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Support to the development of the fourth Clean Air Outlook

Final Report

Written by IIASA, EMRC, MET Norway,
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better technologies cleaner transport
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List of acronyms

AAQD	Ambient Air Quality Directives
ALRI	Asthma in adults and acute Lower respiratory Infection
BAT	Best Available Techniques
BAT-AEL	Best Available Techniques-Associated Emissions Levels
BC	Black carbon
CLE	Current legislation
CAO	Clean Air Outlook
CH_4	Methane
COPD	Chronic Obstructive Pulmonary Disease
CO_2	Carbon dioxide
EEA	European Environment Agency
ELAPSE	Effects of Low-level Air Pollution: a Study in Europe
EMAPEC	Estimating the Morbidity from Air Pollution and its Economic Consequences
EMEP	European Monitoring and Evaluation Program of the Convention on Long-range Transboundary Air Pollution
ERC	Emission Reduction Commitment of the NEC directive
EU	European Union
GAINS	Greenhouse gas - Air pollution Interactions and Synergies model
GDP	Gross domestic product
GNFR	'Nomenclature For Reporting' of emission inventories to EMEP/EEA
HRAPIE2	Health Response to Air Pollutants in Europe 2
IED	Industrial Emissions Directive
IIASA	International Institute for Applied Systems Analysis
IIR	Informative Inventory Reports
kt	kilotons = 10^3 tons
MTFR	Maximum technically feasible emission reductions
NAPCP	National Air Pollution Control Programme
NEC Directive	National Emission reduction Commitments Directive
NH_3	Ammonia
NMVOC	Non methane volatile organic compounds
NO_x	Nitrogen oxides
NO_2	Nitrogen dioxide
O_3	Ozone
PaMs	Policies and Measures
PJ	Petajoule = 10^{15} joule
$PM_{2.5}$	Fine particles with an aerodynamic diameter of less than 2.5 µm
PRIMES	Energy Systems Model of the National Technical University of Athens
SECA	Sulphur Emission Control Area
SO_2	Sulphur dioxide
VOLY	Value of a Life Year
VSL	Value of Statistical Life
WHO	World Health Organization
YOLLs / YLLs	Years of Life Lost
ZPAP	Zero Pollution Action Plan

1 Introduction

1.1 This report

This is the final report for the Specific Contract No 090202/2023/906366/SER/ENV.C.3 – "Support to the development of the fourth Clean Air Outlook". The project was led by IIASA with support from the following organisations: Norwegian Meteorological Institute (Met.no), EMRC, TNO, e:misia, Logika Group, RIVM. The macro-economic analysis (chapter 5.5) was undertaken by staff from the Joint Research Centre of the European Commission in Seville.

1.2 Purpose of the Service Request

1.2.1 Introduction

The overall objective for this service request was to provide the underlying analysis to support the preparation of the Commission's fourth Clean Air Outlook report. Alongside this, the outputs will also help to inform the Commission's review of the NEC Directive due in 2025. In line with the service request, the analysis undertaken as part of this contract should help to address a series of research questions:

- *To what extent will the national emission reduction commitments (ERC) set in the NEC Directive be achieved for the periods 2020-29 and 2030 onwards with the implementation of the existing and proposed EU and national legislation?*
- *To what extent will the 2030 target of the Zero Pollution Action Plan to "reduce by more than 55% compared to 2005 the health impacts (premature deaths) of air pollution" be achieved with the implementation of the existing and proposed EU and national legislation?*
- *To what extent will the 2030 target of the Zero Pollution Action Plan to "reduce by 25% compared to 2005 the EU ecosystems where air pollution threatens biodiversity" be achieved with the implementation of the existing and proposed EU and national legislation?*
- *What are the most effective and efficient measures per Member State to reduce ammonia emissions so as to achieve their ammonia emission reduction commitments for the periods 2020-29 and 2030 onwards and the Zero Pollution Action Plan ecosystem related target?*
- *How has the implementation of the NEC Directive influenced air pollutant emissions in recent and current years as opposed to source legislation at EU or national level?*

As with previous iterations of the Clean Air Outlook, the engagement with, and involvement of, Member State experts has been critical for ensuring the analysis is robust and reflective of the situation across the EU.

1.2.2 Scope of the study

In order to deliver on the objectives outlined above, the project covers the following **activities**:

- Up-to-date modelling framework for the analysis.
- Updated baseline reflecting the latest policy developments and sectoral changes.
- Direct engagement with the Member States on the baseline assumptions.
- Development and modelling of a series of policy scenarios and further analysis of the outputs.
- Assessment of the costs and benefits associated with each scenario.

The **geographical scope** of the analysis is each EU Member State as well as the EU as a whole. The analysis considers transboundary pollution within the EU and to and from non-EU neighbouring countries.

The **temporal scope** of the analysis includes 2005 as the base year (as set out in the NEC Directive) and modelling for the years 2025, 2030, 2040, and 2050.

Finally, as set out in the terms of reference, the analysis is expected to be consistent with the following:

- The analysis undertaken in support of the third Clean Air Outlook (CAO3) (Klimont et al. 2022).
- Member States' air pollutant emission inventories and projections submitted in 2023.
- Member States' National Air Pollution Control Programmes (NAPCPs) & Policies and Measures (PaMs).
- The analysis developed in support of the most recent REPowerEU package or other impact assessments developed in support of climate and energy policies (2040 climate target analysis).
- Analysis or modelling work done as part of the review of the amended Gothenburg Protocol to the Air Convention, where relevant and appropriate.
- Latest reviewed critical loads available, as developed by the Air Convention EMEP-Working Group on Effects.
- Latest WHO air quality guidelines
- Latest reviewed HRAPIE health impacts values or alternative datasets duly justified.

1.3 Policy context

The previous three Clean Air Outlook reports[1] presented results on the prospects of achieving the national emission reduction commitments for five air pollutants (sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds, ammonia and fine particulate matter) as set in Directive (EU) 2016/2284[2] on the reduction of national emissions of certain atmospheric pollutants (also known as the "NEC Directive"). They also presented the related air quality, health, ecosystems and economic impacts, as well as other elements such as transboundary pollution and synergies with climate and energy policies.

In May 2021, the Commission adopted its Zero Pollution Action Plan (COM(2021) 400 final)[3], including a corresponding monitoring and outlook framework (SWD(2021) 141 final)[4], as per the European Green Deal. The Zero Pollution Action Plan sets out two clean air related targets, to reduce health and ecosystem impacts linked to air pollution. In October 2022, the Commission adopted a proposal (COM(2022) 542 final/2)[5] to align the EU's air quality standards set in the Ambient Air Quality Directives more closely with the 2021 WHO air quality guidelines (WHO 2021). The impact assessment underpinning this proposal was developed in close coordination with the third Clean Air Outlook.

