gas emissions with the DG MOVE Transport cost handbook (EC, 2019), though the pollutant modelling approach used here is more detailed and permits direct implementation of the recommendations from HRAPIE (WHO, 2013).

Further on the issue of consistency between current studies for the European Commission and the EEA, it might be useful to consider comparability beyond the impact indicators and unit values applied in the assessments. While the work in the DG MOVE Transport Cost Handbook estimates background pollutant concentrations on the basis of the relationship between damage and emissions for various emission scenarios from NEEDS (2008a), the present study is based on up to date pollution information, using recent EMEP SRMs.

Based on emission data from E-PRTR the results of this report illustrate industrial pollution problems in terms of the impacts and damage costs caused. 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, along with the associated costs, helps convey the real nature of pollution problems in a way that a simple measure of emissions cannot (EEA, 2014).

The results of the current report highlight the importance of not limiting damage cost assessments to the "internal" damage of a country, but to account for transboundary impacts. The ranking of countries by damage from air emissions also underlined the importance of the work extending beyond the European Union and the EEA countries to include cooperating countries such as Serbia.

([40]) EEA (2014) used a limited dataset from the Eurodelta II study (JRC, 2008) https://op.europa.eu/en/publication-detail/-/publication/564e13e9-5e1e-4812-98a7-e97e969de107.

Similar to the earlier analysis of EEA (2014), results show that a large part of damage is attributable to only a small number of facilities. For 2017, 50 % of damage from the main air pollutants and GHG emissions was linked to only 211 facilities, 75 % of damage to 711 facilities and 90 % of damage to 1,572 facilities, out of a total reporting air pollutant and greenhouse gas emissions to the E-PRTR of 11,655 facilities([41]). The situation is more extreme when considering damage specifically from organic pollutants and toxic metals, though the reporting of these emissions to the E-PRTR appears very incomplete. This is a matter of concern partly because of the bias it introduces to underestimation of damage, and partly because it serves to shine a spotlight on the operators that have reported their emissions more completely.

The analysis would profit from the availability of production data (quantities and economic value) that complements emission reporting. This would allow assessing the efficiency of the facilities' production. Without this, it is difficult to know whether a given facility causes high damage costs because of their size and level of activity, or because of inefficient processes or abatement equipment. It is noted that much of this production and economic data is publicly available through company reporting, though separate collation of it would be extremely time consuming. This is issue is expected to be resolved from 2022, once reporting production volumes becomes compulsory. As a second-best approach, we have normalised externalities by CO_2 emissions. This approach assumes that CO_2 emissions are related to the size of facilities and their level of production. Of course, this is an imperfect proxy, as high CO_2 emissions can also result from inefficient processes. Also, the work covers many different sectors with different types of output (power, heat, glass, metals, cement, fuel processing, etc.) and direct comparison between them is questionable.

As a result, most of the top 30 facilities accounting for the highest absolute damage are not amongst the top polluters when damage is normalised by CO_2 emissions as a proxy for production.

The assessment also showed that results are sensitive to the indicator used for valuing mortality. Not only are absolute damage costs higher when using the VSL estimate, also the ranking of facilities is to a limited extent affected by this choice of indicator.

Damage costs per tonne of emission (MDCs) change significantly between the previous (EEA, 2014) and the current report. Price increases by 28 % between 2005 (price base used in EEA, 2014) and 2019 (price base used in the current report) contribute to this result, as well as the update of monetary unit values. For heavy metals, changes are also due to the inclusion of additional health impacts in the present analysis. For the main air pollutants, an important impact of changes in SRMs between 2010 (EEA, 2014) and 2017 on marginal damage costs was identified in the report.

It has, thus, become apparent that a systematic approach is needed to understand the temporal dependence of the source receptor matrices. The current study uses EMEP SRMs as of 2017. New country-to-country SRMs (for 2018) have just been published. They appear to vary significantly from the 2017 edition. It is obvious that SRMs change over time, due to changes in meteorological conditions between years, emission source characteristics that can vary with time, evolutions in the EMEP methodology and variation in the relative levels of pollutants in the atmosphere that will influence pollutant chemistry. Therefore, it would be helpful to explore the time trend of the SRMs and understand the reasons behind any observed variance, and then to seek to identify some appropriate solutions (identify and use a 'representative year', development of SRMs based on average meteorology over several years…). In this process, close attention should also be paid to the geographical location of any discrepancies above some tolerance level, and to the importance of emission sources in that area.

In a future update, priorities for refining the methods are (i) updating of the health response functions to account for new information on response-coefficients and the range of effects to be included in the analysis, and (ii) valuation of new health endpoints.

([41]) Including also reporting of emissions of heavy metals and organic pollutants, there were 11,893 reporting facilities in 2017.

Also, the scientifically recommended indicator to assess impacts on crops and forests from ozone, the stomatal ozone flux, should be used. However, currently no PODy SRMs are available, which is the reason why calculation of impacts of ozone on crops and forests in the present report had to continue using the AOT40 indicator. For the future we recommend the creation and publication of POD SRMs.

The possibility of extending the assessment of ecosystems impacts beyond the Natura 2000 sites should be considered.

A specific effort was conducted here to increase the spatial resolution of exposure modelling, especially for NO_2. We reach out to a granularity of about 7km. Further efforts to increase the spatial refinement should be sought.

For a more accurate use of sectoral adjustment factors it would also be useful to improve the mapping from the E-PRTR sector nomenclature to SNAP, in order to avoid the necessity of regrouping different industrial sectors that differ in emission height and proximity to population.

Finally, while marginal damage costs related to impacts from ozone, fine particulate matter, heavy metals and organic pollutants are calculated using 2017 population data and emissions, this has not been possible for impacts related to NO_2. For this pollutant, the SHERPA model had to be used which relies on emissions for 2010. Consistency in all input data would, of course, have been preferable.

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Annex 1
Corrections made to reported E-PRTR emissions data

Table 46 Information on corrections made to the reported E-PRTR emission data

Facility ID	Facility Name	City	Country	Activity Code	Activity Name	Year	Pollutant	Reported emissions	Revised emissions	Unit
495	CEMEX Polska Sp. z o.o.;Zaklad Cementownia Chelm	Chelm	Poland	3.(c)	Installations for the production of cement clinker in rotary kilns, lime in rotary kilns, cement or lime in other furnaces	2011	PAH	1 010	101	kg
509	Zaklady Azotowe Pulawy S.A.	Pulawy	Poland	4.(c)	Chemical installations for the production on an industrial scale of phosphorous-; nitrogen- or potassium-based fertilisers (simple or compound fertilisers)	2008	N_2O	6 800 000	680 000	kg
509	Zaklady Azotowe Pulawy S.A.	Pulawy	Poland	4.(c)	Chemical installations for the production on an industrial scale of phosphorous-; nitrogen- or potassium-based fertilisers (simple or compound fertilisers)	2012	PAH	24 000	11 800	kg
1298	PGE Elektrownia Belchatów S.A.	Rogowiec	Poland	1.(c)	Thermal power stations and other combustion installations	2008	PM_{10}	3 660 000	1 810 000	kg
4273	ArcelorMittal FOS	FOS-SUR-MER	France	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2011	Benzene	151 000	36 200	kg
5453	Petróleos de Portugal- Petrogal; S.A. (Refinaria de Sines)	SINES	Portugal	1.(a)	Mineral oil and gas refineries	2009	Cadmium	1 760	804	kg
5951	Eesti Energia Narva Elektrijaamad AS; Balti elektrijaam	Narva linn	Estonia	1.(c)	Thermal power stations and other combustion installations	2011	PM_{10}	20 800 000	6 070 000	kg
5952	Eesti Energia AS	Auvere küla; Vaivara vald	Estonia	1.(c)	Thermal power stations and other combustion installations	2012	SO_2	2 230 000	22 300 000	kg

Facility ID	Facility Name	City	Country	Activity Code	Activity Name	Year	Pollutant	Reported emissions	Revised emissions	Unit
6668	Celsa Huta Ostrowiec Sp. z o.o.	Ostrowiec Swietokrzyski	Poland	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2015	Cadmium	208	21	kg
6668	Celsa Huta Ostrowiec Sp. z o.o.	Ostrowiec Swietokrzyski	Poland	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2016	Cadmium	330	33	kg
6789	ALCOA INESPAL; S.A. - LA CORUÑA	GRELA (LA)	Spain	2.(e)	Installations for the production of non-ferrous crude metals from ore, concentrates or secondary raw materials by metallurgical, chemical or electrolytic processes	2010	PAH	24 900	2 490	kg
7019	ILVA S.P.A. Stabilimento di Taranto	TARANTO	Italy	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2012	Chromium	7 840	784	kg
7121	PGE Zespól Elektrowni Dolna Odra S.A.	Nowe Czarnowo	Poland	1.(c)	Thermal power stations and other combustion installations	2008	Dioxins & furans	0.0022	0.2180	kg
8670	COMPAÑIA ESPAÑOLA DE LAMINACION (CELSA 1-4)	Castellbisbal	Spain	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2013	Cadmium	542	54	kg
10218	ThermPhos International BV	Ritthem	Netherlands	4.(b)	Chemical installations for the production on an industrial scale of basic inorganic chemicals	2010	Dioxins & furans	0.00390	0.00039	kg
10251	U.S.Steel s.r.o.	Košice	Slovakia	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2008	Arsenic	1 240	124	kg
10251	U.S.Steel s.r.o.	Košice	Slovakia	2.(b)	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	2008	Nickel	1 090	109	kg
10300	Elektrárna Chvaletice	Chvaletice	Czech Republic	1.(c)	Thermal power stations and other combustion installations	2017	Arsenic	1 000	100	kg
13013	ESSO PETROLEUM CO LTD; ESSO REFINERY	SOUTHAMPTON	United Kingdom	1.(a)	Mineral oil and gas refineries	2009	Benzene	73 700	35 000	kg
14290	HELLENIC PETROLEUM S.A. - INDUSTRIAL	ASPROPYRGOS	Greece	1.(a)	Mineral oil and gas refineries	2017	Cadmium	182	18	kg

Facility ID	Facility Name	City	Country	Activity Code	Activity Name	Year	Pollutant	Reported emissions	Revised emissions	Unit
	DIVISION OF ASPROPYRGOS									
14388	AES Kilroot Power Ltd	Carrickfergus	United Kingdom	1.(c)	Thermal power stations and other combustion installations	2017	SO_2	127 000 000	1 270 000	kg
14409	DELIMARA POWER STATION	MARSAXLOKK	Malta	1.(c)	Thermal power stations and other combustion installations	2011	Nickel	149	1 490	kg
20177	Polski Koncern Naftowy ORLEN S.A.	Plock	Poland	1.(a)	Mineral oil and gas refineries	2009	Nickel	116	1 160	kg
20607	Jastrzebska Spólka Weglowa S.A. Kopalnia Wegla Kamiennego Pniówek	Pawlowice	Poland	3.(a)	Underground mining and related operations	2017	Dioxins & furans	11	0.11	kg
43959	ERFTCARBON GmbH	Grevenbroich	Germany	9.(d)	Installations for the production of carbon (hard-burnt coal) or electro-graphite by means of incineration or graphitisation	2009	PAH	8 470	847	kg
74740	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	1.(c)	Thermal power stations and other combustion installations	2013	Cadmium	614	61	kg
109453	BASF SE	Ludwigshafen am Rhein	Germany	4.(a)	Chemical installations for the production on an industrial scale of basic organic chemicals	2008	N_2O	16 800 000	1 680 000	kg
109453	BASF SE	Ludwigshafen am Rhein	Germany	4.(a)	Chemical installations for the production on an industrial scale of basic organic chemicals	2009	N_2O	27 600 000	2 760 000	kg
124056	'CEMEX' SIA; Brocenu cementa rupnica	Broceni	Latvia	3.(c)	Installations for the production of:	2012	Mercury	56	16	kg

Annex 2
Crops for which ozone damage is assessed

Table 47: Crops included in ozone damage cost assessment and associated response functions

Crops for which ozone impacts are assessed	Response function
Almonds, with shell	0.00453
Anise, badian, fennel, coriander	0.00453
Apples	0.00453
Apricots	0.00453
Artichokes	0.00453
Asparagus	0.00453
Avocados	0.00453
Bananas	0.00453
Barley	0.00543
Bastfibres, other	0.00453
Beans, dry	0.02717
Beans, green	0.02717
Beeswax	0
Berries nes	0.00453
Blueberries	0.00453
Broad beans, horse beans, dry	0.02717
Buckwheat	0.00453
Cabbages and other brassicas	0.00453
Canary seed	0.00453
Carobs	0.00453
Carrots and turnips	0.01992
Castor oil seed	0.00453
Cauliflowers and broccoli	0
Cereals, nes	0
Cherries	0.00453
Cherries, sour	0.00453
Chestnut	0.00453
Chick peas	0.02717
Chicory roots	0.00453
Chillies and peppers, dry	0.00453
Chillies and peppers, green	0.00453
Coffee, green	0.00453
Cotton lint	0.00453
Cottonseed	0.00453
Cow peas, dry	0.02717
Cranberries	0.00453
Cucumbers and gherkins	0.00453
Currants	0.00453
Dates	0.00453

Crops for which ozone impacts are assessed	Response function
Eggplants (aubergines)	0.00453
Figs	0.00453
Flax fibre and tow	0.00453
Fruit, citrus nes	0.00453
Fruit, fresh nes	0.00453
Fruit, pome nes	0.00453
Fruit, stone nes	0.00453
Fruit, tropical fresh nes	0.00453
Garlic	0.00453
Gooseberries	0.00453
Grain, mixed	0.00000
Grapefruit (inc. pomelos)	0.00453
Grapes	0.00453
Groundnuts, with shell	0.00453
Hazelnuts, with shell	0.00453
Hemp tow waste	0.00453
Hops	0.00453
Kiwi fruit	0.00453
Leeks, other alliaceous vegetables	0.00453
Lemons and limes	0.02445
Lentils	0.02717
Lettuce and chicory	0.01721
Linseed	0.00453
Lupins	0.02717
Maize	0.00356
Maize, green	0.00906
Melons, other (inc.cantaloupes)	0.00453
Melonseed	0.00453
Millet	0.00453
Mushrooms and truffles	0.00000
Mustard seed	0.01087
Nuts, nes	0.00453
Oats	0.00000
Oilseeds nes	0.00996
Okra	0.00453
Olives	0.01177
Onions, dry	0.02083
Onions, shallots, green	0.00453
Oranges	0.02445
Peaches and nectarines	0.00453
Pears	0.00453
Peas, dry	0.02717
Peas, green	0.02717
Persimmons	0.00453
Pineapples	0.00453

Crops for which ozone impacts are assessed	Response function
Pistachios	0.00453
Plums and sloes	0.01992
Poppy seed	0.00453
Potatoes	0.00815
Pulses, nes	0.02717
Pumpkins, squash and gourds	0.00453
Pyrethrum, dried	0.00453
Quinces	0.00453
Rapeseed	0.00996
Raspberries	0.00453
Rice, paddy	0.00415
Roots and tubers, nes	0.01992
Rye	0.00000
Safflower seed	0.00453
Sesame seed	0.00453
Sorghum	0.00453
Soybeans	0.01130
Spices, nes	0.00453
Spinach	0.00453
Strawberries	0.00091
String beans	0.02717
Sugar beet	0.00996
Sunflower seed	0.00453
Sweet potatoes	0.02536
Tangerines, mandarins, clementines, satsumas	0.00453
Tea	0.00453
Tobacco, unmanufactured	0.00453
Tomatoes	0.01029
Triticale	0.00453
Tung nuts	0.00453
Vegetables, fresh nes	0.00453
Vegetables, leguminous nes	0.00453
Vetches	0.02717
Walnuts, with shell	0.00453
Watermelons	0.01268
Wheat	0.01630
Yams	0.00453

Annex 3
Input data to price adjustments

This table presents the values for the harmonised indices of consumer prices (HICP) used in the present study.

Table 48 HICP (2015 = 100) – annual data (mean annual indices)

GEO/TIME	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
EU27 (from 2020)	73.13	75.73	77.81	79.59	81.55	83.45	85.38	87.41	90.64	91.35	93.03	95.69	98.19	99.49	99.89	100.00	100.18	101.74	103.57	105.04
EU28 (2013-2020)	73.07	75.42	77.32	78.98	80.78	82.63	84.54	86.54	89.72	90.61	92.49	95.35	97.87	99.35	99.90	100.00	100.25	101.96	103.89	105.42
BE – Belgium	74.96	76.78	77.97	79.16	80.63	82.67	84.60	86.13	90.00	89.99	92.09	95.18	97.68	98.90	99.38	100.00	101.77	104.03	106.44	107.77
BG – Bulgaria	54.08	58.06	61.44	62.88	66.75	70.78	76.02	81.78	91.55	93.81	96.66	99.94	102.33	102.72	101.08	100.00	98.68	99.85	102.48	104.99
CZ – Czechia	73.8	77.1	78.2	78.2	80.2	81.5	83.2	85.6	91.0	91.5	92.6	94.6	98.0	99.3	99.8	100.0	100.7	103.1	105.1	107.8
DK - Denmark	77.5	79.3	81.2	82.7	83.5	85.0	86.5	88.0	91.2	92.1	94.1	96.6	98.9	99.4	99.8	100.0	100.0	101.1	101.8	102.5
DE – Germany	78.9	80.4	81.5	82.4	83.8	85.5	87.0	89.0	91.4	91.6	92.7	95.0	97.0	98.6	99.3	100.0	100.4	102.1	104.0	105.5
EE – Estonia	58.22	61.50	63.71	64.59	66.55	69.29	72.37	77.25	85.45	85.62	87.96	92.43	96.33	99.46	99.93	100.00	100.80	104.48	108.05	110.50
IE - Ireland	77.1	80.2	84.0	87.3	89.3	91.3	93.7	96.4	99.5	97.8	96.2	97.4	99.2	99.7	100.0	100.0	99.8	100.1	100.8	101.7
EL - Greece	71.01	73.59	76.48	79.12	81.51	84.35	87.14	89.75	93.55	94.81	99.27	102.36	103.42	102.54	101.11	100.00	100.02	101.15	101.94	102.46
ES – Spain	71.22	73.23	75.86	78.21	80.60	83.33	86.29	88.75	92.41	92.19	94.08	96.94	99.31	100.83	100.63	100.00	99.66	101.69	103.46	104.26
FR - France	78.23	79.62	81.16	82.93	84.86	86.47	88.10	89.52	92.34	92.44	94.05	96.20	98.33	99.31	99.91	100.00	100.31	101.47	103.60	104.95
HR – Croatia	69.32	72.28	74.11	75.88	77.51	79.83	82.46	84.65	89.56	91.56	92.55	94.59	97.76	100.04	100.26	100.00	99.37	100.67	102.23	103.04
IT – Italy	74.2	75.9	77.9	80.1	81.9	83.7	85.6	87.3	90.4	91.1	92.6	95.3	98.4	99.7	99.9	100.0	99.9	101.3	102.5	103.2
CY – Cyprus	74.91	76.40	78.53	81.65	83.20	84.88	86.79	88.67	92.55	92.71	95.09	98.40	101.45	101.84	101.57	100.00	98.78	99.45	100.23	100.78
LV - Latvia	55.18	56.58	57.69	59.39	63.06	67.40	71.83	79.08	91.14	94.11	92.96	96.88	99.09	99.11	99.79	100.00	100.10	103.00	105.63	108.53
LT – Lithuania	68.68	69.74	69.98	69.22	70.02	71.89	74.59	78.93	87.69	91.34	92.43	96.24	99.28	100.44	100.68	100.00	100.68	104.42	107.07	109.47
LU - Luxembourg	70.43	72.12	73.60	75.47	77.91	80.85	83.24	85.45	88.94	88.95	91.44	94.85	97.59	99.25	99.94	100.00	100.04	102.15	104.21	105.93
HU – Hungary	51.95	56.67	59.64	62.43	66.66	68.98	71.76	77.45	82.12	85.43	89.47	92.98	98.24	99.92	99.94	100.00	100.45	102.84	105.84	109.46