The fourth Clean Air Outlook updates the policy baseline assumptions to bring them in line with latest political and legislative developments. This has involved updating the baseline to include the "Fit for 55" package that is adopted by Council and Parliament and legislative proposals on other source legislation, such as on industrial emissions and vehicle emission standards, as well as the energy market measures to speed up the clean energy

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[1] COM(2018)446, COM(2021)3 and COM(2022)673 final; https://environment.ec.europa.eu/topics/air/clean-air-outlook_en

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016L2284&from=EN

[3] https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en

[4] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A52021SC0141

[5] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A542%3AFIN

transition and end Europe's dependency on gas, oil and coal imports from Russia (REPowerEU). Furthermore, new modelling assessing the impacts of different options to reach a 2040 climate target[6] in line with the European Climate Law has been reflected (Regulation (EU) 2021/1119)[7]. The impact of climate and energy measures on air quality, health and ecosystems is analysed.

Scenarios to support the fourth Clean Air Outlook show the prospects of achieving national emission reduction commitments for air pollutants as set in the NEC Directive. Scenario results are compared with the policy targets for air quality, health and ecosystem protection that are formulated in the European Green Deal, the Zero Pollution Action Plan and the air quality standards of the revised Ambient Air Quality Directive (AAQD)[8].

The fourth Clean Air Outlook complements the second NEC Directive implementation report, due by April 2024, in order to feed into the review of the NEC Directive, due by 2025.

The study includes the costs and benefits of policy packages including potential macro-economic impacts.

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[6] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021R1119

[8] Directive (EU) 2024/2881 of the European Parliament and of the Council of 23 October 2024 on ambient air quality and cleaner air for Europe (recast). https://eur-lex.europa.eu/eli/dir/2024/2881/oj

2 Approach and methodology

2.1 Overview

Five main tasks were addressed in the Service Request:

- ***Task 1: Provide an up-to-date modelling framework and a Baseline scenario***: Task 1 establishes an integrated assessment modelling framework that is based on latest scientific understanding and best available data reflecting most recent Member State's emission submissions for use in all following analysis. The developed Baseline scenario includes all relevant EU legislation proposed by the Commission or adopted by the co-legislators since the CAO3 as well as updates considering latest national communication on policy implementation and plans of Member States.
- ***Task 2: Consult the Baseline with the Member States***: Under this task, we presented, discussed, and validated the assumptions and key results of the Baseline scenario developed in Task 1 with the Member States. As a result of consultations with the Member State, the assumptions used in the Baseline have been complemented or modified accordingly, where necessary.
- ***Task 3: Develop, run, and analyse policy scenarios***: Under Task 3, a set of scenarios (in addition to the Baseline) has been developed and implemented in GAINS (see 2.2, below), and emissions as well as air quality indicators quantified. Scenarios are designed to explore and illustrate the air quality, health and ecosystem impacts, and co-benefits of recently proposed legislation aligning the climate and pollution targets as well as the likely scope for further mitigation to achieve increasing ambition of air quality targets. Additional analysis explores the sensitivity to the choice of emission factors (measurement method) for condensable PM and analysis of the impacts of EU and non-EU mitigation measures addressing methane on ozone concentrations in the EU, including target values specified in the AAQD.
- ***Task 4: Assess the costs and benefits of air pollution reduction***: Under Task 4 we have quantified cost of air pollution, and benefits of reductions, now and in the future for each of the scenarios developed in Task 3. The assessment has been performed with updated modelling framework where most recent data and methodological updates drawing on the EMAPEC outcomes have been considered to the possible extent. Originally planned updates for mortality drawing on HRAPIE-2 outcomes have not been possible since the results of that study are not yet available.
- ***Task 5: Ad-hoc support to inform the review of the NEC Directive***: Under this task, upon request, we provide the Commission with further analysis and comparison of the results of this service request with the previous Outlooks as well as of Member States' reported air pollutant emissions for recent years, in view of identifying the role of policies and measures resulting from the implementation of the NEC Directive versus other (national or EU level) source control policies.

2.2 Approach

While maintaining the consistency of the modelling approach applied in the CAO3 and in the impact assessment for the revision of the EU AAQD[9], the modelling framework has been updated considering latest improvements and recalculations of reported historic emissions by Member States, in particular for 2005, the base year for the NEC Directive, as well as 2020, and is consistent with the recently updated EMEP/EEA air pollutant emission inventory guidebook (EEA 2023). Special attention has been paid to condensable and non-

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[9] https://environment.ec.europa.eu/topics/air/air-quality/revision-ambient-air-quality-directives_en

condensable parts of particulate matter emissions, identifying in which Member States and sectors the condensable part is included in the national inventories.

IIASA employs its Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model[10] to calculate emissions of air pollutants as well as ambient concentrations of $PM_{2.5}$ and NO_2 based on a linearized version of the EMEP atmospheric chemistry transport model[11]; the same approach and model version was used in CAO3. Ozone (O_3) concentrations were calculated with the EMEP model, which is different from CAO3 where the GAINS model with its linear approach was applied; a summary of the key differences between the approaches is provided in Box 1.

Box 1: Summary of major differences for ozone modelling between CAO3 and CAO4

The EMEP model was used to calculate ozone concentrations in CAO4. This leads to differences compared to CAO3 where the linearized GAINS approach was applied but assures consistency for Baseline and policy scenario for the EU as well as sensitivity cases to global changes of methane and non-methane ozone precursors. The approach implemented in GAINS does not consider changes in boundary initial conditions and therefore such sensitivity cases cannot be evaluated with GAINS. Here a summary of key differences in approaches and their impacts:

- Model resolution: EMEP calculates concentrations at 0.1 x 0.1 leading to higher population exposure than in GAINS where calculation in CAO3 was at 0.3 x 0.2 spatial resolution,
- Boundary Conditions (inflow from outside Europe): The EMEP model considers dynamic (scenario year dependent) boundary conditions while they are constant in the source receptor (SR) runs for the GAINS model. Since O_3 from boundary conditions (hemispheric ozone) increased from 2005 to 2020 it has been counteracting the effects of decreases in European emissions and thus leads to slower reductions in ambient O_3 concentrations over time,
- Ozone non-linearity: The impact of titration (availability of NOx to destroy ozone in areas of high population density and/or with high traffic density) and particularly its change over time cannot be well represented in a linear GAINS approach. Consequently, GAINS would tend to overestimate ozone in some highly populated areas, especially in the earlier years when NOx emissions are still relatively high – this is visible for 2005 when comparing CAO3 and CAO4 results,
- An updated chemistry scheme implemented in the EMEP model after the generation of the transfer coefficients for GAINS used in CAO3, leading to higher ozone production rates, and
- Different meteorological conditions assumed in both models: GAINS SR rely on five-year (2016-2020) average meteorological conditions, while EMEP used 2013-2017 average. This last factor, however, had very small impact on the overall results.

Overall, the impact of different approach translates into CAO4 showing lower SOMO35 in 2005 and higher in future years, with 2020 being very similar. This translates in similar way to assessment of premature deaths.

The baseline scenario for this work is an update of the CAO3 baseline incorporating all relevant EU legislation proposed by the Commission or adopted by the co-legislators since the CAO3 analysis was undertaken. In particular this relates to the climate and energy legislation, reflecting latest political agreements on the legislative initiatives part of the Fit for 55 package as well as of the REPowerEU initiatives, and most recent developments in relevant source legislation, e.g., Euro 7, revision of the Industrial Emissions Directive (IED), etc. The fourth Clean Air Outlook (CAO4) furthermore builds upon the modelling assessing the impacts of

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[10] See Amann et al. (2011) for a general description and the GAINS release notes https://gains.iiasa.ac.at/gains/download/release_notes.pdf?version=4.03 for the latest updates.

[11] See Simpson et al. (2012) for a general description and Simpson et al. (2023) for the latest updates.

different options to reach a 2040 climate target, as mentioned above. More details are provided in section 3.3 and in the Annex section 2.1.

Ambient air quality, health and environmental impacts are assessed with the GAINS model, although for ozone, the results of the EMEP model are used. GAINS calculates premature deaths from exposure to $PM_{2.5}$ and exceedance of critical loads for acidification and eutrophication due to deposition of sulphur and nitrogen. For the latter, the latest database of critical loads (CLs) applied within the Air Convention is used (approved by the Executive Body of the Convention in 2021), which is consistent with the CAO3 study. For ozone, health impacts are calculated by EMRC making use of the results of the EMEP chemical transport model runs for the baseline and respective policy scenarios. Monetary evaluation of health and other benefits is performed with the ALPHA-RiskPoll model, based on the GAINS outputs. Overall, the impact assessment methodology is consistent with the one used in the CAO3 but includes updates taking into account most recent advancements, including the EMAPEC (Estimating the Morbidity from Air Pollution and its Economic Consequences) study results for morbidity (Forastiere et al., 2024). A detailed discussion of assumptions is provided in Section 2.3 and summarized in Box 2.

2.3 Update of impact and benefit assessment modelling

This section provides a discussion and documentation of updates to the modelling of impacts and benefits with key developments summarized in Box 2.

Box 2: Summary of major method updates for health impact assessment and valuation

Morbidity functions for $PM_{2.5}$ and NO_2 have been updated since CAO3 using results from the EMAPEC (Estimating the Morbidity from Air Pollution and its Economic Costs) study coordinated by WHO and published in summer 2024. These cover updated functions for ischaemic heart disease, chronic obstructive pulmonary disease (COPD), stroke, diabetes, acute lower respiratory infections and new incidence of asthma, and an additional function for dementia. Incidence data for morbidity effects has also been reviewed and updated using estimates from Global Burden of Disease initiative. Valuation data were reviewed for all quantified effects, but no changes made.

In October 2024, a second study coordinated by WHO, HRAPIE2 (Health Response to Air Pollutants in Europe 2) released papers considering mortality functions for $PM_{2.5}$, NO_2 and O_3. Whilst these were published too late for inclusion here, a commentary is provided on their implications for analysis.

For impacts to materials, crops, forests and ecosystems, the methods remain the same as in the CAO3.

The changes to morbidity assessment alter their contribution to total damage (with mortality valued using the VOLY and including only Tier 1 and Tier 2 effects – see Table 2-3) from a range of 25% to 31% in CAO3 to 18% to 27% in CAO4 baseline leading to a slight reduction in the estimated economic benefits of pollution control measures. However, CAO4 analysis also shows that including Tier 3 effects would increase the contribution from morbidity to between 37% and 58%. The ranges reflect population ageing with the lower bound being for 2005 and the upper bound for 2050.

2.3.1 Concentration-response functions: Mortality

Mortality functions have been adopted for $PM_{2.5}$, NO_2 and O_3, drawing on findings from the WHO 2021 Air Quality Guidelines (WHO 2021) and are reported in Table 2-1. As previously, estimates of mortality can be calculated in terms of both life years lost or deaths for the economic assessment: these are alternative positions for valuation for which the results are not additive.

Table 2-1: All-cause mortality functions as relative risk (RR) per 10 µg/m^3 adopted for CAO4.

Poll.	Effect	RR	Source
$PM_{2.5}$	Adults, chronic exposure	1.08	Chen and Hoek (2020)
	Infant (1-12 months) mortality	1.04	Woodruff et al. (1997)
NO_2	Adults, chronic exposure	1.02	Huangfu and Atkinson (2020)
O_3	Adults, chronic exposure	1.01	Huangfu and Atkinson (2020)

Three important papers were published during the writing-up phase of this work but after completion of analysis. Two papers were published from the ongoing update to the Health Risks of Air Pollution in Europe (HRAPIE2) assessment coordinated by WHO: Orellano et al. (2024) dealing with effects of chronic exposure to $PM_{2.5}$ and mortality, and Kasdagli et al. (2024) addressing effects of chronic exposure to NO_2 and O_3. The third paper (Chen et al. 2024) investigated the use of 'two-pollutant models' to consider the effect of $PM_{2.5}$ and NO_2 combined, recognising the potential for double counting of impacts when using epidemiological methods for pollutants whose concentrations are correlated as a result of them sharing some common sources (e.g. traffic, and burning of solid and liquid fuels more generally). Relative risks for $PM_{2.5}$ and NO_2 linked to all-cause mortality from these studies are compared with the functions used here from WHO (2021) in Table 2-2.

Table 2-2: Comparison of relative estimates (with 95% confidence intervals) per 10 ug/m^3 from recent $PM_{2.5}$ and NO_2 mortality studies.