MT – Malta	72.34	74.16	76.10	77.56	79.68	81.69	83.79	84.38	88.33	89.95	91.79	94.10	97.13	98.08	98.84	100.00	100.90	102.18	103.95	105.54
NL – Netherlands	74.51	78.32	81.35	83.16	84.32	85.57	86.99	88.36	90.32	91.20	92.05	94.32	96.99	99.47	99.79	100.00	100.11	101.40	103.02	105.78
AT - Austria	75.02	76.74	78.04	79.05	80.60	82.30	83.69	85.53	88.29	88.64	90.14	93.35	95.75	97.77	99.20	100.00	100.97	103.22	105.41	106.98
PL – Poland	70.0	73.8	75.2	75.7	78.5	80.2	81.2	83.3	86.8	90.3	92.7	96.3	99.8	100.6	100.7	100.0	99.8	101.4	102.6	104.8
PT - Portugal	73.18	76.41	79.24	81.80	83.85	85.64	88.25	90.39	92.78	91.95	93.22	96.54	99.22	99.65	99.50	100.00	100.64	102.20	103.40	103.71
RO – Romania	28.01	37.66	46.14	53.18	59.51	64.90	69.19	72.58	78.33	82.70	87.73	92.84	95.98	99.04	100.41	100.00	98.93	100.00	104.08	108.15
SI – Slovenia	61.98	67.33	72.37	76.46	79.26	81.19	83.25	86.42	91.19	91.97	93.86	95.81	98.50	100.40	100.77	100.00	99.85	101.40	103.36	105.11
SK – Slovakia	61.50	65.90	68.21	73.96	79.49	81.71	85.19	86.80	90.22	91.05	91.69	95.43	99.00	100.45	100.35	100.00	99.52	100.90	103.46	106.33
FI – Finland	76.79	78.84	80.42	81.46	81.58	82.21	83.26	84.57	87.89	89.32	90.83	93.85	96.81	98.96	100.16	100.00	100.39	101.23	102.42	103.58
SE - Sweden	79.78	81.92	83.51	85.44	86.32	87.03	88.34	89.82	92.83	94.63	96.43	97.75	98.66	99.10	99.30	100.00	101.14	103.02	105.12	106.93
UK – United Kingdom	72.7	73.6	74.5	75.5	76.5	78.1	79.9	81.8	84.7	86.6	89.4	93.4	96.1	98.5	100.0	100.0	100.7	103.4	105.9	107.8
EEA - (EEA18-1995, EEA28-2004, EEA30-2007, EEA31-2013, EEA30-2020)	74.64	76.29	77.87	79.40	80.98	82.73	84.56	86.52	89.69	90.60	92.49	95.34	97.84	99.31	99.88	100.00	100.29	102.01	103.95	105.49
IS – Island	47.60	50.74	53.44	54.18	55.43	56.19	58.80	60.94	68.71	79.89	85.85	89.46	94.84	98.76	99.74	100.00	100.79	99.13	99.86	101.83
NO – Norway	77.1	79.1	79.7	81.3	81.8	83.1	85.1	85.7	88.7	90.7	92.8	94.0	94.3	96.2	98.0	100.0	103.9	105.8	109.0	111.5
CH – Switzerland	:	:	:	:	:	97.43	98.40	99.17	101.51	100.77	101.39	101.49	100.76	100.83	100.84	100.00	99.47	100.11	101.03	101.41
MK – North Macedonia	:	:	:	:	:	80.44	83.39	85.20	91.67	91.61	92.57	95.52	97.26	99.91	99.87	100.00	100.24	102.35	104.66	105.42
RS – Serbia	:	:	:	:	:	:	55.1	58.3	65.2	70.5	74.9	83.3	89.4	96.3	98.5	100.0	101.3	104.7	106.8	108.8
TR – Turkey	13.14	20.60	30.28	37.94	41.76	45.15	49.34	53.66	59.27	62.97	68.37	72.79	79.31	85.22	92.81	100.00	107.66	119.63	139.17	160.30
US – United States	:	:	75.32	77.04	79.19	82.25	84.88	87.11	90.97	90.25	92.56	96.16	98.23	99.48	100.81	100.00	100.55	102.29	104.52	105.92

Source: EUROSTAT, https://ec.europa.eu/eurostat/web/hicp/data/database.

The following table presents the Purchasing power parities (PPP) used in the present study.

Table 49: Purchasing Power Parities for GDP (measure: national currency per US dollar)

Year		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Australia	Australian Dollar	1.3116	1.3276	1.3365	1.3540	1.3668	1.3884	1.4039	1.4275	1.4791	1.4415
Austria	Euro	0.9073	0.9228	0.8998	0.8891	0.8789	0.8819	0.8611	0.8691	0.8544	0.8429
Belgium	Euro	0.8998	0.8922	0.8733	0.8771	0.8891	0.8918	0.8753	0.8799	0.8669	0.8493
Canada	Canadian Dollar	1.2275	1.2211	1.2293	1.2263	1.2332	1.2136	1.2058	1.2127	1.2344	1.2014
Chile	Chilean Peso	286.5797	291.2559	296.4464	304.3678	319.6534	333.6900	318.5747	323.8790	340.4008	354.3259
Colombia	Colombian Peso	735.0146	771.5826	810.8411	870.4059	913.9657	951.9091	977.6083	1 001.5589	1 057.8753	1 092.5409
Czech Republic	Czech Koruna	14.3271	14.3202	14.4583	14.1915	14.4392	14.5625	14.4320	14.2736	13.9167	13.6253
Denmark	Danish Krone	8.6681	8.6907	8.5616	8.6573	8.4675	8.5694	8.2971	8.1709	7.9441	7.7237
Estonia	Euro	0.4687	0.4878	0.4862	0.4863	0.4941	0.5033	0.5214	0.5518	0.5451	0.5166
Finland	Euro	0.9838	1.0025	0.9981	1.0031	0.9741	0.9794	0.9540	0.9358	0.9121	0.8956
France	Euro	0.9300	0.9116	0.9007	0.9309	0.9360	0.9165	0.8958	0.8897	0.8819	0.8621
Germany	Euro	0.9429	0.9296	0.9133	0.8969	0.8759	0.8727	0.8486	0.8382	0.8204	0.8103
Greece	Euro	0.6695	0.6684	0.6630	0.6858	0.6951	0.7090	0.6933	0.7191	0.7080	0.7038
Hungary	Forint	110.0454	114.3913	118.1413	122.1456	128.4985	130.9299	131.6493	134.2063	131.0054	127.5675
Iceland	Iceland Krona	84.7018	88.2832	91.1054	92.7095	93.3714	95.8407	101.7555	107.4725	114.5270	121.8587
Ireland	Euro	0.9436	0.9692	0.9820	1.0050	0.9921	1.0117	0.9794	0.9588	0.9444	0.9004
Israel	New Israeli Sheqel	3.4418	3.4269	3.4627	3.6289	3.5377	3.7169	3.7913	3.7287	3.8672	3.9653
Italy	Euro	0.8051	0.8162	0.8235	0.8344	0.8526	0.8551	0.8238	0.8102	0.7837	0.7706
Japan	Yen	154.7179	149.7249	143.7742	139.5161	134.3631	129.5520	124.5368	120.3942	116.8458	115.1501
Korea	Won	747.2360	757.8896	769.7718	792.0772	794.3287	788.9201	772.3965	770.2221	785.7179	824.6188
Latvia	Euro	0.3607	0.3533	0.3610	0.3786	0.3997	0.4386	0.4895	0.5664	0.5755	0.5206
Lithuania	Euro	0.4516	0.4327	0.4207	0.4044	0.4144	0.4352	0.4468	0.4707	0.4928	0.4689
Luxembourg	Euro	0.9555	0.9632	0.9570	0.9658	0.9521	0.9464	0.9178	0.9224	0.9000	0.9021
Mexico	Mexican Peso	6.1030	6.3328	6.5537	6.6481	6.9892	7.1269	7.1579	7.3742	7.4695	7.4287
Netherlands	Euro	0.8902	0.9047	0.9009	0.9265	0.9086	0.8971	0.8730	0.8611	0.8478	0.8475

Year		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
New Zealand	New Zealand Dollar	1.4436	1.4742	1.4690	1.4970	1.5076	1.5350	1.4817	1.5053	1.4907	1.4706
Norway	Norwegian Krone	9.0832	9.1731	9.0567	9.2075	9.1339	9.0052	8.7907	8.9322	8.8593	9.0752
Poland	Zloty	1.8325	1.8368	1.7998	1.8064	1.8317	1.8676	1.8527	1.8559	1.8422	1.8674
Portugal	Euro	0.6609	0.6708	0.6721	0.6705	0.6768	0.6643	0.6409	0.6475	0.6361	0.6267
Slovak Republic	Euro	0.5163	0.5156	0.5215	0.5449	0.5650	0.5647	0.5553	0.5543	0.5374	0.5151
Slovenia	Euro	0.5264	0.5600	0.5833	0.6086	0.6084	0.6101	0.6104	0.6310	0.6338	0.6449
Spain	Euro	0.7396	0.7474	0.7423	0.7601	0.7666	0.7695	0.7369	0.7332	0.7259	0.7180
Sweden	Swedish Krona	9.1608	9.4002	9.4137	9.4964	9.3027	9.4792	9.1225	8.8821	8.7790	8.9122
Switzerland	Swiss Franc	1.7882	1.7684	1.7098	1.7171	1.6933	1.6865	1.6008	1.5337	1.4930	1.4686
Turkey	Turkish Lira	0.2815	0.4149	0.5913	0.7374	0.7929	0.8346	0.8428	0.8522	0.8800	0.9038
United Kingdom	Pound Sterling	0.7043	0.6944	0.6899	0.6966	0.6885	0.7076	0.6973	0.7100	0.7017	0.7094
United States	US Dollar	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
European Union (28 countries)	Euro	0.8763	0.8684	0.8591	0.8487	0.8465	0.8501	0.8282	0.8246	0.7903	0.7600
Australia	Australian Dollar	1.5028	1.5111	1.5401	1.4471	1.4525	1.4741	1.4499	1.4658	1.4509	1.4398
Austria	Euro	0.8416	0.8314	0.8136	0.7971	0.7988	0.7986	0.7770	0.7704	0.7672	0.7598
Belgium	Euro	0.8360	0.8319	0.8221	0.8062	0.8002	0.7998	0.7811	0.7729	0.7697	0.7552
Canada	Canadian Dollar	1.2214	1.2399	1.2446	1.2240	1.2304	1.2480	1.2068	1.2047	1.1983	1.1938
Chile	Chilean Peso	359.8370	348.0168	347.2285	349.6805	367.2139	391.3606	409.9778	411.2637	412.3604	416.2466
Colombia	Colombian Peso	1 121.0475	1 168.2430	1 203.5852	1 206.6791	1 220.6073	1 276.4794	1 285.2104	1 314.7869	1 326.8935	1 349.0119
Czech Republic	Czech Koruna	13.6629	13.3453	13.2977	12.7853	12.7032	12.9345	12.5776	12.3776	12.3995	12.4432
Denmark	Danish Krone	7.5858	7.4665	7.5641	7.3548	7.3287	7.3034	7.0806	6.8518	6.7751	6.6685
Estonia	Euro	0.5118	0.5116	0.5211	0.5224	0.5269	0.5374	0.5279	0.5336	0.5417	0.5446
Finland	Euro	0.8999	0.8981	0.9085	0.9054	0.9072	0.9075	0.8810	0.8635	0.8579	0.8474
France	Euro	0.8541	0.8414	0.8443	0.8116	0.8076	0.8085	0.7801	0.7664	0.7564	0.7317
Germany	Euro	0.8045	0.7887	0.7872	0.7748	0.7689	0.7779	0.7527	0.7406	0.7408	0.7372
Greece	Euro	0.7215	0.7132	0.6847	0.6313	0.6111	0.6089	0.5886	0.5761	0.5670	0.5571
Hungary	Forint	126.3262	124.2718	125.6236	124.9794	129.4150	132.5180	132.0471	134.3631	138.1982	140.9354
Iceland	Iceland Krona	132.7921	135.1520	136.9677	137.0226	138.5479	141.9368	140.0441	137.1220	136.8588	136.6584

Year		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Ireland	Euro	0.8489	0.8315	0.8231	0.8112	0.8190	0.8095	0.7944	0.7911	0.7882	0.7963
Israel	New Israeli Sheqel	3.9815	3.9448	3.9554	3.8396	3.9404	3.9241	3.7876	3.7451	3.7206	3.6868
Italy	Euro	0.7726	0.7587	0.7477	0.7373	0.7396	0.7385	0.7006	0.6865	0.6827	0.6708
Japan	Yen	111.6666	107.4543	104.2740	101.3027	103.0521	103.4497	105.5026	105.3790	104.6100	101.4739
Korea	Won	840.8902	854.5857	854.8873	869.0814	871.8781	857.3680	858.9928	871.6958	870.7730	860.2140
Latvia	Euro	0.4867	0.4985	0.5062	0.4993	0.4976	0.4974	0.4846	0.4843	0.4920	0.4947
Lithuania	Euro	0.4501	0.4519	0.4527	0.4433	0.4426	0.4457	0.4385	0.4419	0.4509	0.4548
Luxembourg	Euro	0.9250	0.9051	0.9068	0.8953	0.8841	0.8810	0.8520	0.8444	0.8458	0.8448
Mexico	Mexican Peso	7.6768	7.6730	7.8587	7.8844	8.0453	8.3259	8.4456	8.8709	9.1270	9.3088
Netherlands	Euro	0.8535	0.8361	0.8244	0.7982	0.8088	0.8098	0.7955	0.7785	0.7803	0.7849
New Zealand	New Zealand Dollar	1.4961	1.4859	1.4956	1.4460	1.4407	1.4755	1.4407	1.4534	1.4500	1.4534
Norway	Norwegian Krone	9.1451	9.0827	9.0371	9.0293	9.2785	9.9299	10.0429	9.9218	9.8271	9.9308
Poland	Zloty	1.8036	1.8014	1.7962	1.7620	1.7671	1.7646	1.7330	1.7374	1.7541	1.7499
Portugal	Euro	0.6227	0.6231	0.6054	0.5836	0.5789	0.5848	0.5715	0.5750	0.5785	0.5669
Slovak Republic	Euro	0.5018	0.5064	0.5045	0.4911	0.4854	0.4914	0.5032	0.5028	0.5050	0.5052
Slovenia	Euro	0.6375	0.6240	0.6068	0.5904	0.5912	0.5951	0.5772	0.5676	0.5694	0.5655
Spain	Euro	0.7264	0.7141	0.6950	0.6748	0.6624	0.6646	0.6427	0.6301	0.6346	0.6266
Sweden	Swedish Krona	9.0186	8.8440	8.6548	8.5977	8.7271	8.8520	8.8235	8.7195	8.8287	8.7459
Switzerland	Swiss Franc	1.4651	1.3975	1.3541	1.3125	1.2818	1.2355	1.2021	1.1799	1.1677	1.1478
Turkey	Turkish Lira	0.9197	0.9662	1.0199	1.0703	1.1045	1.1621	1.2412	1.3730	1.6078	1.8405
United Kingdom	Pound Sterling	0.7018	0.7061	0.7016	0.6952	0.6984	0.6924	0.6887	0.6821	0.6871	0.6804
United States	US Dollar	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
European Union (28 countries)	Euro	0.7648	0.7546	0.7560	0.7348	0.7374	0.7517	0.7147	0.6964	0.6933	0.6841

Source: OECD, https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm.

Annex 4
Damage costs perceived only in the emitter country

Information on damage perceived in the emitter country is provided for information. The marginal damage cost set that should be used to assess damage from European installations or countries is the marginal damage cost set accounting for impacts wherever they occur (6.1). The impact of transboundary pollution is an important issue to consider when assessing the damage cost of emitter country releases that affect its nearest neighbours. This issue is most relevant for smaller emitter countries when considering primary pollutants, and for secondary pollutants in general.

Table 50 shows marginal damage costs related to health damage perceived in the emitter country per tonne of pollutant emissions for $PM_{2.5}$ and O_3 precursors.

Table 50: Marginal damage costs of major air pollutants – impacts on health from fine particulate matter and ozone

ISO code	Country	Damage in the emitter country - €$_{2019}$/tonne of pollutant emissions for the $PM_{2.5}$ and O_3 precursors											
		NO_X VOLY	NO_X VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
AL	**Albania**	6 767	15 773	58 875	138 571	38 230	89 981	12 964	30 512	256	552	7 063	16 625
AM	**Armenia**	4 681	11 042	150 246	343 156	97 562	222 828	35 547	81 189	3 500	7 717	23 515	53 706
AT	**Austria**	2 908	9 437	40 666	130 847	26 406	84 966	11 141	35 849	326	990	7 806	25 117
AZ	**Azerbaijan**	10 770	16 469	28 103	43 070	18 249	27 968	20 167	30 908	292	428	6 401	9 809
BA	**Bosnia and Herzegovina**	2 252	6 627	23 464	71 670	15 237	46 539	3 946	12 053	97	268	11 380	34 758
BE	**Belgium**	834	3 028	99 314	318 747	64 490	206 979	15 684	50 336	409	1 252	16 600	53 276
BG	**Bulgaria**	2 734	10 472	69 469	271 233	45 110	176 125	5 030	19 637	241	835	10 602	41 393
BY	**Belarus**	1 401	4 485	26 931	85 023	17 488	55 210	7 118	22 471	54	146	3 835	12 108
CH	**Switzerland**	13 563	39 025	72 358	207 448	46 986	134 706	40 458	115 993	1 100	2 979	9 959	28 552
CY	**Cyprus**	1 063	2 360	17 886	41 012	11 614	26 631	2 076	4 760	34	53	5 887	13 500
CZ	**Czechia**	2 195	7 014	47 891	152 256	31 098	98 868	5 389	17 132	321	973	16 051	51 030
DE	**Germany**	6 869	25 097	62 665	226 082	40 691	146 806	20 312	73 282	754	2 504	16 757	60 455
DK	**Denmark**	1 100	3 597	29 482	92 740	19 144	60 221	5 715	17 976	43	120	3 263	10 264
EE	**Estonia**	126	458	5 892	20 072	3 826	13 034	319	1 088	12	36	2 494	8 496
ES	**Spain**	3 806	11 973	59 959	188 915	38 934	122 672	15 352	48 370	779	2 266	5 820	18 338
FI	**Finland**	397	1 327	19 257	61 812	12 505	40 138	3 459	11 104	35	103	3 595	11 539
FR	**France**	5 224	16 415	49 855	156 852	32 374	101 852	16 420	51 659	519	1 512	6 867	21 604
GB	**United Kingdom**	4 120	13 034	76 588	235 335	49 732	152 815	25 583	78 611	544	1 584	22 967	70 570
GE	**Georgia**	4 249	12 280	174 527	493 763	113 329	320 625	26 756	75 697	1 423	3 898	6 397	18 097
GR	**Greece**	215	1 090	38 704	137 869	25 132	89 525	6 544	23 309	768	2 426	10 109	36 009
HR	**Croatia**	2 296	8 453	29 532	110 729	19 177	71 902	4 817	18 061	138	479	6 036	22 631
HU	**Hungary**	4 727	16 256	52 038	179 164	33 791	116 341	9 212	31 715	272	879	8 727	30 047
IE	**Ireland**	912	2 012	11 477	24 777	7 453	16 089	6 031	13 020	29	59	754	1 628
IT	**Italy**	17 110	61 740	159 267	573 203	103 420	372 209	21 578	77 660	3 999	13 775	23 464	84 449