Study	$PM_{2.5}$	NO_2
WHO (2021) (used here)	1.08 (1.06-1.09)	1.02 (1.01-1.04)
Orellano et al (2024)	1.095 (1.064-1.127)	
Kasdagli et al (2024)		1.05 (1.05-1.07)
Chen et al (2024) 1 pollutant models	1.106 (1.068-1.142)	1.032 (1.014-1.049)
Chen et al (2024) 2 pollutant models	1.070 (1.028-1.104)	1.024 (1.000-1.049)

From the one-pollutant models our estimates from WHO (2021) are lower for both $PM_{2.5}$ and NO_2 than the results from Orellano et al (2024), Kasdagli et al (2024), and Chen et al (2024). However, the two-pollutant modelling from Chen et al (2024) shows our estimates to be higher for $PM_{2.5}$ and lower for NO_2. In the light of the evidence from the two-pollutant modelling of Chen et al (2024), it is concluded that our continued use of information from WHO (2021) and the sensitivity analysis including/excluding NO_2 effects with potential for double counting against $PM_{2.5}$ effects, remains reasonable. It is noted that the results of the Orellano et al (2024) and Kasdagli et al (2024) papers, although published from work coordinated by WHO, will be further discussed in the HRAPIE2 assessment and do not represent recommendations of WHO at the present time.

Association of $PM_{2.5}$ exposure with post-neonatal mortality was not assessed by Orellano et al (2024) because only two studies (Son et al. 2011; Liao et al. 2022), in India and South Korea, respectively) reported estimates. However, both were positive and significant, supporting quantification of the endpoint. A function from Woodruff et al. (1997) is retained from CAO3 for this endpoint. Given the limited number of papers available on this endpoint, it is subject to potentially large uncertainty taken in isolation. However, very low rates of infant mortality in the EU lead to it making only a very small contribution to overall impacts and benefits. The inclusion of impacts to children (including also functions for asthma, below) is important in demonstrating that pollution affects people throughout the life course.

The situation for ozone is more complex. WHO (2021) concluded on a function for a relative risk of 1.01 (1.00-1.02) per 10 ug/m^3 increase in peak season average of daily 1-hour maximum ozone for all-cause (non-accidental) mortality from Huangfu and Atkinson (2020). The ELAPSE study (Brunekreef et al. 2021) found no significant relationships between long-term ozone exposure and mortality from a series of European cohorts.

Kasdagli et al (2024) found no significant relationship for peak-season ozone with all-cause, respiratory, COPD or ALRI (acute lower respiratory symptom) mortality, or for annual ozone exposure with all-cause or ALRI mortality. They did, however, find significant relationships with annual ozone and respiratory mortality (1.05, 1.02-1.08) and COPD mortality (1.06, 1.03-1.08). There is more consistent evidence supporting the inclusion of impacts linked to short-term exposure (Orellano et al. 2020; WHO 2021), but a long-term impact cannot be ruled out. The decision was taken here to retain the risk estimate for all-cause mortality from Huangfu and Atkinson (2020) as adopted in WHO (2021), but apply it to the SOMO35 exposure indicator, consistent with the approach for CAO3. Given high variability in the conclusions of work on chronic impacts of ozone, a conservative approach has been taken to valuation of ozone mortality, in line with earlier quantification of effects of short-term exposure (and in line with the approach taken in CAO3), where it is assumed that ozone deaths are equivalent to the loss of 1 year of life expectancy per death. It is possible that this undervalues ozone health impacts.

An alternative source of updated functions for both mortality and morbidity would be the ELAPSE (Effects of Low-level Air Pollution: a Study in Europe) study (Brunekreef et al. 2021). ELAPSE focused on European cohorts, and hence may be considered by some to be more appropriate for application in a European assessment. However, ELAPSE data are only from a selection of affluent countries in Europe: Austria, Belgium, Denmark, France, Germany, Italy, the Netherlands and Sweden, so relevance to other parts of Europe might be questioned. EMAPEC is preferred here as it considers eligible studies (those meeting quality criteria) globally, and by doing so draws on a larger amount of data. The approach of preferring studies that consider the global literature was also adopted in earlier CAO reports.

Some analysts prefer to use cause-specific functions for quantification of pollutant impacts on mortality. Reasons given include that part of the all-cause estimate will feature causes unrelated to air pollutant exposure, there is a desire to link mortality to specific types of impact and there is some assumption that the use of cause-specific functions will generate more accurate results. The accuracy argument seems reasonable in regions where few air pollution epidemiology studies have been carried out and where the dominant causes of death differ to those where there has been extensive epidemiological research. However, this argument is weaker in the context of CAO4 given that epidemiological studies have been carried out on air pollution in many European countries. The finding by Hegelund et al. (2024) that $PM_{2.5}$ and NO_2 were both positively correlated with the onset of more than 700 health conditions in Denmark, 80% of registered health conditions, also supports the use of all-cause functions. A further factor is that it has been noted previously that there is an unexpected level of variation in attribution of mortality to causes between countries in Europe. The decision has therefore been taken to continue using all-cause functions to quantify mortality for CAO4.

2.3.1 Concentration-response functions: Morbidity

Response functions for morbidity are shown in Table 2-4 ($PM_{2.5}$), Table 2-5 (NO_2) and Table 2-6 (O_3). Since CAO3, research by Forastiere et al. (2024) under the EMAPEC (Estimating the Morbidity from Air Pollution and its Economic Consequences) project[12] coordinated by WHO has provided new response functions for a series of chronic health conditions. The EMAPEC functions are derived from a global assessment of systematic reviews, of which only those that met high quality standards were used to inform the final recommendations. The EMAPEC functions have been adopted for CAO4, replacing many of those used in CAO3.

The EMAPEC functions applying to adults are all standardised for application above the age of 30, except for asthma. For CAO3, analysis of the same conditions included different age groups depending on the function used, in some cases covering all ages, in others, above 20 or 27 years, but consistently below the 30-year boundary used in EMAPEC. The impact on results will be small given that the conditions referred to (chronic bronchitis, stroke, lung cancer, Type 2 diabetes and ischaemic heart disease events) are far more prevalent in

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[12] https://www.who.int/activities/estimating-the-morbidity-from-air-pollution-and-its-economic-costs

older age groups. The EMAPEC recommendations for asthma cover all age groups (0 to 18 years, and 19 years and over). Data on incidence of the conditions brought in through the EMAPEC analysis has been taken from Global Burden of Disease (https://www.healthdata.org/research-analysis/gbd).

Two effects were not recommended for quantification by EMAPEC, atrial fibrillation and Parkinson's disease, with evidence considered insufficient for risk assessment. Two functions, for dementia and ASD (autism spectrum disorder), which have the largest RRs of all outcomes, were marked by Forastiere et al (2024) as having applicability over a restricted range, not more than 10 µg/m^3, and should be regarded as having added uncertainty. ASD, however, has not been included in the estimates made here given data constraints on incidence and valuation. Hypertension was also not quantified for CAO4 given potential for significant overlap with ischaemic heart disease and stroke. Similarly, some other effects included for CAO3 were omitted through concerns over the potential for double counting (e.g. asthma symptoms, given inclusion of new incidence of asthma).

For CAO3, health impacts were arranged into 'Tiers' of varying confidence, based on whether or not functions had been evaluated by reviews conducted for WHO. Mortality functions taken from WHO (2021) formed Tier 1 (highest confidence). A selection of mainly short-term impacts formed Tier 2 based on HRAPIE (WHO 2013) recommendations, whilst long-term morbidity impacts from non-WHO literature review were included as Tier 3. For CAO4 the Tiers again indicate variation in confidence, though the contents of each Tier differ to before, reflecting advances in the knowledge base. Tier 1 now includes both mortality (again from WHO, 2021) and those long-term impacts on morbidity given an 'A' rating by Forastiere et al (2024). Tier 2 includes a truncated account of morbidity recommendations from WHO (2013) eliminating a function for chronic bronchitis as this would double count against COPD (now in Tier 1). Tier 3 includes $PM_{2.5}$ impacts on dementia and diabetes which were given a 'B+' rating, indicating lower confidence, by Forastiere et al (2024). The Tiering systems for CAO3 and CAO4 are summarised in Table 2-3.

Results reported in this report (main text) exclude the Tier 3 results as they reflect a lower level of confidence than the Tier 1 and 2 results. For CAO3 main text all tiers were included, as the difference in confidence across the 3 Tiers was not considered to be so pronounced. Results for dementia (CAO4/Tier3) are particularly large and merit further evaluation by expert groups, explaining the cautious approach adopted here of excluding them from the main text results.

Table 2-3: Tiering of functions in CAO3 and CAO4.

	CAO3	CAO4
Tier 1	All mortality from WHO (2021).	All mortality from WHO (2021). Long-term morbidity from Forastiere et al (2024) where functions were given an 'A' rating.
Tier 2	Short-term morbidity functions and $PM_{2.5}$/ chronic bronchitis from WHO (2013).	Short-term morbidity functions carried over from WHO (2013) / CAO3. Chronic bronchitis excluded though COPD (which includes it) is now Tier 1.
Tier 3	Long-term morbidity functions introduced for CAO3 but without WHO review.	Long-term morbidity from Forastiere et al (2024) for $PM_{2.5}$ dementia and diabetes ('B+' rating).

NO_2 functions were distinguished between those quantifying an impact not addressed for $PM_{2.5}$ (Asthma in adults and acute Lower Respiratory Infection/ALRI) and those quantifying effects also quantified for $PM_{2.5}$ where there was considered significant risk of double counting. This allowed for a sensitivity analysis, whereby the potentially duplicated NO_2 effect would, respectively, be added to or omitted from totals to give a range for the total impact.

Table 2-4: Functions used for analysis of impacts of PM exposure. Normal text: functions used in CAO4 analysis. *Grey italic text: functions from CAO3 that have been replaced with updated estimates from EMAPEC, shown for comparison*.

Health impact	Impact	Pollutant	Tier	Relative risk	Source
Chronic Mortality (30yr +)	Life years lost, deaths	PM2.5	1	1.08	CAO3 (WHO 2021)
Infant Mortality (0-1yr)	Premature deaths	PM10	2	1.04	CAO3 (Woodruff et al. 1997)
Chronic Bronchitis (27yr +)	*Cases*	*PM10*		*1.12*	*CAO3* (Abbey et al. 1995; Schindler et al. 2012),
COPD (>30)	Cases	PM2.5	1	1.18	Forastiere et al (2024)
Stroke (all ages)	*Cases*	*PM2.5*		*1.13*	*CAO3* (Alexeeff et al. 2021)
Stroke (30+)	Cases	PM2.5	1	1.16	Forastiere et al 2024
Lung cancer (>20)	*Cases*	*PM2.5*		*1.09*	*CAO3* (Hamra et al. 2014)
Lung cancer (>30)	Cases	PM2.5	1	1.16	Forastiere et al 2024
Type 2 diabetes (all ages)	*Cases*	*PM2.5*		*1.10*	*CAO3* (Yang et al. 2020)
Type 2 diabetes (>30)	Cases	PM2.5	3	1.10	Forastiere et al 2024
Myocardial infarction (all ages)	*Cases*	*PM2.5*		*1.08*	*CAO3* (Alexeeff et al. 2021)
IHD events (>30)	Cases	PM2.5	1	1.13	Forastiere et al 2024
Asthma (new incidence, 0-15)	*Cases*	*PM2.5*		*1.03*	*CAO3* (Khreis et al. 2017)
Asthma (new incidence, 0-18)	Cases	PM2.5	1	1.34	Forastiere et al 2024
Morbidity effects from EMAPEC not previously addressed in CAO studies					
Dementia (60+) (restricted applicability)	Cases	PM2.5	3	1.46	Forastiere et al 2024
Morbidity effects of short-term exposure not covered in EMAPEC					
Bronchitis in children aged 6 to 12	Cases	PM10	2	1.08	CAO3 (Hoek et al. 2012)
Respiratory Hospital Admissions (All ages)	Cases	PM2.5	2	1.019	CAO3 (APED studies [WHO, 2013])
Cardiac Hospital Admissions All ages)	Cases	PM2.5	2	1.0091	CAO3 (APED studies [WHO, 2013])
Restricted Activity Days (all ages)	Days	PM2.5	2	1.047	CAO3 (Ostro 1987)
Asthma symptom days (children 5-19yr)	*Days*	*PM10*		*1.028*	*CAO3*
Lost working days (15-64 years)	Days	PM2.5	2	1.046	CAO3 (Ostro, 1987)

COPD = Chronic Obstructive Pulmonary Disease, IHD = Ischaemic Heart Disease, APED = Air Pollution Epidemiology Database

Table 2-5: Functions used for analysis of impacts of NO_2 exposure. Normal text: functions used in CAO4 analysis. *Italic text: functions from CAO3 that have been replaced with updated estimates from EMAPEC, shown for comparison*.