ISO code	Country	Damage in the emitter country - €2019/tonne of pollutant emissions for the $PM_{2.5}$ and O_3 precursors											
		NO_X VOLY	NO_X VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
LT	**Lithuania**	636	2 316	14 852	52 992	9 644	34 410	3 106	11 082	15	46	3 270	11 668
LU	**Luxembourg**	68	257	24 398	59 614	15 843	38 710	4 780	11 678	25	54	2 846	6 953
LV	**Latvia**	279	1 156	23 766	88 658	15 433	57 570	4 982	18 586	32	112	3 069	11 447
MD	**Moldova**	2 905	7 692	43 236	115 782	28 075	75 183	7 372	19 741	59	146	8 136	21 789
ME	**Montenegro**	720	2 027	7 441	22 185	4 832	14 406	954	2 845	76	196	6 138	18 300
MK	**North Macedonia**	1 539	4 144	44 984	121 851	29 210	79 124	5 078	13 755	564	1 461	13 155	35 633
MT	**Malta**	-573	-967	49 975	141 687	32 452	92 005	2 051	5 816	410	1 110	29 614	83 961
NL	**Netherlands**	2 329	7 213	64 550	190 240	41 916	123 533	16 220	47 802	457	1 300	12 733	37 527
NO	**Norway**	168	483	16 692	45 818	10 839	29 752	2 019	5 542	35	88	2 107	5 785
PL	**Poland**	2 104	6 318	35 127	104 691	22 810	67 981	7 026	20 939	327	907	17 216	51 308
PT	**Portugal**	2 092	7 410	63 755	222 044	41 399	144 184	6 350	22 117	353	1 083	6 437	22 418
RO	**Romania**	6 342	21 317	53 177	182 077	34 530	118 232	10 205	34 942	396	1 267	9 172	31 405
RS	**Serbia**	2 021	6 453	40 480	130 621	26 286	84 819	3 517	11 348	188	555	11 311	36 499
RU	**Russian Federation**	1 700	4 945	41 326	121 638	26 835	78 986	12 977	38 197	563	1 591	14 089	41 468
SE	**Sweden**	427	1 416	14 488	46 004	9 408	29 873	2 802	8 897	21	57	3 115	9 890
SI	**Slovenia**	3 046	9 757	58 631	186 710	38 072	121 240	5 140	16 368	252	751	7 297	23 237
SK	**Slovakia**	1 987	5 600	34 010	95 829	22 084	62 227	4 634	13 058	165	443	12 787	36 030
TR	**Turkey**	6 360	10 229	61 070	98 482	39 656	63 949	14 864	23 970	1 078	1 697	15 456	24 925

Results for Malta show that according to the SRMs for the NO_X precursor a 15 % increase in NO_X emissions results in a reduction in $PM_{2.5}$ concentrations (and hence to negative damage costs). The reasons have been discussed with EMEP. Reductions in $PM_{2.5}$ concentrations due to NO_X emissions are very small. They occur only due to NO_X emissions, not due to any other PM precursors. A comparable result can be seen for Iceland (not shown here). What Malta and Iceland have in common is they are both islands and affected by nearby volcanic sources of SO_2. It could be that NO_X emissions lead to more ammonium nitrate at the expense of ammonium sulphate in these areas, and since ammonium nitrate is present closer to the surface it is more readily deposited. Note that this is just one theory, and EMEP has not investigated this particular case in detail. There is also a possibility that ozone chemistry might play a role here too. NO_X emissions lead to less ozone in Malta and less ozone implies less oxidizing capacity which implies less oxidation into particles. This could be one of many factors for Malta.

The fact that the marginal damage costs from direct exposure to NO_X emissions (reflected in the contribution to NO_2 health impacts, Table 51) exceed the marginal damage costs from indirect exposure to NO_X emissions through formation of secondary species (O_3, secondary $PM_{2.5}$, Table 50) appears plausible. Secondary species take a while to form in the air, and thus atmospheric dilution reduces the concentration of the chemical products. Switzerland and Italy stand out as exceptions to this rule. In part, this is probably related to constrained pollutant transport because of geographical barriers or unfavourable meteorological conditions. It is well known, for example, that PM concentrations are very high in the Padana Valley in Italy due to inadequate ventilation and low atmospheric ceiling heights. The direct damage cost exceeds the indirect exposure cost in countries along the European perimeter or in the proximity of large water bodies, such is the case for Belgium, The Netherlands, Spain, Portugal and Greece. The same pattern can also be observed for small countries, e.g., Luxembourg, while the costs are similar when considering larger and somewhat more uniformly populated countries, such as Germany and France.

Table 51: Marginal damage costs of major air pollutants – impacts on health from nitrogen dioxide

Damage in the emitter country - €$_{2019}$/tonne of pollutant emissions for the NO_2 precursor NO_X			
ISO code	**Country**	**NO_X VOLY**	**NO_X VSL**
AT	**Austria**	4 840	18 509
BE	**Belgium**	5 356	20 372
BG	**Bulgaria**	2 932	13 319
CH	**Switzerland**	9 851	33 665
CY	**Cyprus**	2 951	7 817
CZ	**Czechia**	3 372	12 586
DE	**Germany**	6 494	28 087
DK	**Denmark**	2 329	8 617
EE	**Estonia**	1 041	4 153
ES	**Spain**	6 403	24 181
FI	**Finland**	2 943	11 219
FR	**France**	5 493	20 558
GB	**United Kingdom**	6 738	24 436
GR	**Greece**	4 884	20 858
HR	**Croatia**	3 235	14 323
HU	**Hungary**	6 540	26 151
IE	**Ireland**	2 336	5 751
IT	**Italy**	8 835	38 566
LT	**Lithuania**	2 640	10 867
LU	**Luxembourg**	2 711	7 704
LV	**Latvia**	3 259	14 037
ME	**Montenegro**	1 541	5 284
MT	**Malta**	1 744	5 830
NL	**Netherlands**	7 476	26 061
NO	**Norway**	3 593	11 659
PL	**Poland**	3 639	12 591
PT	**Portugal**	4 448	18 504
RO	**Romania**	4 692	18 669
SE	**Sweden**	3 076	11 687
SI	**Slovenia**	3 761	14 218
SK	**Slovakia**	4 035	13 100
TR	**Turkey**	12 542	21 993

Comparison between Table 51 and Table 22 show that the difference between damage within the emitter country and damage aggregated across Europe is small. An exception is Luxembourg which should be expected given its small size and the fact that it is surrounded by countries of high population density.

Table 52: Marginal damage costs of major air pollutants – impacts on crops

Emitter country		Damage in emitter country - €$_{2019}$/tonne of pollutant emissions for O_3 precursors	
		NO_X	NMVOC
AL	Albania	102	8
AT	Austria	54	9
BA	Bosnia and Herzegovina	48	2
BE	Belgium	-9	10
BG	Bulgaria	87	7
CH	Switzerland	46	11
CY	Cyprus	17	3
CZ	Czechia	52	12
DE	Germany	41	31
DK	Denmark	-5	3
EE	Estonia	0.4	0.1
ES	Spain	399	60
FI	Finland	0.13	0.04
FR	France	138	33
GB	United Kingdom	0.2	6
GR	Greece	99	50
HR	Croatia	71	5
HU	Hungary	147	10
IE	Ireland	1	0.2
IT	Italy	264	110
LT	Lithuania	14	1
LU	Luxembourg	-1	1
LV	Latvia	4	0.4
ME	Montenegro	8	1
MK	North Macedonia	76	8
MT	Malta	-12	1
NL	Netherlands	-23	8
NO	Norway	0.4	0.1
PL	Poland	44	20
PT	Portugal	110	18
RO	Romania	121	10
RS	Serbia	76	14
SE	Sweden	1	0.2
SI	Slovenia	17	3
SK	Slovakia	41	4
TR	Turkey	394	45

Table 53: Marginal damage costs of major air pollutants – impacts on forests

Emitter country		Damage in emitter country - €$_{2019}$/tonne of pollutant emissions for O_3 precursors	
		NO_X	NMVOC
AT	**Austria**	38	9
BE	**Belgium**	-4	2
BG	**Bulgaria**	34	2
CY	**Cyprus**	1	0
CZ	**Czechia**	21	6
DE	**Germany**	7	14
DK	**Denmark**	-3	2
EE	**Estonia**	6	1
ES	**Spain**	44	7
FI	**Finland**	19	2
FR	**France**	97	20
GB	**United Kingdom**	-1	1
GR	**Greece**	4	1
HR	**Croatia**	52	4
HU	**Hungary**	28	3
IE	**Ireland**	0.2	0.1
IT	**Italy**	97	51
LT	**Lithuania**	9	1
LU	**Luxembourg**	-10	2
LV	**Latvia**	16	2
MT	**Malta**	0	0
NL	**Netherlands**	-9	2
PL	**Poland**	11	7
PT	**Portugal**	120	22
RO	**Romania**	132	11
SE	**Sweden**	18	1
SI	**Slovenia**	46	11
SK	**Slovakia**	36	4

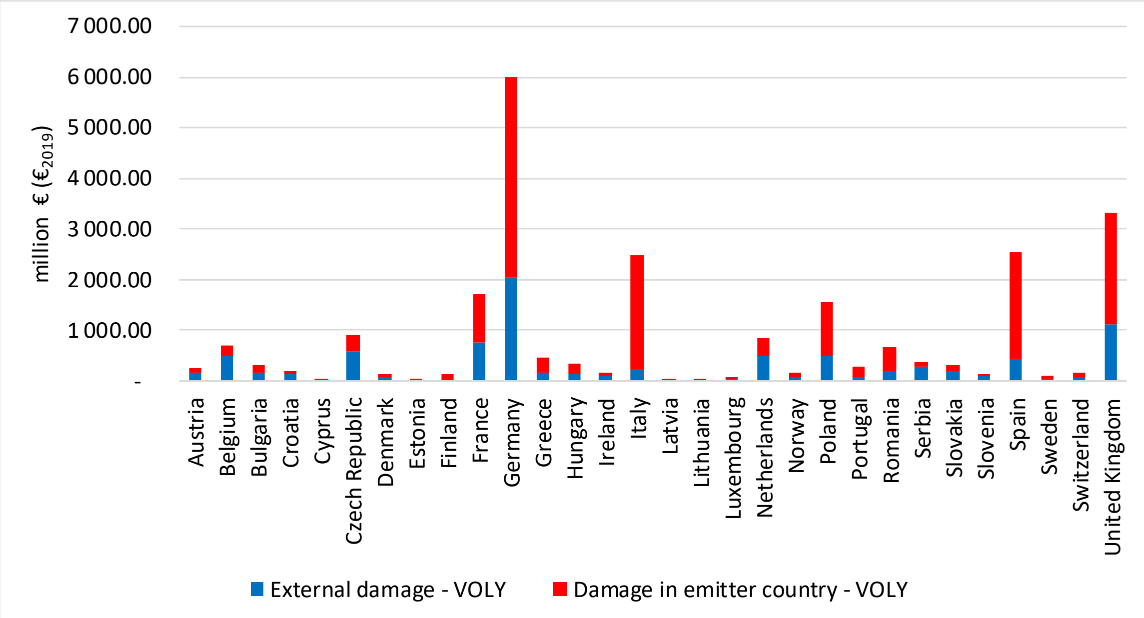
Table 54: Marginal damage costs of major air pollutants – impacts on ecosystems

Country	Country ISO	Damage in emitter country in €2019/tonne of precursors to eutrophication	
		NH_3	NOx
Albania	AL	0	0
Austria	AT	311	78
Bosnia and Herzegovina	BA	0	0
Belgium	BE	11	2
Bulgaria	BG	84	0.17
Belarus	BY	0	0
Switzerland	CH	1	0
Cyprus	CY	0	0
Czechia	CZ	6	1
Germany	DE	52	15
Denmark	DK	5	0
Estonia	EE	2 541	154
Spain	ES	84	21
Finland	FI	74	41
France	FR	218	54
United Kingdom	GB	137	14
Greece	GR	160	25
Croatia	HR	42	7
Hungary	HU	197	70
Ireland	IE	185	58
Iceland	IS	0	0
Italy	IT	417	114
Lithuania	LT	55	12
Luxembourg	LU	0	0
Latvia	LV	43	10
Republic of Moldova	MD	0	0
North Macedonia	MK	0	0
Malta	MT	0	0
Netherlands	NL	8	1
Norway	NO	0	0
Poland	PL	357	80
Portugal	PT	61	21
Romania	RO	65	35
Serbia	RS	0	0
Sweden	SE	24	3
Slovenia	SI	69	37
Slovakia	SK	9	16

(*) Missing emitter countries: Liechtenstein, Turkey, Kosovo, Montenegro. Additional emitter countries: Belarus, Republic of Moldova.

The following figures show, for each pollutant, in graphical form how damage perceived in the emitter country only compares to damage perceived in all other countries of the European region. For each pollutant, these results are presented in absolute values and in percent. The sum of the "internal" and "external" damage is the damage perceived in EEA38+UK.

Figure 51: NO_x – comparison between internal and external damage in million €$_{2019}$ – valuation for VOLY



For some countries "internal" damage related to NO_x emissions exceeds the "external" damage (Germany, Italy, Spain, the UK, France, Sweden, Finland …). For others "external" damage dominates (Austria, Belgium, Czechia, Denmark, Bulgaria, Croatia, Luxembourg …). Amongst the gases, NO_x is the one for which the formation of particles is the fastest. Compared to primary particles, secondary particles formed from NO_x are transported more easily over countries. Furthermore, for small countries it is not astonishing that most of the damage occurs outside their borders. In Italy, on the contrary, most pollutants are emitted in the Po Valley and because of geographical and related meteorological conditions a large part remains in this area.

Figure 52: NO_x – comparison between internal and external damage in % – valuation for VOLY

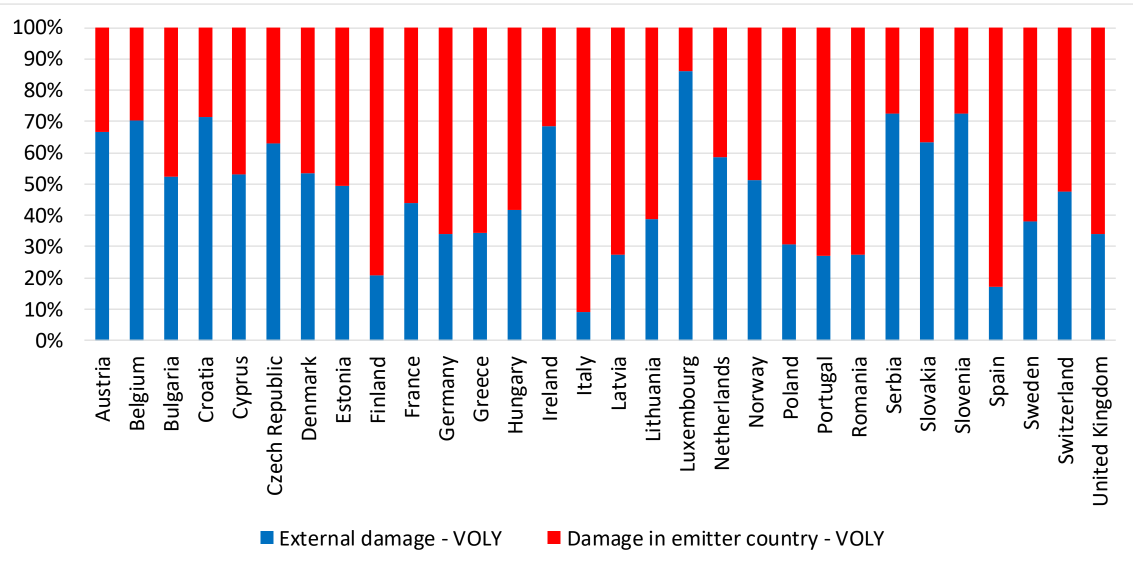
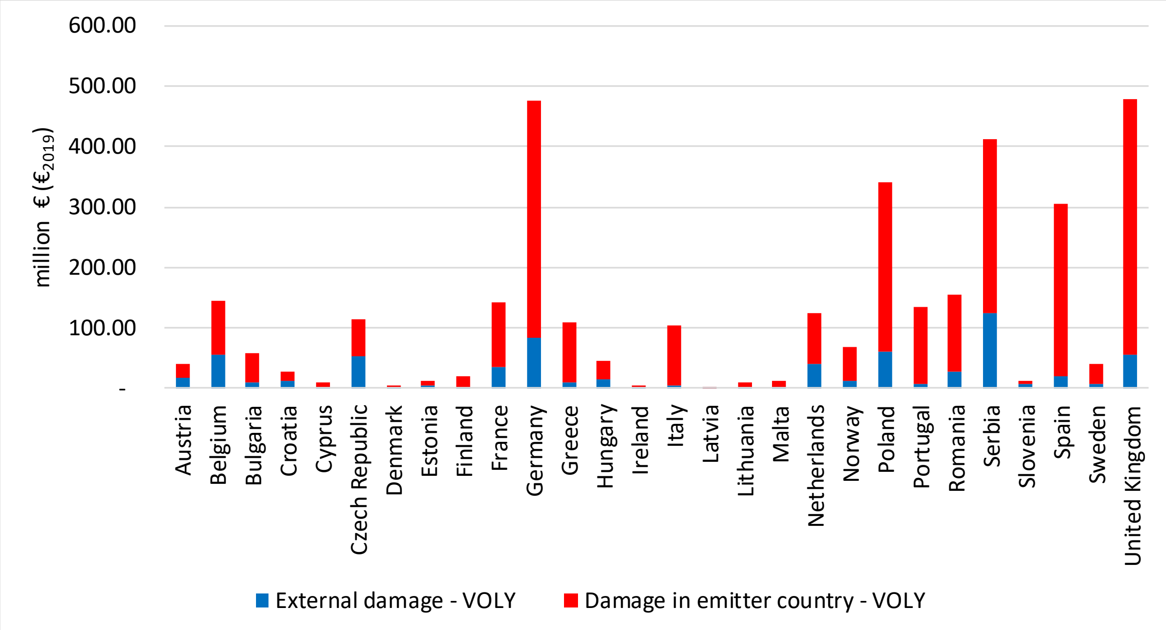


Figure 53: PM$_{10}$ – comparison between internal and external damage in million €$_{2019}$ – valuation for VOLY



For primary PM$_{10}$ emissions, "internal" damage exceeds the "external" damage in all countries. Impacts are related directly to the primary pollutant without chemical transformation. Particles emitted are deposited closer to the emitting source than is the case for gases.