Health impact	Impact	Pollutant	Tier	Relative risk	Source
Chronic Mortality (30yr +)	Life years lost, deaths	NO_2	1*	1.02	CAO3 (Huangfu and Atkinson 2020; WHO 2021)
Asthma in children (0-18)	Cases	NO_2	1*	1.10	Forastiere et al (2024)
Asthma, (new incidence 30-75)	*Cases*	*NO_2*		*1.17*	*CAO3 (Brunekreef et al, 2021)*
Asthma in adults (19+)	Cases	NO_2	1	1.10	Forastiere et al (2024)
ALRI in children (0-12)	Cases	NO_2	1	1.09	Forastiere et al (2024)
Morbidity effects of long-term exposure not covered in EMAPEC					
Stroke (40-89)	Cases	NO_2	1*	1.08	CAO3 (Brunekreef et al (2021)
Morbidity effects of short-term exposure not covered in EMAPEC					
Bronchitis in asthmatic children (5 to 14)	Cases	NO_2	2*	1.021	CAO3 (McConnell et al. 2003)
Respiratory Hospital Admissions (All ages)	Cases	NO_2	2*	1.018	CAO3 (WHO, 2013)

ALRI = Acute Lower Respiratory Infection;* Impacts also addressed for $PM_{2.5}$, that are omitted for a sensitivity case targeted at avoiding potential for double counting

Table 2-6: Functions used for analysis of impacts of O_3 exposure. EMAPEC did not consider O_3 and so this list is the same as used for CAO3.

Health impact	Impact	Pollutant	Tier	Relative risk	Source
Chronic Mortality (30yr +)	Life years lost, deaths	O_3	1	1.01	CAO3 (WHO, 2021, following Huangfu and Atkinson, 2020)
Morbidity effects of short-term exposure not covered in EMAPEC					
Respiratory hospital admissions (>64 years)	Cases	O_3	2	1.0044	CAO3 (WHO, 2013)
Cardiovascular hospital admissions (>64 years)	Cases	O_3	2	1.0089	CAO3 (WHO, 2013)

2.3.2 Data on population and health

Population and mortality projections have been taken from EUROPOP2023, from Eurostat[13]. Disease incidence data have been taken from WHO databases and Global Burden of Disease.

2.3.3 Valuation of health impacts

The valuation estimates adopted here are shown in Table 2-7. Further commentary is provided in the appendix, with some evidence suggesting that the values shown here for morbidity are conservative[14]. The high valuation for dementia stands out in the table, with more than half of the estimate linked to health and social care costs. The other major component is lost utility, reflecting a significant decline in quality of life that can persist for a number of years.

Table 2-7: Values applied to estimates of health impacts (all units €, 2015 prices). Source: as per sources referred to in the technical support report to CAO3 (Klimont et al. 2022) , Annex Section 5.3, unless otherwise noted.

Impact	Value (€, 2015)
Mortality	
Mortality – life years lost	94,660
Mortality – deaths	3.6 million (adults) 5.5 million (infants)
Morbidity	
ALRI	490 (Walton et al, 2024)[15]
Asthma in children	6,927
Asthma in adults	6,927
Bronchitis in children	358
Cardiac hospital admissions	5,900
COPD	63,800
Dementia	490,000 (Walton et al, 2024)
IHD events	33,559
Lost working days	155
Lung cancer	29,832
Minor restricted activity days	48
Respiratory hospital admissions	4,800
Restricted activity days	131
Stroke	98,113
Type 2 diabetes	21,194

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[13] https://ec.europa.eu/eurostat/cache/metadata/en/proj_23n_esms.htm#:~:text=EUROPOP2023%20are%20the%20latest%20Eurostat,horizon%20from%202022%20to%202100.

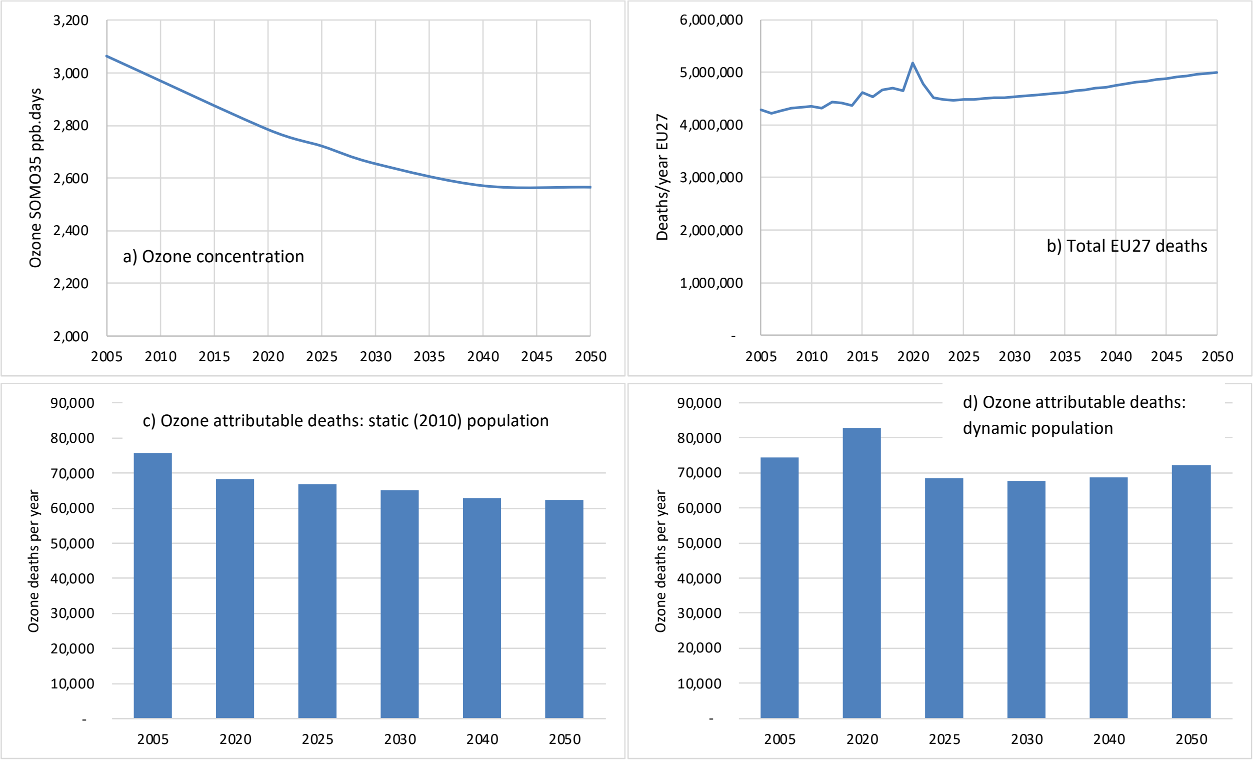
[14] The adult VSL of €3.6 million originates from an OECD study (OECD 2012). OECD is currently updating the earlier study, with results due to be published in early 2025; https://www.oecd.org/en/topics/sub-issues/environmental-cost-benefit-analysis-and-valuation/valuation-of-statistical-life.html

[15] Walton, H. et al (2024, submitted for publication) How can the UK's public health and economic burden from air pollution in 2030/40 and 2050 be reduced by the early introduction of the 2050 net-zero climate policies?

2.3.4 Static and dynamic analysis of health impacts

Quantification of health impacts with the GAINS model is focused on the population structure in 2010, providing a static perspective of the risk faced. This is relevant for analysing the effects of changes in emissions only and also allows an assessment of attainment of the ZPAP target. The CBA, in contrast, accounts for changes in population over time, taking a dynamic perspective accounting for population change. This can be illustrated using the example of mortality linked to ozone exposure (expressed using the SOMO35 metric) under the baseline scenario. Under this scenario, SOMO35 falls over time (Figure 2-1a). Assuming a static population (here fixed at 2010), deaths linked to ozone also (naturally) fall over time (Figure 2-1c). However, the number of deaths in the population is not constant (Figure 2-1b). For the first half of the 21st century the Eurostat EUROPOP2023 forecast indicates that the annual number of deaths in the EU will increase as the mid-20th century baby boom works its way through the population. Change year on year is not smooth: Figure 2-1b shows, particularly, the peak from the COVID pandemic in 2020. Combining these data with declining ozone concentrations leads to a more complex pattern in estimated ozone deaths (Figure 2-1d), peaking in 2020, reaching a low point in 2030 before increasing again to 2050.

Figure 2-1: Analysis of ozone attributable deaths using static and dynamic population



Both estimates are useful, but in different ways. The ‘static’ estimate demonstrates better how risk from exposure to ozone changes year on year. This has advantages for optimisation within the GAINS model as the impact is not affected by a factor (population change) over which GAINS has no control. The static result also provides a clear basis for considering how individual risk from ozone exposure changes. In the example, the static analysis (Figure 2-1c) indicates an 18% reduction in individual risk of mortality from ozone over the period 2005 to 2050, whilst the dynamic analysis indicates only a 3% change (Figure 2-1d). Results comparing 2005 with 2020, or 2030 with 2050 accounting for population dynamics could suggest that no progress was being made with ozone when the modelling of ozone (Figure 2-1a) indicates otherwise.

The ‘dynamic’ estimate, in contrast is better suited for use in the economic analysis. The costs of controlling emissions in the future are partly a function of population change as this influences demand for polluting activities in the future and hence the costs of pollution control. It would be inconsistent for the CBA to use an estimate of impact/benefit based on a static population for comparison with costs for which account is taken of population change via demand forecasting.

2.3.5 Non-health impacts

The following non-health impacts have been quantified:

- Impacts of O_3 on crop production
- Impacts of O_3 on wood production
- Impacts of O_3 on carbon sequestration
- Impacts of N deposition on terrestrial ecosystems
- Effects of acid gases on building materials

In all cases the methods used are the same as adopted in CAO2 and CAO3.

3 An up-to-date *Baseline* scenario for Europe

3.1 Introduction

The objective of this task is to develop a Baseline scenario that includes updates considering all relevant EU legislation proposed by the Commission or adopted by the co-legislators since the CAO3.

For this purpose, updates to the GAINS model database have been made, described in Section 3.2. Assumptions for the Baseline scenario are described in Section 3.3. The Baseline scenario was discussed with EU Member States in bilateral consultations, as summarized in Section 3.4.

3.2 Update of the GAINS model databases

New methods for emission estimation and newly assessed or developed emission factors are reflected in the regularly updated EMEP/EEA Guidebook (latest release in October 2023)[16] which supports Member States in estimating their national emissions. As shown and discussed in previous Clean Air Outlooks, several Member States recalculate their historic emission inventories (including those for 2005) leading sometimes to substantial changes when compared to data reported earlier, which in turn has implications for the achievement of the NEC Directive emission reduction requirements in 2030. Beyond updated methods, revised estimates reflect corrections of calculation errors, revision of activity data and/or emissions factors, and implementation of recommendations from reviews of respective submissions. The Member States have continued to update the emission estimates since 2021 submission and IIASA has reviewed the major recalculations included in the 2023 submission, as well as their impact on the GAINS model estimates for historical years and the baseline scenario.

Compared to the GAINS model version used in the CAO3 study, updates were made to PM emission factors for wood and coal use in the residential sector in order to improve consistency of accounting for condensable PM. This is specifically the case for Austria, Estonia, Germany where updated emission factors in GAINS are consistent with the latest EMEP/EEA Guidebook. This means they are much larger than emission factors used by these Member States in their submissions, since these three countries do not account for the condensable fraction when reporting PM. On the other hand, some countries reported new updated emissions from residential sector, considering condensable PM and revised (in information) structure of combustion installations which lead to large increase; the most pronounced changes are for France and Poland.

Section 2.2 in the Annex provides a comparison of changes in the national emission reporting in 2021 (used in CAO3) and 2023 (used in CAO4) for the year 2005 and 2015 as well as comparison of GAINS and Member State reported emissions for 2005 and 2020. While most of the updates and revision result in changes smaller than 10%, there are several cases for each pollutant where differences are very significant also illustrating a challenge modelling teams face in addressing such updates. These updates were subject of exchange between IIASA and national experts during Member State consultations (Task 2; for detailed account and country-sector-level comparison see Section 3 in the Annex).

3.3 Development of the Baseline scenario

The Baseline scenario for CAO4 is an update of the Baseline developed for the CAO3. It relies on the latest available expectations on future development trends and on the most recent climate, energy, transport, and agricultural policies, including the most recent REPowerEU package. The energy projections have been used before for the analysis of different options for the 2040 Climate Target (CT). The "S3" scenario from the 2040

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[16] https://www.eea.europa.eu/publications/emep-eea-guidebook-2023

CT Impact Assessment[17], which illustrates a pathway to meet the greenhouse gas emission reductions of the preferred target option in that impact assessment, was the starting point for the development of the CAO4 Baseline. The source of these projections are scenarios developed with the PRIMES energy model[18] within the EUCLIMIT-6 project[19] in 2023 and the CAO4 Baseline uses the reference case from that project.