Figure 54: PM$_{10}$ – comparison between internal and external damage in % – valuation for VOLY

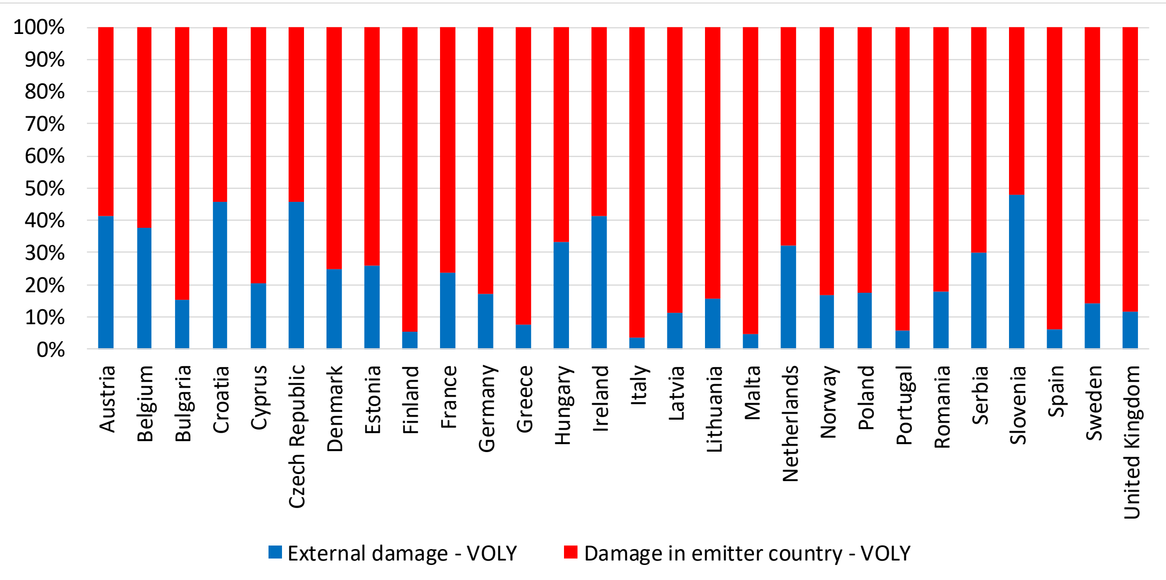
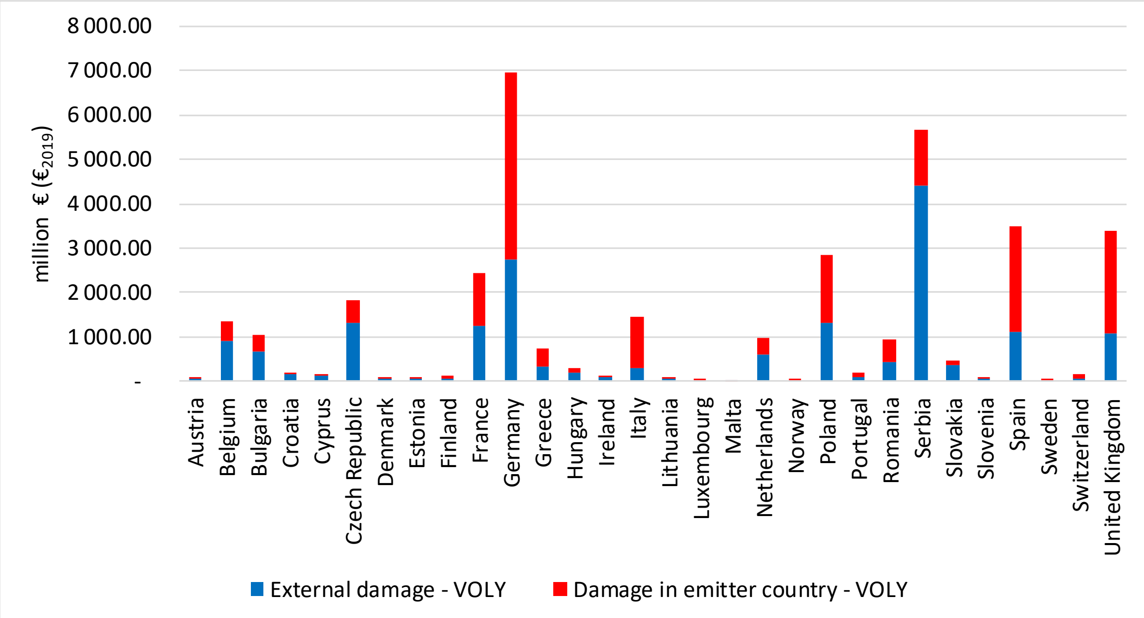


Figure 55: SO_2 – comparison between internal and external damage in million €$_{2019}$ – valuation for VOLY



For SO_2 emissions, "external" damage exceeds the "internal" damage in most countries. This gas takes more time to form particles than NO_x, which explains the generally larger damage outside the emitter country's borders. Notable exceptions are Finland, Germany, Greece, Italy, Spain, the UK …

Figure 56: SO_2 – comparison between internal and external damage in % – valuation for VOLY

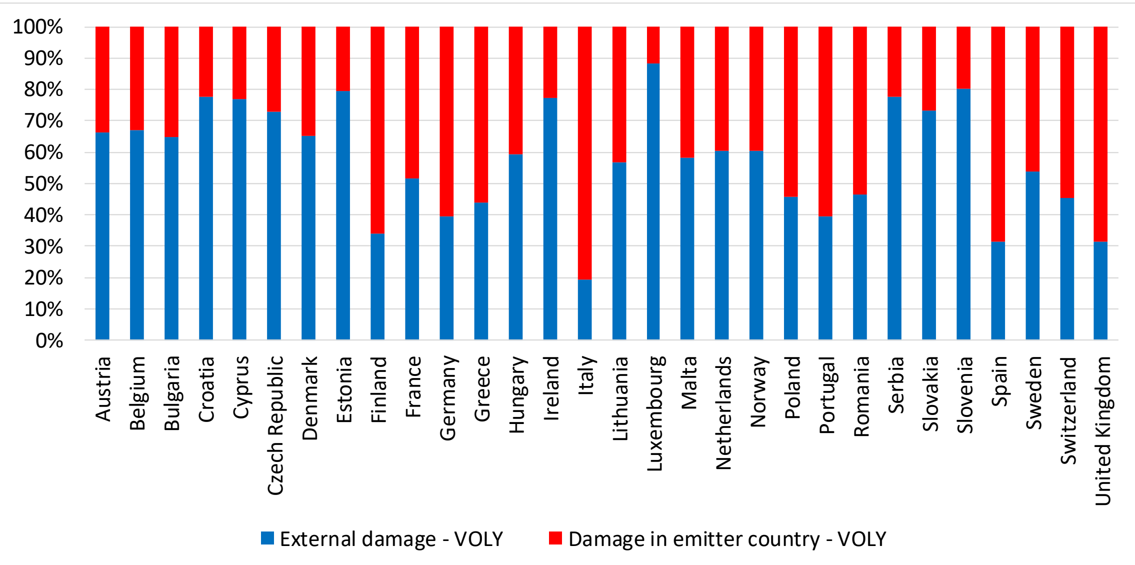
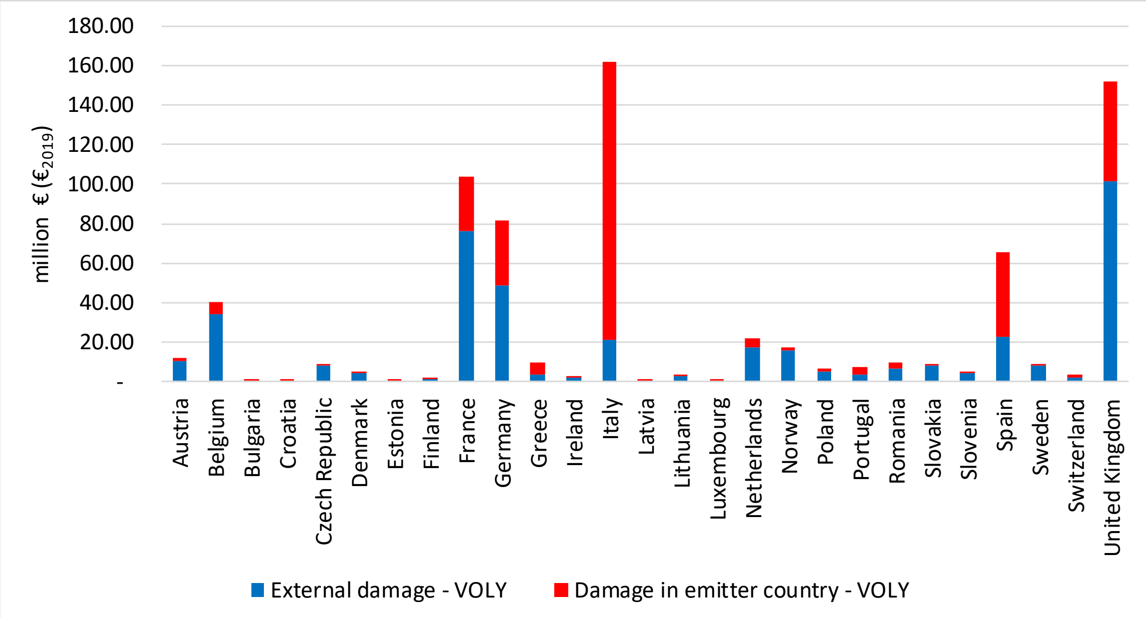


Figure 57: NMVOC – comparison between internal and external damage in million €$_{2019}$ – valuation for VOLY



For NMVOC emissions, "external" damage exceeds the "internal" damage in most countries. Explanations are similar to those given for SO_2 emissions. But there are countries where the opposite is the case, for example Italy or Spain.

Figure 58: NMVOC – comparison between internal and external damage in % – valuation for VOLY

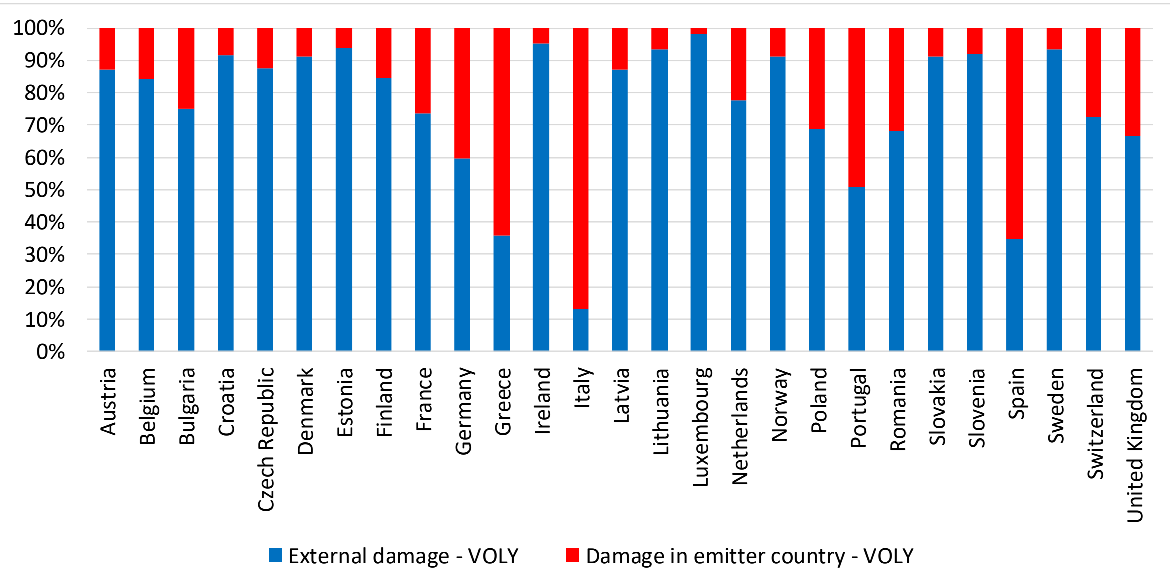
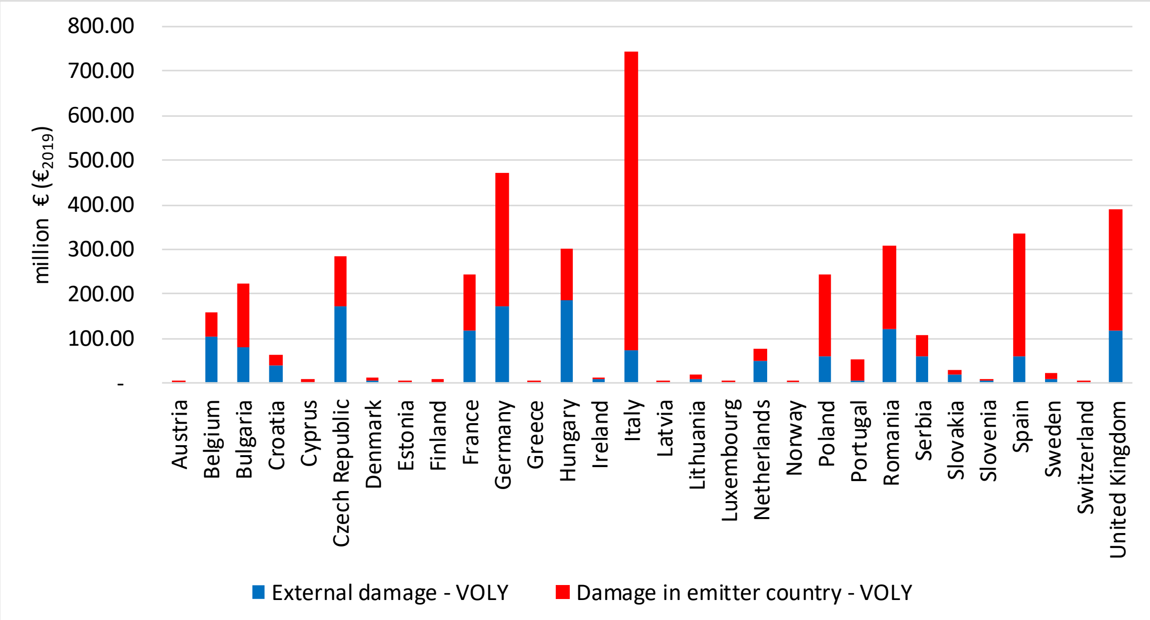
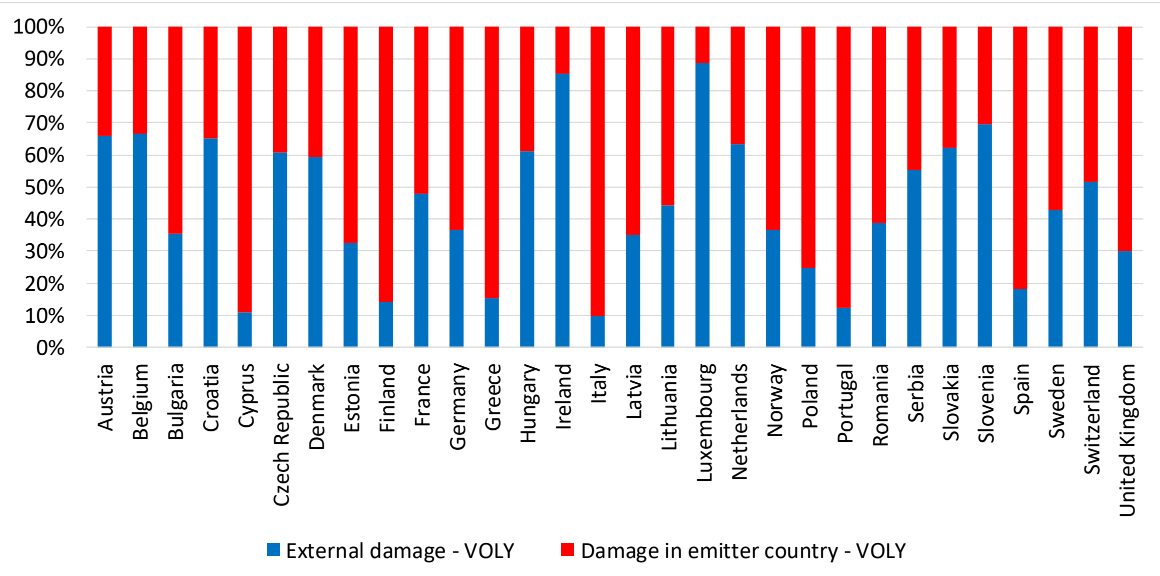


Figure 59: NH_3 – comparison between internal and external damage in million €$_{2019}$ – valuation for VOLY



As was the case for NO_x, whether "internal" or "external" damage related to NH_3 emissions dominates is country dependent.

Figure 60: NH_3 – comparison between internal and external damage in % – valuation for VOLY



Annex 5
Sensitivity calculations for health impacts and effect on the damage cost set

The two following tables present the change in damage costs (expressed in percent) per country and precursor pollutant, when introducing supplementary analysis to provide an indication of possible levels of underestimation of impacts by using the HRAPIE functions. In these tables damage is aggregated over EU38+UK (missing emitter countries are indicated in the tables).

Table 55 presents the influence of the following alternative assumptions

- An increased estimate of $PM_{2.5}$ related mortality, using the relative risk of 1.08 per 10 µg/m^3 overall estimate from Chen and Hoek (2020), compared to 1.06 per 10 µg/m^3 from HRAPIE.
- Adoption of additional response functions for stroke and cardiovascular disease via incidence of non-fatal myocardial infarction linked to $PM_{2.5}$ exposure.

Marginal damage costs are increased on average between 30 % and 40 % depending on emitter country and precursor pollutant.

Table 55: Percentage increase in marginal damage costs from health impacts of $PM_{2.5}$ precursors when applying sensitivity assumptions

Emitter country		Damage increase in EEA38 + UK per tonne of pollutant emissions for $PM_{2.5}$ precursors									
		NO_X VOLY	NO_X VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
AL	**Albania**	34 %	32 %	34 %	32 %	35 %	32 %	36 %	32 %	34 %	32 %
AM	**Armenia**	30 %	30 %	30 %	30 %	31 %	30 %	31 %	30 %	30 %	30 %
AT	**Austria**	38 %	33 %	38 %	33 %	38 %	33 %	39 %	33 %	38 %	33 %
AZ	**Azerbaijan**	31 %	31 %	31 %	31 %	31 %	31 %	32 %	31 %	31 %	31 %
BA	**Bosnia and Herzegovina**	37 %	32 %	36 %	32 %	37 %	32 %	37 %	32 %	36 %	32 %
BE	**Belgium**	39 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %
BG	**Bulgaria**	35 %	32 %	37 %	32 %	35 %	32 %	36 %	32 %	36 %	32 %
BY	**Belarus**	36 %	32 %	36 %	32 %	35 %	32 %	36 %	32 %	36 %	32 %
CH	**Switzerland**	39 %	33 %	38 %	33 %	38 %	33 %	39 %	33 %	39 %	33 %
CY	**Cyprus**	31 %	31 %	33 %	32 %	31 %	31 %	31 %	30 %	33 %	32 %
CZ	**Czechia**	38 %	33 %	37 %	33 %	37 %	33 %	38 %	33 %	37 %	33 %
DE	**Germany**	39 %	33 %	39 %	33 %	38 %	33 %	38 %	33 %	39 %	33 %
DK	**Denmark**	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %
EE	**Estonia**	37 %	33 %	37 %	32 %	37 %	32 %	37 %	32 %	38 %	33 %

Emitter country		Damage increase in EEA38 + UK per tonne of pollutant emissions for $PM_{2.5}$ precursors									
		NO_X VOLY	NO_X VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
ES	Spain	38 %	33 %	38 %	33 %	39 %	33 %	39 %	33 %	38 %	33 %
FI	Finland	38 %	33 %	39 %	33 %	39 %	33 %	38 %	33 %	39 %	33 %
FR	France	39 %	33 %	39 %	33 %	39 %	33 %	39 %	33 %	39 %	33 %
GB	United Kingdom	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %
GE	Georgia	31 %	31 %	31 %	30 %	31 %	31 %	31 %	31 %	31 %	31 %
GR	Greece	34 %	32 %	39 %	33 %	37 %	32 %	37 %	33 %	39 %	33 %
HR	Croatia	38 %	33 %	38 %	32 %	38 %	33 %	38 %	33 %	38 %	32 %
HU	Hungary	36 %	32 %	37 %	32 %	36 %	32 %	37 %	32 %	37 %	32 %
IE	Ireland	37 %	33 %	36 %	32 %	37 %	33 %	38 %	33 %	37 %	33 %
IT	Italy	41 %	33 %	41 %	33 %	40 %	33 %	40 %	33 %	41 %	33 %
LT	Lithuania	37 %	32 %	37 %	32 %	37 %	32 %	36 %	32 %	37 %	32 %
LU	Luxembourg	39 %	33 %	37 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %
LV	Latvia	37 %	32 %	37 %	32 %	37 %	32 %	36 %	32 %	37 %	32 %
MD	Moldova	35 %	32 %	35 %	32 %	35 %	32 %	36 %	32 %	35 %	32 %
ME	Montenegro	36 %	32 %	35 %	32 %	36 %	32 %	36 %	32 %	35 %	32 %
MK	North Macedonia	35 %	32 %	34 %	32 %	35 %	32 %	35 %	32 %	34 %	32 %
MT	Malta	38 %	33 %	39 %	33 %	39 %	33 %	39 %	33 %	39 %	33 %
NL	Netherlands	39 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %
NO	Norway	38 %	33 %	37 %	33 %	37 %	33 %	37 %	33 %	37 %	33 %
PL	Poland	37 %	32 %	36 %	32 %	36 %	32 %	37 %	32 %	36 %	32 %
PT	Portugal	39 %	33 %	40 %	33 %	39 %	33 %	39 %	33 %	40 %	33 %
RO	Romania	36 %	32 %	36 %	32 %	35 %	32 %	36 %	32 %	36 %	32 %
RS	Serbia	36 %	32 %	36 %	32 %	36 %	32 %	37 %	32 %	36 %	32 %
RU	Russian Federation	34 %	32 %	35 %	32 %	34 %	32 %	35 %	32 %	35 %	32 %
SE	Sweden	38 %	33 %	39 %	33 %	38 %	33 %	37 %	33 %	38 %	33 %
SI	Slovenia	39 %	33 %	38 %	33 %	38 %	33 %	39 %	33 %	38 %	33 %
SK	Slovakia	36 %	32 %	36 %	32 %	36 %	32 %	37 %	32 %	36 %	32 %
TR	Turkey	30 %	30 %	30 %	30 %	30 %	30 %	31 %	30 %	30 %	30 %
ATL	NE Atlantic Ocean	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %		
BAS	Baltic Sea	38 %	33 %	38 %	33 %	38 %	33 %	37 %	33 %		

Emitter country		Damage increase in EEA38 + UK per tonne of pollutant emissions for $PM_{2.5}$ precursors									
		NO_X VOLY	NO_X VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
BLS	**Black Sea**	31 %	31 %	31 %	31 %	31 %	31 %	31 %	31 %		
MED	**Mediterranean Sea**	38 %	33 %	35 %	32 %	37 %	33 %	37 %	33 %		
NOS	**North Sea**	38 %	33 %	38 %	33 %	38 %	33 %	38 %	33 %		
Missing emitter countries: Liechtenstein, Kosovo, North Macedonia											

Table 56 presents the influence of the following alternative assumptions

- Use of the relative risk of 1.02 per 10 µg/m^3 from Huangfu and Atkinson (2020), applied without cut point at 20 µg/m^3.

The effect is an increase in marginal damage costs of roughly 150 %.

Table 56: Percentage increase in marginal damage costs from health impacts of NO_2 precursors when applying sensitivity assumptions

Emitter country		Damage increase in EEA38 + UK per tonne of pollutant emissions for NO_2 precursors	
		NO_X VOLY	NO_X VSL
AT	**Austria**	148 %	149 %
BE	**Belgium**	148 %	150 %
BG	**Bulgaria**	148 %	150 %
CH	**Switzerland**	148 %	150 %
CY	**Cyprus**	149 %	150 %
CZ	**Czechia**	149 %	150 %
DE	**Germany**	148 %	150 %
DK	**Denmark**	148 %	150 %
EE	**Estonia**	149 %	150 %
ES	**Spain**	148 %	149 %
FI	**Finland**	148 %	149 %
FR	**France**	148 %	149 %
GB	**United Kingdom**	148 %	149 %
GR	**Greece**	148 %	150 %
HR	**Croatia**	149 %	150 %
HU	**Hungary**	149 %	150 %
IE	**Ireland**	148 %	149 %
IT	**Italy**	148 %	150 %
LT	**Lithuania**	148 %	150 %
LU	**Luxembourg**	148 %	149 %
LV	**Latvia**	148 %	150 %
ME	**Montenegro**	148 %	150 %
MT	**Malta**	148 %	149 %
NL	**Netherlands**	148 %	150 %
NO	**Norway**	148 %	149 %
PL	**Poland**	149 %	150 %
PT	**Portugal**	148 %	150 %
RO	**Romania**	149 %	150 %
SE	**Sweden**	149 %	150 %
SI	**Slovenia**	148 %	150 %
SK	**Slovakia**	149 %	150 %
TR	**Turkey**	148 %	149 %

Missing emitter countries: Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo

Annex 6

Completeness of reporting for particulate matter and CO_2 by the 2017 top 30 polluters

Table 57: Completeness of reporting of PM_{10} and CO_2 emissions by the 2017 top 30 polluters

Facility	Facility ID	Country	Activity	CO_2 emissions in kt					PM_{10} emissions in t				
				2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
PGE Górnictwo i Energetyka Konwencjonalna S.A.; Oddzial Elektrownia Belchatów	1298	Poland	Thermal power stations and other combustion installations	37 200	36 800	37 000	34 900	37 600	1 010	880	1 110	698	855
ArcelorMittal FOS	4273	France	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	7 990	7 920	7 860	7 240	7 930	1 260	989	1 610	1 500	1 600
ARCELORMITTAL ATLANTIQUE ET LORRAINE SITE DE DUNKERQUE	4797	France	Installations for the processing of ferrous metals	11 900	12 300	11 400	13 500	12 600					
ENEA Wytwarzanie Sp. z o.o.	4951	Poland	Thermal power stations and other combustion installations	10 600	11 400	11 600	12 000	12 100	856	747	752	235	155
Central Termoeléctrica Sines	5485	Portugal	Thermal power stations and other combustion installations	7 180	7 400	8 680	7 320	8 400					

Facility	Facility ID	Country	Activity	CO_2 emissions in kt					PM_{10} emissions in t				
				2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Mátrai Eromu Zrt.	5791	Hungary	Thermal power stations and other combustion installations	6 330	6 400	6 400	6 480	5 770					312
Enefit Energiatootmine AS; Eesti elektrijaam	5952	Estonia	Thermal power stations and other combustion installations	10 700	9 680	7 080	7 940	8 360	5 090	4 340	2 300	2 130	1 750
Centrale Torrevaldaliga Nord	6262	Italy	Thermal power stations and other combustion installations	9 730	10 900	10 700	10 200	9 750	61	70	59	115	
Enea Elektrownia Polaniec Spólka Akcyjna	6672	Poland	Thermal power stations and other combustion installations	5 570	6 120	6 300	7 730	7 030	515	330	395	520	472
Tata Steel IJmuiden BV	7974	Netherlands	Thermal power stations and other combustion installations	5 990	5 930	6 210	6 300	6 930	790	755	696	721	642
CENTRAL TÉRMICA DE ABOÑO	8521	Spain	Thermal power stations and other combustion installations	6 860	6 790	7 550	5 540	8 190	350	283	565	491	461
CENTRAL TERMICA DE ANDORRA	8966	Spain	Thermal power stations and other combustion installations	3 630	4 790	4 660	3 370	4 810					352
UNIDAD DE PRODUCCION TERMICA AS PONTES	8972	Spain	Thermal power stations and other	6 610	6 910	7 540	6 930	8 110	435	305	225	248	355

Facility	Facility ID	Country	Activity	CO_2 emissions in kt					PM_{10} emissions in t				
				2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
			combustion installations										
Drax Power Station	13777	United Kingdom	Thermal power stations and other combustion installations	23 100	23 700	23 400	17 700	18 000	752	846	767	897	737
Port Talbot Steel Works	13829	United Kingdom	Metal ore (including sulphide ore) roasting or sintering installations	8 030	8 540	7 550	6 720	6 720	2 130	2 830	2 080	1 300	1 620
PPC S.A. SES AGIOY DHMHTRIOY	14245	Greece	Thermal power stations and other combustion installations	13 100	11 800	10 600	9 050	8 940	365	616	366	522	458
TETs Maritsa iztok 2 EAD	15875	Bulgaria	Thermal power stations and other combustion installations	9 460	10 300	11 300	9 650	10 500					
Salzgitter Flachstahl GmbH	43283	Germany	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	7 710	8 030	7 430	9 460	7 940	212	266	222	177	176
RWE Power AG	43843	Germany	Thermal power stations and other combustion installations	33 300	32 400	32 100	31 300	29 900	401	454	529	483	405

Facility	Facility ID	Country	Activity	CO_2 emissions in kt					PM_{10} emissions in t				
				2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
RWE Power AG Kraftwerk Niederaußem	44073	Germany	Thermal power stations and other combustion installations	29 500	27 200	27 300	24 800	27 200	409	412	373	309	375
RWE Power AG	44118	Germany	Thermal power stations and other combustion installations	18 800	18 800	18 300	18 900	19 100	277	229	235	325	309
LEAG; Kraftwerk Jänschwalde	46361	Germany	Thermal power stations and other combustion installations	25 700	24 500	23 700	24 100	24 000	675	607	571	539	535
LEAG; Kraftwerk Schwarze Pumpe	46366	Germany	Thermal power stations and other combustion installations	11 400	11 700	12 300	12 300	11 500	101	67	59	105	68
Kraftwerk Boxberg	74662	Germany	Thermal power stations and other combustion installations	19 200	18 700	19 500	18 600	19 100	460	409	427	393	353
LEAG Lausitz Energie Kraftwerke AG Kraftwerk Lippendorf	74740	Germany	Thermal power stations and other combustion installations	11 800	11 900	10 300	10 800	11 400	229	173	108	96	95
Ogranak Termoelektrane Nikola Tesla - TENT A	109453	Germany	Chemical installations for the production on an industrial scale of basic organic chemicals	6 870	6 910	7 120	7 180	7 350	137	130	93	119	120

Facility	Facility ID	Country	Activity	CO_2 emissions in kt					PM_{10} emissions in t				
				2013	2014	2015	2016	2017	2013	2014	2015	2016	2017
Ogranak Termoelektrane Nikola Tesla - TENT B	124090	Serbia	Thermal power stations and other combustion installations						4 420	3 640	1 970	2 680	3 140
Ogranak Termoelektrane i kopovi Kostolac - TE Kostolac A	124091	Serbia	Thermal power stations and other combustion installations						1 290	921	1 320	1 020	1 520
Ogranak Termoelektrane i kopovi Kostolac - TE Kostolac B	124106	Serbia	Thermal power stations and other combustion installations						3 720	355	950	2 340	1 250
Scunthorpe Integrated Iron And Steel Works	167657	United Kingdom	Installations for the production of pig iron or steel (primary or secondary melting) including continuous casting	4 860	7 170	7 100	5 240	4 960	2 550	2 710	2 810	2 780	2 710

Annex 7
Sectoral adjustment factors calculated with SHERPA

Relying on a unique national average estimate of damage per tonne of pollutant ignores the proximity of industry with population and in some cases the release of pollutants at high altitude that can introduce strong differences in exposure and health impact. One way to reduce associated errors is to differentiate the national damage per tonne of pollutant by activity sector. This sectorisation has been added to the EEA (2014) methodology using results from the first report on sectoral approaches from the Eurodelta-II exercise (Thunis et al., 2008). In that report, sectoral potencies were elaborated to reflect the relative efficiency of a specific sector compared to all sectors in reducing $PM_{2.5}$ exposure by reducing precursors emissions. Unfortunately, there has not been any update of the Eurodelta-II exercise. And already at the time of the 2014 report, the limitation that those results were only relevant for a handful of European countries was brought forward. This Annex presents the methodology used to calculate the potencies with the SHERPA tool as well as results by country and SNAP.

Methodology:

The methodology used to estimate country-based sectoral adjustment factors is similar to the one developed in Eurodelta-II and used in the EEA 2014 report. The main difference is that we do not rely on a full-CTM but on the SHERPA surrogate model that provides the grid-to-grid impact of emission reductions (NO_x, NH_3, PM, SO_2, NMVOC) to $PM_{2.5}$ and NO_2 concentrations. Sectoral adjustment factors are calculated using the CHIMERE version of the SHERPA-tool for NO_2 exposure and the EMEP version for the $PM_{2.5}$ exposure. The EMEP version of SHERPA is more recent, but at a lower spatial resolution (10 km instead of 7 km) and not available for NO_2.

The main steps followed to compute the adjustments factors are summarised here:

1) First, for each country an emission efficiency is computed in terms of population exposure over the whole domain covered by SHERPA. This efficiency is a measure of the response in terms of population exposure (i.e. pollutant concentration multiplied by population) to an emission reduction. Therefore, this efficiency is defined for a couple pollutant concentration C & precursor emission P. To be comparable from one sector to another, the efficiency of a country CT is normalised by the magnitude of the emissions reduction:

   Efficiency(CT,C,P)=$\frac{\sum_i \Delta Concentration(C)_i \times Population_i}{\sum_j \Delta Emission}$ with i=grid points over EU-28 countries

   j=grid points over the country CT

   ΔEmission: difference in net emission (kg) corresponding to a 15 % decrease of precursors emissions P.

   ΔConcentration=resulting reduction in concentrations C (µg/m^3)

For a country C, this emission efficiency (here expressed in µg.m^{-3}.kg^{-1}) is calculated for each sector (or group of sectors) independently and for the “all sectors” case for which emissions of all activity sectors are reduced at the same time (proportionally to their contributions). The higher the efficiency, the higher is the potential to reduce exposure by a reduction in one kg of emitted pollutant.

2) The adjustment factor is the relative efficiency of a specific sector to reduce exposure (by a reduction in 1 kg of emitted pollutant) compared to the efficiency of "all sectors". For a specific sector S, it is evaluated through the following formula:

   Adjustment factors (CT,C,P,S) = $\frac{Sector\ S\ efficiency}{Allsector\ efficiency}$

   An adjustment factor > 1 means that emission reductions relative to on that sector are more efficient to reduce exposure than a homogeneous reduction of emissions over all sectors.

SHERPA relies on the sector nomenclatures SNAP. E-PRTR emission data are reported according to their own specific nomenclature. An attempt was made in the current project to create a mapping between EPRTR and SNAP activity codes. For some sectors, a one to one mapping was possible. In these cases, adjustments factors were calculated for the individual SNAP sectors:

- SNAP 1 sector: combustion in energy and transformation industries, mainly thermal power stations and urban heating, from large sources (> 300 MW) to smaller ones (<50 MW). Emissions emitted from tall stacks (high level sources). Sources not uniformly distributed across the country.
- SNAP 3 sector: combustion in manufacturing industries, from large sources with tall stacks to smaller ones with emissions released at low levels. Sources distributed over the whole country, mainly in industrial areas.
- SNAP 4 sector: Production processes. Mainly low-level sources distributed over the whole country, mainly in industrial areas.
- SNAP 5: Extraction and distribution of fossil fuels and geothermal energy. Sources not uniformly distributed across the country. Represents only a small part of total emissions.
- SNAP 6: Use of solvents and other products. Uniformly distributed across the country, mainly low-level sources.
- SNAP 9 sector: Waste treatment and disposal. Mostly high-level sources.

When unambiguous matching between E-PRTR and SNAP activities has not been possible, we have calculated aggregated adjustments factors over several SNAP classes. This is the case for:

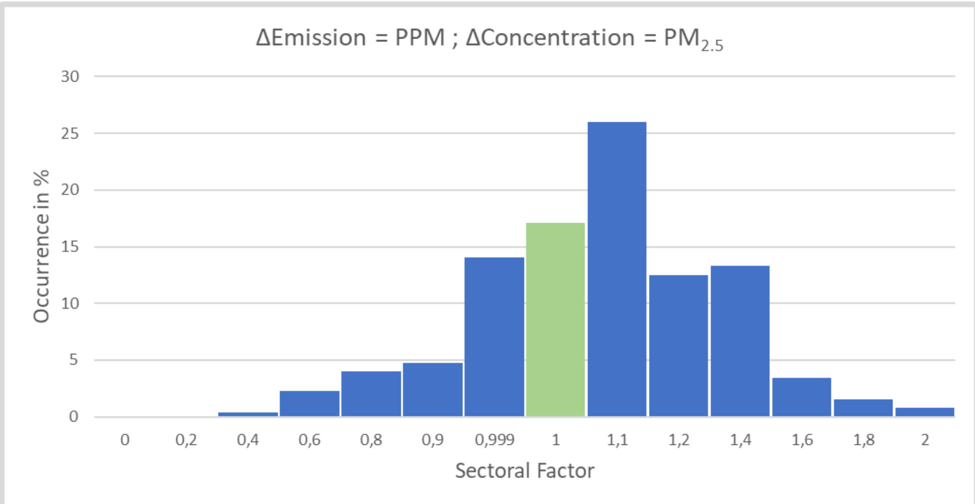
- SNAP 01 (Combustion in the production and transformation of energy), 02 (Non-industrial combustion plants), 03 (Industrial combustion plants) – "SNAP123" in the following tables
- SNAP 01 (Combustion in the production and transformation of energy), 04 (Industrial processes without combustion) – "SNAP14" in the following tables
- SNAP 01 (Combustion in the production and transformation of energy), 04 (Industrial processes without combustion), 05 (Extraction and distribution of fossil fuels and geothermal energy), 06 (Use of solvents and other products) – "SNAP156" in the following tables
- SNAP 01 (Combustion in the production and transformation of energy), 09 (Waste treatment and disposal) – "SNAP19" in the following tables
- SNAP 03 (Industrial combustion plants), 04 (Industrial processes without combustion) – "SNAP34" in the following tables
- SNAP 03 (Industrial combustion plants), 04 (Industrial processes without combustion), 06 (Use of solvents and other products) – "SNAP346" in the following tables
- SNAP 04 (Industrial processes without combustion), 05 (Extraction and distribution of fossil fuels and geothermal energy) – "SNAP45" in the following tables
- SNAP 04 (Industrial processes without combustion), 06 (Use of solvents and other products) – "SNAP46" in the following tables

- SNAP 04 (Industrial processes without combustion), 06 (Use of solvents and other products), 09 (Waste treatment and disposal) – "SNAP469" in the following tables
- SNAP 04 (Industrial processes without combustion), 09 (Waste treatment and disposal) – "SNAP49" in the following tables

For some countries, emissions over specific SNAP level 1 sectors are very small. In that case, 15 % reductions in these small emission quantities of precursors (Δemissions) lead to a very small impact in terms of concentrations (low ΔConcentration), sometimes below the uncertainties of the model. Moreover, due to the equation used to calculate the adjustment factors, very small values of both Δemission and Δconcentration may lead to artificially high numbers.

For these reasons, we decided to define lower limit values on Δemission and Δconcentration. If Δemission or Δconcentration falls below those values, no sectoral adjustments are made (the adjustment factor is set to 1). Limit values have been defined by striking a compromise between (i) not having unrealistic values for sectoral adjustment factors (for example values of 10) and (ii) avoiding unbalancing the sectoral adjustment factor distribution over the totality of countries and for each couple emission & concentration. The distribution of adjustment factors for the impact of PPM emissions on $PM_{2.5}$ concentrations is shown on Figure 61 as an example. With the chosen limit values, the number of countries with factor=1 (green bar) is consistent with the overall distribution.

Figure 61: Distribution over all countries of adjustment factors for the precursor PPM emissions on $PM_{2.5}$ concentrations. The green bar represents countries for which the adjustment factor is set to one.



Then constraining limit values are summarised in Table 58.

Table 58: Lower limit values for Δemission and Δconcentration below which sectoral adjustment factors are set to one

Limit values	ΔEmissions (in % of total emissions over all sectors in the country)	ΔMean concentration for the country (in $\mu g.m^{-3}$)	ΔMax concentration (in $\mu g.m^{-3}$) over the domain
$PM_{2.5}$ exposure	1	0.001	0.01
NO_2 exposure	0.1	0.0001	0.001

Results:

Reduction in NO_2 exposure consecutive to reduction in SO_2, primary particles, NMVOC or NH_3 emission reductions is almost nil. Therefore, sectoral adjustment factors for NO_2 exposure are only calculated for NO_X precursors. Sectoral adjustment factors are calculated for each SNAP level 1 sector and combinations of sectors as mentioned above. Adjustment factors for the sectors SNAP2, SNAP7 and SNAP8 are not used here, for not being part of the industrial sectors.

In the following tables, where sectoral adjustment factors were set to 1 to avoid artificially huge factors (because delta emissions were extremely low or because delta emissions and delta concentrations were very small), they are highlighted in grey. All factors having values of 1 without being highlighted in grey are not 'limited` and actually differ from one after several digits.

Table 59: Sectoral adjustment factors for the NO_2 precursor NO_X

NO_x	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	0.99	1.00	1.03	0.98	0.98	0.99	1.33	0.82	0.81	0.81	0.77	0.77	0.77	0.79	0.79	1.00	1.00	0.98	0.88	1.15
BE	0.86	1.00	0.90	0.87	0.87	0.86	1.18	0.82	0.83	0.83	0.90	0.90	0.90	0.90	0.90	1.00	1.00	1.05	1.03	0.85
BG	0.66	0.59	0.89	0.62	0.62	0.66	1.78	1.67	0.93	0.93	0.49	0.49	0.49	0.49	0.49	1.00	1.00	1.29	1.26	0.86
CH	0.92	0.71	1.01	0.91	0.91	0.93	1.18	0.86	0.86	0.86	0.78	0.78	0.78	0.85	0.85	1.00	1.00	1.00	0.88	1.45
CY	0.46	0.86	0.57	0.46	0.46	0.46	2.17	0.47	0.47	0.47	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.49	0.58	1.00
CZ	0.74	1.00	0.85	0.76	0.76	0.74	1.28	0.85	0.87	0.87	0.94	0.94	0.94	0.94	0.94	1.00	1.00	1.18	0.92	0.79
DE	1.00	1.00	1.04	0.99	0.99	1.00	1.14	1.01	0.98	0.98	0.84	0.84	0.84	0.85	0.85	1.00	1.00	1.01	0.68	1.06
DK	1.00	0.55	1.15	1.00	1.00	1.00	1.61	1.16	1.13	1.13	0.98	0.98	0.98	0.99	0.99	1.00	1.00	1.23	0.63	1.25
EE	0.43	0.45	0.70	0.44	0.44	0.43	2.68	0.49	0.54	0.54	1.31	1.00	1.31	1.13	1.13	0.50	1.00	1.57	0.64	0.88
ES	0.47	0.28	0.82	0.49	0.49	0.47	2.11	0.77	0.74	0.74	0.60	0.60	0.60	0.61	0.61	1.00	1.00	1.34	0.48	0.80
FI	1.11	0.81	1.12	1.02	1.02	1.11	1.56	0.76	0.57	0.57	0.20	0.20	0.20	0.21	0.21	0.35	1.00	1.07	0.71	1.10
FR	0.90	0.32	1.15	0.87	0.87	0.90	1.62	0.91	0.89	0.89	0.72	0.72	0.72	0.72	0.72	1.00	1.00	1.08	0.54	0.69
GB	0.90	1.00	0.98	0.90	0.90	0.90	1.29	0.97	0.95	0.95	0.78	0.78	0.78	0.77	0.77	1.00	1.00	1.05	0.71	0.73
GR	0.37	0.29	0.68	0.37	0.37	0.37	2.73	0.91	0.85	0.85	0.25	0.25	0.25	0.25	0.25	1.00	1.00	1.47	0.86	1.00
HR	0.78	0.75	0.80	0.71	0.71	0.78	0.87	0.78	0.68	0.68	0.58	0.58	0.58	0.58	0.58	1.00	1.00	1.31	0.85	0.79
HU	1.16	0.51	1.17	1.12	1.12	1.16	1.10	1.24	1.16	1.16	0.44	0.44	0.44	0.50	0.50	1.00	1.00	0.86	1.00	0.89
IE	0.91	1.00	1.07	0.91	0.91	0.91	1.47	0.97	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.79	1.00
IT	0.69	0.65	0.82	0.69	0.69	0.69	1.32	0.66	0.67	0.67	0.75	0.75	0.75	0.73	0.73	1.00	1.00	1.11	0.94	0.53
LT	0.88	0.54	1.05	0.76	0.76	0.87	1.63	0.85	0.69	0.69	0.57	0.57	0.57	0.57	0.57	0.57	1.00	1.07	0.58	0.73
LU	1.29	1.00	1.12	1.27	1.27	1.29	1.07	1.09	1.09	1.09	0.97	0.97	0.97	0.96	0.96	1.00	1.00	0.99	0.88	1.00
LV	1.03	0.32	1.22	0.82	0.82	1.03	1.27	1.35	1.01	1.01	0.47	0.47	0.47	0.47	0.47	0.64	1.00	0.99	0.65	0.94
ME	0.62	0.70	0.77	0.64	0.64	0.62	1.16	0.77	0.80	0.80	0.91	0.91	0.91	0.91	0.91	1.00	1.00	1.15	0.87	1.00
MT	1.17	1.00	1.17	1.17	1.17	1.17	1.11	1.19	1.19	1.19	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.40	1.00
NL	0.84	1.00	0.90	0.86	0.86	0.84	1.04	0.80	0.84	0.84	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.05	0.95	0.95
NO	0.84	0.42	0.91	0.75	0.75	0.81	1.53	0.72	0.55	0.55	0.30	0.30	0.30	0.27	0.27	1.00	1.00	1.30	0.65	0.16

NO_x	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
PL	0.84	0.51	0.91	0.84	0.84	0.84	1.37	0.75	0.76	0.76	0.81	0.81	0.81	0.81	0.81	0.50	1.00	1.23	0.70	1.01
PT	0.54	0.32	0.78	0.53	0.53	0.53	1.66	0.75	0.72	0.72	0.46	0.46	0.46	0.44	0.44	1.00	1.00	1.22	0.92	0.10
RO	0.67	0.67	0.98	0.68	0.68	0.67	1.87	1.19	1.12	1.12	0.82	0.82	0.82	0.84	0.84	1.00	1.00	1.04	0.94	1.41
SE	1.43	1.00	1.41	1.15	1.15	1.43	1.54	1.31	1.00	1.00	0.32	0.32	0.32	0.32	0.32	1.00	1.00	0.94	0.73	1.00
SI	0.82	1.00	0.90	0.82	0.82	0.82	1.06	0.98	0.98	0.98	0.92	0.92	0.92	0.91	0.91	1.00	1.00	1.12	0.75	0.95
SK	0.77	1.00	0.92	0.76	0.76	0.77	1.25	0.84	0.83	0.83	0.74	0.74	0.74	0.74	0.74	1.00	1.00	1.09	0.85	0.88

For industrial sectors, adjustment factors are lower than one in most cases. The main impact on NO_2 exposure is found close to NO_x emission sources. As NO_x emissions are dominated by the road sector (SNAP7) located close to population, reducing emissions over specific industrial sectors is generally less efficient than an equivalent reduction over all sectors.

For $PM_{2.5}$ exposure, sectoral adjustments are calculated for all five precursors.

Table 60: Sectoral adjustment factors for the $PM_{2.5}$ precursor NH_3

NH_3	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	1.00	0.95	1.55	1.32	1.32	1.54	1.58	1.00	1.00	1.00	1.00	1.00	1.00	1.46	1.46	1.00	1.00	1.35	1.00	1.53
BE	1.02	1.00	1.03	1.01	1.01	1.04	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.04	1.04	1.00	1.00	1.03	1.00	1.05
BG	1.00	0.95	1.00	1.25	1.25	1.06	1.00	1.00	1.25	1.25	1.25	1.25	1.25	1.07	1.07	1.00	1.00	1.00	1.00	1.06
CH	1.00	0.99	1.00	1.00	1.14	1.07	1.00	1.00	1.00	1.00	1.00	1.12	1.00	1.08	1.08	1.10	1.00	1.09	1.00	1.04
CY	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CZ	1.00	0.99	1.13	0.94	0.94	1.15	1.00	1.00	0.91	0.91	0.89	0.89	0.89	1.08	1.08	1.00	1.00	1.07	1.00	1.16
DE	1.27	0.98	1.25	1.24	1.24	1.25	1.00	1.00	1.22	1.22	1.22	1.22	1.22	1.22	1.22	1.00	1.00	1.22	1.00	1.23
DK	1.41	0.98	1.37	1.41	1.41	1.37	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.33	1.33	1.00	1.00	1.29	1.00	1.33
EE	1.00	0.90	1.94	1.86	1.86	2.18	2.04	1.00	1.74	1.74	1.83	1.83	1.83	2.12	2.12	1.00	1.00	1.69	1.00	2.21
ES	1.00	0.76	1.00	2.46	2.46	2.69	1.00	1.00	2.49	2.49	2.52	2.52	2.52	2.65	2.65	1.00	1.00	2.32	1.00	2.73
FI	1.65	0.78	2.08	1.49	1.49	2.36	2.74	1.00	1.28	1.28	1.27	1.27	1.27	2.33	2.33	1.00	1.00	2.90	1.00	2.92
FR	1.00	0.95	1.00	1.35	1.35	1.96	1.00	1.00	1.35	1.35	1.34	1.34	1.34	1.78	1.78	1.00	1.00	1.86	1.00	2.00

NH_3	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
GB	1.00	0.91	1.00	1.58	1.58	1.49	1.00	1.00	1.61	1.61	1.62	1.62	1.62	1.52	1.52	1.00	1.00	1.48	1.00	1.49
GR	1.00	0.76	2.68	1.00	1.00	3.36	1.00	1.00	1.00	1.00	1.00	1.00	1.00	3.63	3.63	1.00	1.00	3.29	1.00	3.66
HR	1.00	0.98	1.00	1.41	1.39	1.33	1.00	1.00	1.41	1.41	1.41	1.39	1.41	1.37	1.37	1.00	1.00	1.17	1.00	1.33
HU	1.00	0.96	1.00	1.06	1.06	1.65	1.00	1.00	1.07	1.07	1.06	1.06	1.06	1.48	1.48	1.00	1.00	1.47	1.00	1.71
IE	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.47	1.00	1.00
IT	1.00	0.95	1.00	1.00	1.00	1.53	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.54	1.54	1.00	1.00	1.46	1.00	1.58
LT	1.00	0.99	1.00	1.02	1.02	1.21	1.00	1.00	1.02	1.02	1.02	1.02	1.02	1.03	1.03	1.00	1.00	1.00	1.00	1.19
LU	1.00	0.99	1.00	1.03	1.03	1.06	1.00	1.00	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.00	1.00	1.02	1.00	1.00
LV	1.00	0.93	2.02	1.00	1.00	2.15	2.09	1.00	1.00	1.00	1.00	1.00	1.00	2.21	2.21	1.00	1.00	1.43	1.00	2.21
ME	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MT	1.00	0.90	1.00	1.00	1.00	1.09	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.09	1.09	1.00	1.00	1.00	1.00	1.09
NL	1.00	0.99	1.03	0.98	0.98	1.07	1.00	1.00	0.97	0.97	0.97	0.97	0.97	1.07	1.07	1.00	1.00	1.09	1.00	1.08
NO	1.00	0.96	1.00	1.69	1.69	1.00	1.00	1.00	1.67	1.67	1.69	1.69	1.69	1.41	1.41	1.00	1.00	1.48	1.00	1.00
PL	1.00	0.96	1.47	0.98	0.98	1.53	1.56	1.00	1.01	1.01	0.99	0.99	0.99	1.44	1.44	1.00	1.00	1.52	1.00	1.56
PT	1.00	0.74	1.00	1.90	1.90	1.98	1.00	1.00	1.92	1.92	1.93	1.93	1.93	1.98	1.98	1.00	1.00	1.70	1.00	1.99
RO	1.00	0.97	1.41	1.24	1.24	1.47	1.00	1.00	1.24	1.24	1.24	1.24	1.24	1.32	1.32	1.00	1.00	1.00	1.00	1.47
SE	1.44	0.87	1.39	1.27	1.27	1.59	1.00	1.21	1.21	1.21	1.22	1.22	1.22	1.43	1.43	1.00	1.00	1.52	1.00	1.63
SI	1.00	0.99	1.17	1.00	1.00	1.19	1.18	1.00	1.00	1.00	1.00	1.00	1.00	1.19	1.19	1.00	1.00	1.08	1.00	1.19
SK	1.00	0.98	1.10	1.08	1.08	1.11	1.10	1.00	1.08	1.08	1.08	1.08	1.08	1.10	1.10	1.00	1.00	1.07	1.00	1.12

Because NH_3 emissions are dominated by agriculture (SNAP10), generally located far from population, NH_3 reduction over specific industrial sectors is usually more efficient to reduce $PM_{2.5}$ exposure than the reduction over all sectors together (implying: mainly over agriculture).

Table 61: Sectoral adjustment factors for the $PM_{2.5}$ precursor NMVOC

NMVOC	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	1.00	1.00	0.90	1.00	1.05	1.00	1.00	1.00	1.00	1.05	1.00	1.00	1.05	1.05	1.00	1.00	1.06	1.00	1.00	1.00
BE	1.00	1.00	0.93	1.04	1.03	0.98	0.91	1.00	1.05	1.03	1.05	1.04	1.03	1.03	1.05	0.99	1.02	0.96	0.93	1.00
BG	0.84	1.00	0.89	1.02	1.07	0.86	0.90	1.00	1.05	1.09	1.05	1.05	1.09	1.09	1.05	1.00	1.13	1.03	1.00	1.00
CH	1.00	1.00	1.00	1.01	1.02	1.00	1.00	1.00	1.01	1.02	1.01	1.01	1.02	1.02	0.97	1.00	1.03	1.03	1.00	1.00
CY	1.00	1.00	1.00	1.00	1.10	1.00	1.00	1.00	1.00	1.09	1.00	1.14	1.09	1.08	1.00	1.17	1.10	0.90	1.00	1.00
CZ	1.00	1.00	0.96	1.07	1.03	1.00	0.95	1.00	1.08	1.03	1.09	1.06	1.03	1.03	1.09	1.00	1.02	0.99	1.00	1.00
DE	1.10	1.00	0.97	1.08	1.01	1.08	0.84	1.00	1.06	1.00	1.07	1.04	1.00	1.00	1.06	1.00	0.99	1.08	1.00	1.00
DK	1.00	1.00	0.97	1.00	1.02	1.00	0.91	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00
EE	1.00	1.00	0.93	1.00	1.00	1.00	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ES	1.00	1.00	1.00	0.91	1.04	1.00	1.00	1.00	0.95	1.05	0.95	0.93	1.05	1.05	0.95	1.00	1.07	1.15	1.00	1.00
FI	1.00	1.00	0.85	1.00	1.08	1.00	0.84	1.00	1.00	1.09	1.00	1.00	1.09	1.09	1.00	1.00	1.00	1.00	1.00	1.00
FR	1.00	1.00	0.83	1.00	1.06	1.00	0.83	1.00	1.02	1.10	1.03	0.92	1.10	1.10	1.04	1.00	1.12	1.00	1.00	1.00
GB	1.00	1.00	1.00	0.85	0.96	1.00	1.00	1.00	0.87	0.98	0.87	0.86	0.98	0.98	0.88	1.00	1.03	1.00	1.00	1.00
GR	0.55	1.00	0.65	0.87	1.03	0.55	0.68	1.00	1.00	1.09	1.04	0.98	1.10	1.10	1.04	1.00	1.11	1.15	1.03	1.00
HR	1.00	1.00	0.93	1.00	1.04	1.00	1.00	1.00	1.00	1.05	1.00	1.00	1.05	1.05	1.00	0.99	1.05	1.00	1.00	1.00
HU	1.00	1.00	0.90	1.07	1.07	1.00	0.90	1.00	1.09	1.08	1.09	1.08	1.08	1.08	1.09	1.00	1.08	0.99	1.00	1.00
IE	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
IT	0.70	1.00	0.77	1.01	1.06	0.89	0.77	1.00	1.09	1.10	1.09	0.96	1.10	1.10	1.10	0.80	1.10	1.01	0.76	1.15
LT	1.00	1.00	1.00	0.99	1.03	1.00	1.00	1.00	1.00	1.03	1.00	1.00	1.03	1.03	1.00	1.00	1.00	1.00	1.00	1.00
LU	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.01	1.01	1.00	1.00	1.01	0.99	1.00	1.00
LV	1.00	1.00	0.89	1.00	1.13	1.00	0.89	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
ME	1.00	1.00	1.00	1.00	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
MT	1.00	1.00	1.00	1.05	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.03	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
NL	0.81	1.00	0.90	0.94	0.99	0.85	0.93	1.00	0.98	1.00	0.97	0.97	1.00	1.00	0.98	0.93	1.01	1.05	0.94	1.00
NO	1.00	1.00	1.00	0.85	1.06	1.00	1.00	1.00	0.85	1.08	0.85	0.86	1.09	1.00	0.73	1.00	1.14	1.00	1.00	1.00
PL	1.15	1.00	0.95	1.08	1.06	1.14	0.92	1.00	1.06	1.05	1.06	1.05	1.06	1.05	1.06	1.00	1.05	1.06	1.00	1.00
PT	1.00	1.00	1.00	0.99	1.02	1.00	1.00	1.00	1.00	1.03	1.00	0.99	1.03	1.03	1.00	1.00	1.06	1.00	1.00	1.00

NMVOC	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
RO	1.21	1.00	0.89	1.07	1.07	1.13	0.87	1.00	1.06	1.08	1.06	1.04	1.08	1.08	1.06	0.96	1.09	1.02	1.00	1.00
SE	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.02	1.00	1.00	1.00
SI	1.03	1.00	0.96	1.04	1.05	1.04	0.96	1.00	1.00	1.06	1.00	1.00	1.06	1.06	1.00	1.00	1.07	1.00	1.00	1.00
SK	1.00	1.00	0.96	1.10	1.03	1.00	0.95	1.00	1.12	1.04	1.14	1.07	1.04	1.04	1.14	1.00	1.00	0.97	1.00	1.00

NMVOCs are mainly emitted by sector SNAP6 (solvents use), which tends to be highly spatially correlated with population. This leads to adjustment factors higher than one for this SNAP sector, and lower than one for others (in most cases).

It can be noticed that emissions from SNAP 6 of pollutants other than NMVOC are very low, below the chosen limit value. Therefore, no adjustment factors are calculated for SNAP6 for the other $PM_{2.5}$ precursors.

Table 62: Sectoral adjustment factors for the $PM_{2.5}$ precursor NO_X

NO_x	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	1.02	1.00	1.07	1.04	1.04	1.02	1.08	1.11	1.12	1.12	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.01	1.00
BE	1.01	1.00	1.02	1.02	1.02	1.01	1.04	1.01	1.01	1.01	1.05	1.05	1.05	1.05	1.05	1.00	1.00	0.99	0.97	1.00
BG	0.95	1.00	0.98	0.97	0.97	0.95	1.00	1.06	1.05	1.05	1.04	1.04	1.04	1.04	1.04	1.00	1.00	1.02	0.97	1.00
CH	0.84	0.91	0.98	0.86	0.86	0.85	1.04	0.98	0.98	0.98	1.00	1.00	1.00	0.96	0.96	1.00	1.00	1.01	1.02	1.00
CY	0.97	1.00	1.01	0.97	0.97	0.97	1.21	1.05	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.10	1.00
CZ	1.04	1.00	1.03	1.03	1.03	1.04	1.04	1.00	0.99	0.99	0.92	0.92	0.92	0.93	0.93	1.00	1.00	0.99	0.96	1.00
DE	1.01	1.00	1.01	1.01	1.01	1.01	1.02	1.03	1.04	1.04	1.08	1.08	1.08	1.08	1.08	1.00	1.00	1.00	0.95	1.00
DK	1.11	1.00	1.11	1.11	1.11	1.11	1.11	1.07	1.06	1.06	0.99	0.99	0.99	0.99	0.99	1.00	1.00	1.04	0.90	1.00
EE	1.11	1.00	1.10	1.11	1.11	1.11	1.14	0.89	0.90	0.90	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.91	1.00
ES	0.73	1.00	1.01	0.75	0.75	0.73	1.23	1.25	1.19	1.19	0.88	0.88	0.88	0.88	0.88	1.00	1.00	1.03	0.89	1.00
FI	0.96	1.00	1.00	0.95	0.95	0.96	1.15	1.06	1.03	1.03	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.09	0.89	1.00
FR	0.94	1.00	1.03	0.95	0.95	0.94	1.12	1.02	1.02	1.02	1.00	1.01	1.00	1.01	1.01	1.00	1.00	1.04	0.82	1.00
GB	0.92	1.00	0.96	0.92	0.92	0.92	1.05	1.02	1.00	1.00	0.88	0.88	0.88	0.88	0.88	1.00	1.00	1.09	0.93	1.00

NO_x	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
GR	0.81	1.00	0.92	0.82	0.82	0.81	1.61	1.20	1.22	1.22	1.00	1.00	1.00	1.33	1.33	1.00	1.00	1.16	0.96	1.00
HR	1.11	1.00	1.10	1.11	1.11	1.11	1.05	1.11	1.10	1.10	1.09	1.09	1.09	1.09	1.09	1.00	1.00	0.93	0.94	1.00
HU	0.99	1.00	1.01	0.99	0.99	0.99	1.04	1.03	1.03	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00
IE	0.83	1.00	0.98	0.82	0.82	0.83	1.14	1.07	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.05	0.90	1.00
IT	0.68	1.00	0.97	0.69	0.69	0.68	1.17	1.24	1.20	1.20	0.81	0.81	0.81	0.85	0.85	1.00	1.00	1.11	0.73	1.00
LT	1.16	1.00	1.14	1.08	1.08	1.16	1.30	0.96	0.94	0.94	0.91	0.91	0.91	0.91	0.91	1.00	1.00	0.97	0.97	1.00
LU	1.04	1.00	1.02	1.04	1.04	1.04	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
LV	1.33	1.00	1.20	1.25	1.25	1.32	1.20	1.11	1.12	1.12	1.15	1.15	1.15	1.14	1.14	1.00	1.00	0.92	0.85	1.00
ME	0.98	1.00	0.98	0.98	0.98	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.03	1.00	1.00
MT	1.07	1.00	1.07	1.07	1.07	1.07	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.03	0.88	1.00
NL	0.97	1.00	1.00	0.97	0.97	0.97	1.03	1.02	1.01	1.01	0.96	0.96	0.96	0.96	0.96	1.00	1.00	1.04	0.95	1.00
NO	0.94	1.00	0.96	1.01	1.01	0.97	1.00	1.00	1.03	1.03	1.04	1.04	1.04	1.05	1.05	1.00	1.00	1.07	0.94	1.00
PL	1.02	1.00	1.02	1.02	1.02	1.02	1.02	0.99	1.00	1.00	1.06	1.06	1.06	1.06	1.06	1.00	1.00	0.98	0.96	1.00
PT	0.69	1.00	1.02	0.72	0.72	0.69	1.23	1.21	1.16	1.16	0.84	0.84	0.84	0.85	0.85	1.00	1.00	1.05	0.81	1.00
RO	0.97	1.00	1.03	0.96	0.96	0.97	1.21	1.08	1.05	1.05	0.91	0.91	0.91	0.92	0.92	1.00	1.00	1.00	0.83	1.00
SE	0.95	1.00	0.93	0.91	0.91	0.95	1.00	0.87	0.84	0.84	0.77	0.77	0.77	0.77	0.77	1.00	1.00	1.08	0.98	1.00
SI	1.02	1.00	1.03	1.02	1.02	1.02	1.06	1.03	1.03	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.01	1.00
SK	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1.07	1.07	1.00	1.00	1.00	1.02	1.00

NO_x emissions are dominated by road transport (SNAP7), located close to population. Therefore, reducing emissions over industrial sectors is generally less efficient than an equivalent reduction over all sectors. Factors are closer to one than for NO_2 exposure because it takes more time for NO_x to form particles than NO_2, leading to greater dispersion and a more homogeneous impact on exposure.

Table 63: Sectoral adjustment factors for the $PM_{2.5}$ precursor PM_{10}

PM_{10}	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	1.26	0.78	1.00	1.18	1.18	1.13	0.91	1.14	1.13	1.13	1.12	1.12	1.12	1.07	1.07	1.00	1.00	0.97	1.08	0.98
BE	0.98	0.89	1.01	1.03	1.03	0.98	0.98	1.09	1.05	1.05	1.04	1.04	1.04	1.03	1.03	1.00	1.00	0.99	0.88	0.99
BG	0.79	0.80	1.03	1.03	1.04	0.90	1.03	1.18	1.20	1.20	1.22	1.22	1.21	1.17	1.17	1.00	1.00	1.03	0.85	1.08
CH	0.83	0.88	0.97	1.00	1.01	0.95	0.98	0.98	1.02	1.03	1.03	1.02	1.05	1.04	1.02	0.95	1.10	1.06	1.00	1.00
CY	1.00	1.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00
CZ	1.03	0.96	1.00	1.06	1.06	1.01	1.00	1.04	1.08	1.08	1.09	1.08	1.09	1.05	1.05	1.00	1.00	0.96	1.03	0.98
DE	1.13	0.76	1.00	1.15	1.15	1.03	0.92	1.11	1.16	1.16	1.16	1.16	1.16	1.07	1.07	1.00	1.00	1.07	0.81	0.93
DK	1.60	0.77	1.00	1.44	1.44	1.31	0.97	1.18	1.17	1.17	1.17	1.17	1.17	1.09	1.09	1.00	1.00	1.25	0.93	1.05
EE	1.22	0.64	1.03	1.20	1.20	1.21	0.91	1.00	0.99	0.99	0.96	0.99	0.96	0.98	0.98	1.00	1.00	1.00	0.88	1.00
ES	0.50	0.51	1.11	0.95	0.95	0.92	1.11	1.59	1.21	1.21	1.08	1.08	1.08	1.11	1.11	1.00	1.00	1.46	0.96	1.16
FI	0.93	1.00	0.92	0.97	1.04	0.96	0.87	1.23	1.15	1.15	1.05	1.16	1.05	1.05	1.05	1.24	1.00	1.35	0.99	1.05
FR	1.08	0.57	0.89	1.29	1.29	1.05	0.86	1.31	1.30	1.30	1.30	1.30	1.30	1.24	1.24	1.00	1.00	1.28	0.69	1.04
GB	0.75	0.56	0.88	0.81	0.81	0.83	0.93	0.98	0.98	0.98	0.98	0.98	0.98	0.93	0.93	1.00	1.00	1.37	0.84	0.91
GR	0.52	0.50	0.95	0.79	0.78	0.70	0.94	1.97	1.65	1.65	1.36	1.31	1.35	1.38	1.39	1.00	1.00	1.86	0.91	1.45
HR	0.90	0.82	0.99	1.21	1.21	1.06	0.97	1.29	1.28	1.28	1.28	1.28	1.28	1.22	1.22	1.00	1.00	0.96	0.98	1.12
HU	0.84	0.78	0.98	1.10	1.10	0.97	0.98	1.35	1.32	1.32	1.31	1.30	1.31	1.23	1.23	1.00	1.00	0.98	0.87	1.12
IE	0.21	0.32	1.15	0.51	0.52	0.44	1.27	0.97	0.92	0.92	0.89	0.89	0.89	0.78	0.78	1.00	1.00	0.96	1.00	0.69
IT	0.77	0.80	0.98	1.08	1.08	0.99	0.92	1.44	1.40	1.40	1.33	1.33	1.33	1.20	1.20	1.00	1.00	1.12	0.74	1.12
LT	1.16	0.77	1.08	1.17	1.17	1.12	1.09	0.72	1.06	1.06	1.17	1.17	1.17	1.14	1.14	1.00	1.00	0.96	0.97	1.11
LU	1.00	1.00	1.00	1.02	1.02	0.98	0.98	1.03	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.00	1.00	1.00	1.00	0.97
LV	1.00	0.53	1.02	1.49	1.48	1.21	1.00	1.53	1.54	1.54	1.54	1.54	1.54	1.41	1.41	1.00	1.00	1.22	0.71	1.21
ME	0.83	1.00	0.99	0.85	0.86	0.83	1.09	1.00	1.09	1.06	1.12	1.08	1.08	1.07	1.11	1.00	1.00	1.10	1.00	1.00
MT	1.11	0.91	1.11	1.10	1.10	1.09	1.00	1.00	1.03	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	0.75	0.99
NL	0.95	0.83	0.95	1.02	1.02	0.97	0.94	1.05	1.03	1.03	1.03	1.03	1.03	1.01	1.01	1.00	1.00	1.11	0.90	0.97
NO	0.54	1.00	0.81	1.66	1.66	0.84	0.83	1.00	1.68	1.67	1.87	1.87	1.85	1.75	1.76	1.00	1.00	1.09	0.83	1.14

PM_{10}	SNAP 1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
PL	1.08	0.66	1.05	1.09	1.09	1.03	1.05	1.00	1.06	1.06	1.10	1.11	1.09	1.02	1.02	1.00	1.00	0.91	0.68	0.93
PT	0.65	0.55	0.88	1.22	1.22	0.93	0.77	1.23	1.24	1.24	1.25	1.25	1.25	1.22	1.22	1.00	1.00	0.99	0.96	1.02
RO	0.92	1.04	0.96	1.12	1.12	1.02	0.93	1.22	1.22	1.22	1.23	1.22	1.22	1.17	1.17	1.00	1.00	1.01	1.00	1.09
SE	1.18	0.77	0.93	1.03	1.03	1.13	0.88	0.72	0.86	0.86	0.93	0.93	0.93	0.94	0.94	1.00	1.00	1.33	1.04	1.00
SI	1.08	0.91	1.00	1.07	1.07	1.06	0.98	1.05	1.05	1.05	1.05	1.04	1.05	1.04	1.04	1.00	1.00	0.99	1.00	1.03
SK	0.97	0.95	0.99	1.01	1.01	1.11	0.99	1.02	1.02	1.02	1.02	1.02	1.02	1.07	1.07	1.00	1.00	0.96	1.00	1.20

Primary PM_{10} are mainly emitted by residential heating (SNAP2) and transport. At first glance, it may seem surprising that factors for SNAP2 are below 1. This is so, because emissions for residential heating are predominantly found in rural areas (and are spatialised mainly in rural areas in CTMs), and not close to populated city centres. This can explain values higher than one found for several industrial sectors. Overall, factors are less close to one than for other $PM_{2.5}$ precursors, because primary particles directly contribute to $PM_{2.5}$ formation whereas gases need to be transformed and condensate before they form particulate matter. Their spatial impact on $PM_{2.5}$ exposure is thus closer to emissions sources, and less homogeneous than for gases.

Table 64: Sectoral adjustment factors for the $PM_{2.5}$ precursor SO_2

SOx	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
AT	0.94	1.00	1.00	0.94	0.94	0.94	1.03	1.03	1.01	1.01	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	1.00	1.00
BE	0.98	1.00	1.00	1.02	1.02	0.98	1.04	0.99	1.01	1.01	1.05	1.05	1.05	1.05	1.05	1.00	1.00	1.00	0.74	1.00
BG	0.99	1.00	0.99	1.00	1.00	0.99	1.11	1.07	1.07	1.07	1.08	1.08	1.08	1.08	1.08	1.00	1.00	1.00	1.04	1.00
CH	0.83	1.00	0.98	0.91	0.92	0.84	1.05	1.00	1.01	1.01	1.04	1.04	1.04	1.02	1.02	1.00	1.00	1.00	1.45	1.00
CY	0.99	1.00	1.00	0.99	0.99	0.99	1.00	1.04	1.04	1.04	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.03	1.00
CZ	1.00	1.00	1.00	1.00	1.00	1.00	1.03	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
DE	0.98	1.00	0.99	1.01	1.01	0.98	1.01	1.00	1.04	1.04	1.08	1.08	1.08	1.07	1.07	1.00	1.00	1.00	0.81	1.00
DK	1.28	1.00	1.21	1.23	1.23	1.28	1.19	1.08	1.04	1.04	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	0.79	1.00
EE	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.93	0.92	0.92	0.92	0.92	0.92	1.00	1.00	1.00	0.95	1.00
ES	0.58	1.00	1.01	0.81	0.81	0.58	1.59	1.32	1.12	1.12	0.97	0.97	0.97	0.97	0.97	1.00	1.00	1.00	1.14	1.00
FI	0.92	1.00	1.02	0.92	0.92	0.92	1.26	1.14	1.07	1.07	0.91	0.91	0.91	0.91	0.91	1.00	1.00	1.00	0.81	1.00

SOx	SNAP1	SNAP 10	SNAP 123	SNAP 14	SNAP 1456	SNAP 19	SNAP 2	SNAP 3	SNAP 34	SNAP 346	SNAP 4	SNAP 45	SNAP 46	SNAP 469	SNAP 49	SNAP 5	SNAP 6	SNAP 7	SNAP 8	SNAP 9
FR	0.98	1.00	1.08	0.92	0.92	0.98	1.36	1.04	0.96	0.96	0.83	0.83	0.83	0.83	0.83	1.00	1.00	1.00	0.57	1.00
GB	0.93	1.00	1.01	0.94	0.94	0.93	1.26	1.13	1.09	1.09	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.76	1.00
GR	0.87	1.00	0.95	0.92	0.92	0.87	1.71	1.68	1.75	1.75	1.85	1.85	1.85	1.85	1.85	1.00	1.00	1.00	1.00	1.00
HR	0.98	1.00	1.00	1.01	1.01	0.98	0.98	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.00	1.00	1.00	0.92	1.00
HU	0.94	1.00	0.99	0.97	0.97	0.94	1.04	1.05	1.04	1.04	1.03	1.03	1.03	1.03	1.03	1.00	1.00	1.00	1.00	1.00
IE	0.41	1.00	1.00	0.43	0.43	0.41	1.53	1.16	1.17	1.17	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.83	1.00
IT	0.92	1.00	1.04	0.99	0.99	0.92	1.41	1.32	1.20	1.20	1.14	1.14	1.14	1.14	1.14	1.00	1.00	1.00	0.68	1.00
LT	0.94	1.00	1.02	0.96	0.96	0.94	1.24	0.81	0.94	0.94	0.97	0.97	0.97	0.97	0.97	1.00	1.00	1.00	0.99	1.00
LU	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
LV	0.76	1.00	1.07	0.75	0.75	0.76	1.24	1.07	1.06	1.06	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.71	1.00
ME	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.05	1.05	1.06	1.06	1.06	1.06	1.06	1.00	1.00	1.00	1.00	1.00
MT	1.07	1.00	1.07	1.07	1.07	1.07	1.00	1.05	1.05	1.05	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.81	1.00
NL	1.00	1.00	1.01	1.04	1.04	1.00	1.02	1.01	1.05	1.05	1.06	1.06	1.06	1.06	1.06	1.00	1.00	1.00	0.77	1.00
NO	2.37	1.00	1.85	0.86	0.86	2.17	1.00	1.00	0.80	0.80	0.78	0.78	0.78	0.78	0.78	1.00	1.00	1.00	1.43	1.00
PL	1.01	1.00	1.00	1.01	1.01	1.01	0.99	0.98	1.00	1.00	1.02	1.02	1.02	1.02	1.02	1.00	1.00	1.00	1.00	1.00
PT	0.77	1.00	1.00	0.86	0.86	0.77	1.40	1.21	1.06	1.06	0.95	0.95	0.95	0.95	0.95	1.00	1.00	1.00	1.38	1.00
RO	0.98	1.00	1.00	0.98	0.98	0.98	1.15	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.00	1.00	1.00	0.95	1.00
SE	1.09	1.00	0.99	1.02	1.02	1.09	1.46	0.71	0.87	0.87	0.96	0.96	0.96	0.96	0.96	1.00	1.00	1.00	1.11	1.00
SI	1.00	1.00	1.00	0.99	0.99	1.00	1.04	0.97	0.98	0.98	0.98	0.98	0.98	0.99	0.99	1.00	1.00	1.00	1.01	1.00
SK	0.97	1.00	1.00	0.98	0.98	0.97	1.03	1.03	1.02	1.02	1.01	1.01	1.01	1.01	1.01	1.00	1.00	1.00	1.00	1.00

Discussion:
The following tables indicate the externality results for different aggregations over pollutants and sectors, each time presenting the results obtained when applying sector adjustment factors to the main air pollutants and indicating the percentage change from unadjusted to adjusted results. **Percentage results with a negative sign indicate that the adjusted externalities are lower than the unadjusted ones, results with a positive sign that adjusted values exceed unadjusted values.**

The following table presents the adjusted damage costs by EEA sector from 2008 to 2017, aggregated over all pollutants for the VOLY assessment.

Table 65: Damage costs by EEA sector from 2008 to 2017, aggregate over all pollutants for the VOLY assessment, billion €$_{2019}$ – adjusted

VOLY, billion €2019	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Energy production	233	217	212	200	199	185	170	164	150	147
Heavy industry	113	85	93	90	84	82	83	78	76	74
Fuel production and processing	37	33	32	30	28	25	24	23	23	23
Waste management	16	16	15	16	18	16	15	15	15	16
Light industry	12	12	14	12	13	12	12	12	12	13
Livestock	3	3	3	3	3	3	3	4	3	3
Wastewater treatment	0.8	0.3	0.3	0.2	0.3	0.4	0.4	0.5	0.2	0.2
Sum	**415**	**366**	**369**	**352**	**344**	**323**	**307**	**296**	**280**	**277**

The following table indicates the changes between unadjusted and adjusted values. For most sectors, the sectoral adjustment decreases damage costs, except for the sectors heavy industry and (partly) wastewater treatment, for which they increase. Percentage changes remain below 1 % for the sectors energy production, heavy industry, and waste management. For the sectors light industry and wastewater treatment some percentage changes exceed 1 % but do not exceed 2 %. For fuel production and processing adjusted damage costs are lower by up to 3 % and for livestock up to 6 %. Aggregated over all sectors, adjusted damage costs from all pollutant groups are lower than unadjusted damage costs by less than 0.5 %.

Table 66: Damage costs by EEA sector from 2008 to 2017, aggregate over all pollutants – percentage change between adjusted and unadjusted values

VOLY	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Energy production	-0.32 %	-0.30 %	-0.23 %	-0.30 %	-0.23 %	-0.21 %	-0.27 %	-0.27 %	-0.26 %	-0.27 %
Heavy industry	0.96 %	0.56 %	0.60 %	0.60 %	0.54 %	0.48 %	0.45 %	0.43 %	0.52 %	0.47 %
Fuel production and processing	-3.08 %	-3.00 %	-2.95 %	-2.89 %	-2.69 %	-2.66 %	-2.45 %	-2.33 %	-2.26 %	-2.25 %
Waste management	-0.37 %	-0.39 %	-0.14 %	-0.27 %	-0.47 %	-0.20 %	-0.24 %	-0.25 %	-0.26 %	-0.28 %
Light industry	-1.49 %	-1.54 %	-1.29 %	-1.41 %	-1.27 %	-1.13 %	-1.09 %	-1.17 %	-1.10 %	-1.14 %
Livestock	-6.22 %	-6.74 %	-6.64 %	-6.13 %	-6.41 %	-5.91 %	-5.75 %	-6.00 %	-6.32 %	-6.28 %
Wastewater treatment	0.17 %	-1.09 %	0.54 %	0.97 %	0.54 %	0.32 %	0.27 %	0.27 %	1.92 %	2.01 %
Sum	**-0.31 %**	**-0.45 %**	**-0.35 %**	**-0.39 %**	**-0.35 %**	**-0.32 %**	**-0.34 %**	**-0.36 %**	**-0.33 %**	**-0.36 %**

The following two following tables show the same kind of results for unadjusted versus adjusted damage costs by EEA sector from 2008 to 2017, aggregate over the main air pollutants for the VOLY assessment.

Table 67: Damage costs by EEA sector from 2008 to 2017, aggregate over main air pollutants for the VOLY assessment, million €$_{2019}$ - adjusted

VOLY, million € - Main AP only	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Waste management	837	863	815	1 018	1 699	984	977	970	989	1 056
Heavy industry	35 441	27 423	28 068	27 718	24 993	23 749	23 103	20 693	19 232	18 523
Energy production	88 430	78 359	69 982	69 872	68 196	58 637	50 512	47 034	37 538	35 063
Livestock	2 470	2 466	2 347	2 608	2 532	2 866	3 035	3 428	2 915	3 119
Light industry	3 547	3 100	3 807	3 028	2 748	2 682	2 632	2 600	2 462	2 404
Fuel production and processing	18 033	15 315	13 743	12 770	10 952	9 132	8 278	7 999	7 748	7 986
Wastewater treatment	226	34	20	15	23	20	93	114	12	14
Sum	**148 983**	**127 559**	**118 781**	**117 029**	**111 144**	**98 069**	**88 629**	**82 838**	**70 896**	**68 165**

Again, sectoral adjustment decreases damage costs, except for the sectors heavy industry and (partly) wastewater treatment. In this focus on damage from main air pollutants, the only sector for which the adjustment implies changes to externalities that remain below 1 % is energy production. Decreases in damage costs by around 5-6 % are found for light industry and fuel production and processing, reductions between 6 and 7 % for livestock. The reductions in damage costs from livestock due to the use of adjustment factors is consistent with the correction factor inferior to 1 for SNAP 10. High fluctuations are found for the sector wastewater treatment, where percentage changes range from -6.6 to +39.4. To understand these fluctuations, it is important to stress that the absolute changes between unadjusted and adjusted damage costs remain very limited for wastewater treatment given the small amount of emissions. In addition, the variation in emission reported between different years, and hence in damage costs, is also important for this sector. Aggregated over all sectors, adjusted damage costs from main air pollutants are lower than unadjusted damage costs by roughly 1-1.5 %.

Table 68: Damage costs by EEA sector from 2008 to 2017, aggregate over main air pollutants for the VOLY assessment – percentage change between adjusted and unadjusted values

VOLY	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Waste management	-6.54 %	-6.58 %	-2.59 %	-4.16 %	-4.71 %	-3.06 %	-3.67 %	-3.77 %	-3.80 %	-4.09 %
Heavy industry	3.11 %	1.74 %	2.01 %	1.98 %	1.84 %	1.67 %	1.64 %	1.65 %	2.08 %	1.90 %
Energy production	-0.83 %	-0.82 %	-0.69 %	-0.84 %	-0.68 %	-0.65 %	-0.89 %	-0.92 %	-1.04 %	-1.11 %
Livestock	-7.26 %	-7.34 %	-7.35 %	-6.69 %	-6.99 %	-6.54 %	-6.51 %	-6.75 %	-7.05 %	-6.85 %
Light industry	-4.97 %	-5.62 %	-4.63 %	-5.53 %	-5.52 %	-4.89 %	-4.86 %	-5.23 %	-5.16 %	-6.00 %
Fuel production and processing	-6.16 %	-6.31 %	-6.56 %	-6.58 %	-6.50 %	-6.87 %	-6.68 %	-6.37 %	-6.41 %	-6.35 %
Wastewater treatment	0.59 %	-9.48 %	7.36 %	13.33 %	8.70 %	6.42 %	1.26 %	1.13 %	39.36 %	34.74 %
Sum	**-0.86 %**	**-1.28 %**	**-1.07 %**	**-1.15 %**	**-1.08 %**	**-1.05 %**	**-1.18 %**	**-1.28 %**	**-1.29 %**	**-1.47 %**

The following four tables focus on changes between unadjusted and adjusted damage costs by main air pollutant from 2008 to 2017, aggregate over the main air pollutants. They consider both the valuation by VOLY and by VSL.

Table 69: Damage cost per main air pollutant for the period 2008-2017 and the VOLY assessment, billion €$_{2019}$ - adjusted

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	VOLY	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**
NH_3	4	3	3	4	4	4	4	4	4	4
NO_x	43	37	36	35	35	32	30	28	25	25
NMVOC	1	1	1	1	1	1	1	1	1	1
Primary PM_{10}	9	7	7	7	6	5	5	4	4	3
SO_2	92	79	72	71	66	56	50	46	37	35

Table 70: Damage cost per main air pollutant for the period 2008-2017 and the VSL assessment, billion €$_{2019}$ - adjusted

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	VSL	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**
NH_3	12	11	11	12	12	12	13	14	13	14
NO_x	148	126	124	120	118	110	101	96	87	84
NMVOC	3	3	3	3	2	2	2	2	2	2
Primary PM_{10}	29	23	22	22	19	17	15	13	12	11
SO_2	291	250	227	223	209	177	157	144	118	112

The results indicate that the impact of the sector adjustment factors remains below 0.5 % for SO_2 and does not exceed 3 % for NMVOCs. For ammonia percentage changes are between 1 and 3 %, for NO_X between 4 and 5 % and for PM_{10} between 3 and 7 %. Using the sectoral adjustment factors implies generally increases in damage costs for PM_{10}, NMVOC and NH_3. The low values for SO_2 change the sign. However, the adjustment factors result in a reduction of damage from NO_x emissions.

Table 71: Damage cost per main air pollutant for the period 2008-2017 and the VOLY assessment – percentage change between adjusted and unadjusted values

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	VOLY	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**	**VOLY**
NH_3	3 %	1 %	2 %	2 %	2 %	1 %	0 %	-0.56 %	0 %	0 %
NO_x	-4 %	-5 %	-4 %	-5 %	-5 %	-4 %	-4 %	-5 %	-5 %	-5 %
NMVOC	3 %	3 %	3 %	3 %	2 %	2 %	2 %	2 %	3 %	3 %
Primary PM_{10}	6 %	4 %	5 %	4 %	3 %	3 %	4 %	5 %	7 %	5 %
SO_2	0.09 %	-0.23 %	-0.04 %	-0.05 %	0.24 %	0.33 %	0.22 %	0.19 %	0.16 %	0.15 %

Table 72: Damage cost per main air pollutant for the period 2008-2017 and the VSL assessment – percentage change between adjusted and unadjusted values

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
	VSL	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**	**VSL**
NH_3	3 %	1 %	2 %	2 %	2 %	0 %	0 %	-0.66 %	0 %	0 %
NO_x	-5 %	-5 %	-5 %	-5 %	-5 %	-5 %	-5 %	-5 %	-5 %	-5 %
NMVOC	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %	3 %
Primary PM_{10}	6 %	4 %	5 %	4 %	3 %	3 %	4 %	5 %	7 %	5 %
SO_2	0.13 %	-0.20 %	-0.01 %	-0.02 %	0.27 %	0.36 %	0.24 %	0.21 %	0.18 %	0.17 %

Overall, as shown in the following Table 73, externalities are lower when corrected by sectoral adjustment factors (an exception are the sectors heavy industry and wastewater treatment). And this even though damage by main air pollutant is higher for all pollutants except for NO_x when using sectoral adjustment factors. This is explained as follows: for each pollutant, as a function of the major emitter sectors, externalities are either reduced or increased when adjusted. For NO_x this results in a reduction of damage costs around 5 %, for the other pollutants it results in an increase that varies between 1 % and 7 %. However, as damage costs are dominated by emissions of NO_x and of SO_2 (cf. Figure 24 and Table 69 and Table 70), and as the sectoral adjustment factors hardly impact on SO_2 emissions, the overall impact of using the sectoral adjustment factors is a reduction in assessed externalities (Table 73).

Table 73: Damage costs aggregated over the main air pollutants from 2008 to 2017 for the VOLY and VSL assessments – percentage change between adjusted and unadjusted values

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
VOLY	-0.86 %	-1.28 %	-1.07 %	-1.15 %	-1.08 %	-1.34 %	-1.05 %	-1.30 %	-1.18 %	-1.45 %
VSL	-1.12 %	-1.54 %	-1.32 %	-1.41 %	-1.34 %	-1.05 %	-1.30 %	-1.18 %	-1.45 %	-1.28 %

The overall impact of including sectoral adjustment factors is, therefore, quite small, 1 % being certainly largely within the uncertainties of the overall methodology. However, if focusing on individual sectors, the overestimation of damage costs can reach 5 % to 7 % when ignoring such adjustment. And such overestimations are found for sectors where the annual change in damage costs ranges from -5 %/yr to +3 %/yr. We, therefore, conclude that accounting for these adjustment factors remains relevant.

Annex 8
E-PRTR to SNAP mapping

The mapping presented here relies on a mapping exercise developed by Finnish and Estonian experts and which was provided by EEA. For the E-PRTR activity codes presented in the last 5 rows (shaded grey area), no correspondence with the SNAP nomenclature was provided. The SNAP codes used in these cases rely on our own suggestions.

Table 74: E-PRTR to SNAP mapping

E-PRTR activity code	SNAP level one codes
1.(a)_	01,04,05,06
1.(b)_	01
1.(c)_	01,02,03
1.(d)_	01,04
1.(f)_	01,04
2.(a)_	03,04
2.(b)_	03,04
2.(c)_	04
2.(c)_2.(c).(i)	03,04
2.(c)_2.(c).(ii)	03
2.(d)_	03,04
2.(e)_2.(e).(i)	03,04
2.(e)_2.(e).(ii)	03,04
2.(e)_	03,04
2.(f)_	04,06
3.(a)_	04,05
3.(b)_	04,05
3.(c)_	03,04
3.(c)_3.(c).(i)	03,04
3.(c)_3.(c).(ii)	03,04
3.(c)_3.(c).(iii)	03,04
3.(d)_	04
3.(e)_	03,04,06
3.(f)_	03,04,06
3.(g)_	03,04
4.(a)_4.(a).(i)	04
4.(a)_4.(a).(vi)	04
4.(a)_4.(a).(viii)	04,06
4.(a)_4.(a).(ix)	04,06
4.(a)_4.(a).(ii)	04
4.(a)_4.(a).(iv)	04
4.(a)_	04,06,09
4.(a)_4.(a).(xi)	04,06
4.(a)_4.(a).(x)	04,06

E-PRTR activity code	SNAP level one codes
4.(a)_4.(a).(vii)	04
4.(a)_4.(a).(iii)	04
4.(b)_4.(b).(ii)	04
4.(b)_4.(b).(i)	04
4.(b)_4.(b).(iv)	04
4.(b)_4.(b).(v)	04
4.(b)_	04,09
4.(b)_4.(b).(iii)	04
4.(c)_	04
4.(d)_	04
4.(e)_	04,06
4.(f)_	04
5.(a)_	09
5.(b)_	01,09
5.(c)_	09
5.(e)_	09
5.(f)_	09
5.(g)_	09
6.(a)_	04
6.(b)_	04
6.(c)_	06
7.(a)_	10
7.(a)_7.(a).(ii)	10
7.(a)_7.(a).(i)	10
7.(a)_7.(a).(iii)	10
8.(a)_	04
8.(b)_8.(b).(ii)	04,06
8.(b)_	04
8.(b)_8.(b).(i)	04
8.(c)_	04
9.(a)_	06
9.(b)_	06
9.(c)_	06
9.(d)_	04
9.(e)_	06
1.(e)_	04
2.(c)_2.(c).(iii)	03,04
4.(a)_4.(a).(v)	06
5.(d)_	09
7.(b)_	10

Annex 9
Overall marginal damage costs of main air pollutants including ecosystems damage

Additionally to the impacts included in Table 27 (impacts on health, crops & forests and material damage), the marginal damage costs in Table 75 include also damage costs for ecosystems.

Table 75: Overall marginal damage costs of major air pollutants – including ecosystems

Emitter countries		Aggregate marginal damage costs over EEA38 + UK (*) for major air pollutants including impacts on health, crops & forests, ecosystems and material damage, in €$_{2019}$/tonne of pollutant											
		NO_x VOLY	NO_x VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
AL	**Albania**	9 705	23 399	66 949	163 868	43 474	106 408	19 436	50 678	850	2 170	9 533	24 104
AM	**Armenia**	1 688	2 757	4 013	6 596	2 606	4 283	2 979	5 099	257	444	594	998
AT	**Austria**	22 670	75 781	69 268	227 195	44 979	147 529	34 630	113 123	2 659	8 225	23 241	75 613
AZ	**Azerbaijan**	297	530	336	622	218	404	1 286	2 441	95	184	89	170
BA	**Bosnia and Herzegovina**	10 143	30 473	36 312	115 067	23 579	74 719	14 007	44 712	1 022	3 000	17 557	55 699
BE	**Belgium**	19 501	67 427	159 127	512 037	103 329	332 491	49 322	159 275	2 703	7 953	49 947	162 801
BG	**Bulgaria**	12 036	39 771	82 132	309 647	53 333	201 070	15 114	46 368	1 007	2 791	16 610	58 105
BY	**Belarus**	1 244	3 509	3 112	9 760	2 021	6 338	3 778	11 176	283	741	1 834	5 682
CH	**Switzerland**	44 104	142 718	101 182	306 655	65 703	199 126	74 294	231 497	4 042	12 216	20 945	65 005
CY	**Cyprus**	7 239	15 125	22 448	48 390	14 576	31 422	10 526	18 212	562	889	6 621	14 690
CZ	**Czechia**	15 055	49 117	88 092	282 451	57 202	183 409	22 528	71 277	2 713	8 138	41 151	131 699
DE	**Germany**	20 524	74 688	75 797	266 647	49 219	173 147	34 621	116 457	1 990	5 721	26 596	90 548
DK	**Denmark**	7 642	25 319	39 174	124 113	25 437	80 593	17 274	54 274	549	1 483	8 124	25 524
EE	**Estonia**	2 226	7 117	7 941	26 735	5 157	17 360	2 242	6 789	203	508	6 296	15 020
ES	**Spain**	12 645	42 134	63 795	201 671	41 425	130 955	22 548	71 915	1 299	3 611	7 301	22 805
FI	**Finland**	4 163	14 519	20 346	65 365	13 212	42 445	5 393	17 104	241	634	4 341	13 649

Emitter countries		Aggregate marginal damage costs over EEA38 + UK (*) for major air pollutants including impacts on health, crops & forests, ecosystems and material damage, in €$_{2019}$/tonne of pollutant											
		NO_x VOLY	NO_x VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
FR	**France**	19 503	63 656	65 395	208 191	42 464	135 189	34 580	111 252	2 156	6 209	13 466	42 588
GB	**United Kingdom**	16 587	55 634	86 815	268 250	56 373	174 188	37 714	117 415	1 659	4 721	32 990	102 606
GE	**Georgia**	824	1 448	1 709	3 099	1 110	2 012	2 338	4 307	253	472	419	786
GR	**Greece**	7 351	26 669	41 820	145 705	27 156	94 614	11 901	36 550	1 273	3 480	12 106	41 129
HR	**Croatia**	17 574	59 833	54 289	192 306	35 252	124 874	23 315	79 013	1 736	5 231	17 557	59 914
HU	**Hungary**	20 447	68 922	77 977	261 548	50 635	169 836	24 317	77 634	1 620	4 795	22 839	74 316
IE	**Ireland**	10 585	29 855	19 612	50 219	12 735	32 609	26 844	77 934	636	1 779	5 335	15 632
IT	**Italy**	29 007	108 206	165 372	592 650	107 384	384 838	26 967	93 755	4 803	15 641	26 470	93 026
LT	**Lithuania**	5 222	18 398	17 633	62 144	11 450	40 353	7 845	25 598	263	648	6 039	20 560
LU	**Luxembourg**	21 907	71 956	80 297	247 472	52 141	160 696	45 946	150 220	1 641	4 639	25 481	82 777
LV	**Latvia**	5 051	19 176	26 831	98 627	17 423	64 043	8 276	28 699	262	666	4 955	17 100
MD	**Moldova**	3 753	10 643	10 733	33 341	6 969	21 650	9 970	28 561	532	1 463	5 042	14 951
ME	**Montenegro**	8 089	23 848	13 370	40 341	8 682	26 195	9 550	29 148	715	1 938	11 058	33 796
MK	**North Macedonia**	5 597	15 297	55 022	152 981	35 729	99 338	13 094	37 938	1 232	3 293	17 857	50 921
MT	**Malta**	2 017	7 159	52 496	150 194	34 088	97 529	5 774	17 077	902	2 487	30 502	87 032
NL	**Netherlands**	23 133	79 400	95 143	294 599	61 781	191 298	42 521	135 753	2 068	6 051	34 835	112 157
NO	**Norway**	5 363	16 729	20 096	56 741	13 049	36 845	5 082	15 339	407	1 102	3 342	9 684
PL	**Poland**	8 557	27 010	42 634	129 265	27 684	83 938	14 289	42 598	1 137	3 070	23 270	70 606
PT	**Portugal**	8 835	31 430	67 543	234 012	43 859	151 956	10 555	35 283	802	2 221	7 421	25 361
RO	**Romania**	15 853	52 412	64 723	217 324	42 028	141 119	20 072	61 831	1 309	3 747	15 046	48 662
RS	**Serbia**	7 366	22 994	57 921	185 863	37 611	120 690	15 725	48 616	1 040	3 043	25 220	81 845
RU	**Russian Federation**	247	598	462	1 256	300	815	751	1 964	152	382	215	599
SE	**Sweden**	5 483	18 625	16 854	53 538	10 944	34 765	6 460	20 188	345	933	5 545	17 421
SI	**Slovenia**	24 959	84 407	112 372	373 078	72 969	242 259	28 225	93 509	3 243	10 127	24 064	80 402
SK	**Slovakia**	16 350	50 306	76 992	233 434	49 995	151 580	19 963	60 571	1 958	5 753	34 193	104 309

Emitter countries		Aggregate marginal damage costs over EEA38 + UK (*) for major air pollutants including impacts on health, crops & forests, ecosystems and material damage, in €$_{2019}$/tonne of pollutant											
		NO_x VOLY	NO_x VSL	$PM_{2.5}$ VOLY	$PM_{2.5}$ VSL	PM_{10} VOLY	PM_{10} VSL	SO_2 VOLY	SO_2 VSL	VOC VOLY	VOC VSL	NH_3 VOLY	NH_3 VSL
TR	**Turkey**	19 634	33 710	61 497	99 897	39 933	64 868	15 484	25 939	1 189	1 935	15 691	25 728
ATL	**NE Atlantic Ocean**	2 340	6 886	9 945	31 273	6 458	20 307	5 900	18 762	924	2 744		
BAS	**Baltic Sea**	2 859	9 011	21 233	68 505	13 788	44 484	7 527	24 155	1 278	3 583		
BLS	**Black Sea**	6 642	12 023	59 595	109 859	38 698	71 337	17 688	32 646	1 773	3 287		
MED	**Mediterranean Sea**	3 303	9 458	44 078	112 472	28 622	73 034	10 945	31 509	2 484	6 547		
NOS	**North Sea**	9 455	30 571	66 407	209 322	43 121	135 923	19 137	61 269	3 830	11 431		

(*) Missing emitter countries relative to EEA38+UK.

For health damage for the $PM_{2.5}$ precursors (NO_x, SO_2, $PM_{2.5}$, NMVOC, NH_3): Iceland, Liechtenstein, Kosovo.

For health damage for the O_3 precursors (NO_x, NMVOC): Iceland, Liechtenstein, Kosovo.

For health damage for the NO_2 precursor (NO_x): Iceland, Liechtenstein, Albania, Bosnia and Herzegovina, North Macedonia and Serbia and Kosovo.

For crop damage for the 03 precursors (NO_x, NMVOC): Iceland, Liechtenstein, Serbia, Kosovo.

For forest damage for the 03 precursors (NO_x, NMVOC): Albania, Iceland, Bosnia and Herzegovina, Liechtenstein, Montenegro, Norway, North Macedonia, Switzerland, Serbia and Kosovo, Turkey.

For ecosystems damage from eutrophication (NO_x, NMVOCs): Liechtenstein, Turkey, Kosovo, Montenegro. Additional emitter countries: Belarus, Republic of Moldova.

For building material damage from SO_2 and NO_x: Albania, Iceland, Bosnia and Herzegovina, Liechtenstein, Montenegro, Norway, North Macedonia, Switzerland, Serbia and Kosovo, Turkey.

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