To capture the inflow of pollution from neighbouring countries into the EU, IIASA updated the baseline projections for non-EU countries. For Norway and Switzerland, projections that have been developed in the context of the EU-CLIMIT projects were used. For other non-EU countries in Europe, the activity projections relying on results of the EU funded EUCLIMIT-9EAST project[20] (includes Western Balkan, Republic of Moldova, Ukraine, and Georgia) have been updated considering the results of the recently completed project for Republic of Moldova (led by IIASA and funded by UNECE) and the work for Western Balkan (EU funded project EU4Green where IIASA led work on modelling future emissions and mitigation). In both projects bilateral consultations with national experts have taken place allowing to improve, to some extent, estimates for the past years and consequently also projections, since revised and up to date schedules for implementation of various policies have been communicated. Additionally, several other EECCA countries (Armenia, Georgia, Kazakhstan, Ukraine) took part in a meeting at IIASA in November 2023 discussing national air pollution, air quality measurements and policies. The exchange provided input to GAINS databases (fuel quality, structure of transport sources, residential fuel use information, availability of air quality measurement data) improving data and enabling better validation of atmospheric calculations. For the remaining countries, the projections that have been developed and published by the International Energy Agency (IEA) in its World Energy Outlook 2023 (IEA 2023) are used.

The Baseline reflects the final Euro 7 Regulation[21]. Compared to CAO3, the CAO4 Baseline includes updated implementation of the revision of the IED. The revised IED (Directive 2010/75/EU as amended by Directive 2024/1785)[22] was published in the Official Journal of the EU on 15 July 2024 and entered into force on 4 August 2024. The revised IED will lead to a greater emphasis on, and application of, the lower end of the emission levels associated with the BAT (BAT-AEL ranges) included within the BAT Conclusions. The CAO4 Baseline assumes, as a minimum, compliance with the upper end of the BAT-AELs and the revised IED will likely lead to further reductions although it is not currently possible to estimate the extent of that further reduction.

In the CAO3, the Commission's proposal for a revised IED for agriculture was integrated into the Baseline, meaning cattle, pig and poultry farms with more than 150 livestock units (LSU) were covered by BAT measures as defined under the IED. However, since the European Parliament has adopted amendments to the original proposal, the implementation of the revised IED in GAINS has been reassessed. The revised IED now sets the threshold for the inclusion of poultry and pig farms to 280 LSU for poultry (300 LSU for laying hens) and 350 for pigs or 380 LSU for mixed pig and poultry farms. An exemption is made for organic or low-density pig farms. Cattle farms are excluded with a reassessment of also addressing emissions from cattle farms planned for 2026 [23]. As in CAO3, the EUROSTAT farm structure survey is used to evaluate the individual impact of the implementation of the IED on each Member State using newly available data for 2020 (EUROSTAT, 2022[24]), unless more detailed country level data was received. This information has been discussed with the national

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[17] SWD(2024) 63 final

[18] https://e3modelling.com/modelling-tools/primes/

[19] Service Contract 340201/2019/813567/CLIMA.C.1

[20] Service Contract ENER/A3/SER/2019-563/SI2.840866 - ENER/2020/OP/0005; Extension of the EU Energy and Climate Modelling Capacity to include the Energy Community and its Nine Contracting Parties

[21] Regulation - 2024/1257 - EN - EUR-Lex

[22] The revised IED (Industrial and Livestock Rearing Emissions Directive (IED 2.0)): https://environment.ec.europa.eu/topics/industrial-emissions-and-safety/industrial-and-livestock-rearing-emissions-directive-ied-20_en

[23] Item10-IED_provisionalagreement_20220104COD_EN.pdf (europa.eu)

[24] https://ec.europa.eu/eurostat/databrowser/view/ef_lsk_main/default/table?lang=en

experts during consultations (Task 2, see Section 3.4) to review our assessment and implementation of structural changes as well as policies in the GAINS model, also ensuring that any more stringent national policies are reflected accordingly in the Baseline.

Another key element for inclusion in the Baseline has been the information provided by Member States (since the analysis done for the third Clean Air Outlook) in the latest versions of their air pollutant emission projections and NAPCPs (primarily related to additional Policies and Measures). While, based on our experience, the provided projections often lack quantitative assessment of impact of policies to be able to make changes to the baseline scenario, the information from the NAPCPs[25] and PaM tool has been used to help inform discussions with the Member States in Task 2 and jointly conclude about potential changes to assumptions about policy implementation, if needed.

The potential impact of the EU Urban Mobility Framework[26] initiative that aims to make urban mobility more sustainable, smart, and healthy has not been considered in the CAO4 Baseline. The PRIMES energy system model, which provides the energy sector projections for the Clean Air Outlook, has limitations to provide spatially explicit output reflecting the impact of such an incentive on urban transport and its emissions.

3.4 Consultation of the Baseline with EU Member States

3.4.1 Introduction

The purpose of this task is to present, discuss, and validate the assumptions and key results of the Baseline scenario with the Member States. As a result of consultations with the Member States, the assumptions used in the Baseline have been complemented or modified accordingly, where necessary.

3.4.2 Approach

The consultations were organized as half-day online meetings with experts representing each Member State to share the GAINS model Baseline scenario developed for this assignment and to discuss specific national features included in the Baseline and the modelling framework. Key elements discussed during consultations included policies and measures implemented and planned in the Member State, methodological features which have impact on emission inventories (including condensable PM), discussion of discrepancies between GAINS and the national inventories as well as projections that remain after development and implementation of the Baseline in GAINS.

The summary of introduced changes, in responses to inputs from Member States and discussions at the consultation meetings, as well as the final revised Baseline were presented at the online meeting with all Member States and the Commission.

The detailed country comparisons and discussion of remaining discrepancies is provided in the Annex to this report (see Section 3 in Annex).

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[25] https://ec.europa.eu/environment/air/reduction/NAPCP.htm

[26] EU Urban Mobility Framework (COM(2021) 811)

4 Policy scenarios and their consequences for emissions and ambient air quality

4.1 Introduction

In this section, we develop and analyse a set of scenarios (in addition to the Baseline) exploring further mitigation potential and cost-optimal achievement of air quality and emission reduction targets. The impact of systematic inclusion of condensable particles as well as methane reduction on achievement of EU air quality targets is assessed via sensitivity analysis. For each scenario, the air quality, health and ecosystem impacts and co-benefits are shown.

4.2 Approach

Five key policy scenarios were developed. Additional sensitivity analysis was performed, including two cases where emission factors representing varying measurement methods of condensable particulate matter, and further scenario variants analysing impacts of the EU vs non-EU reduction of methane on ozone concentrations and compliance with legislation (Table 4-1).

The scenarios were developed and implemented in the GAINS model, which is used to calculate emissions of all air pollutants as well as $PM_{2.5}$ and NO_2 concentrations, health, and ecosystem impacts. GAINS was operated in simulation mode for the Baseline scenario (and its sensitivity cases) as well as in optimization mode for the other scenarios. The simulation of ozone concentrations and impact of methane emission changes in the EU and outside was performed with the global EMEP model by Met.no. IIASA developed and provided respective global emission fields for methane and non-methane ozone precursors and calculated health and ecosystem impacts from gridded concentration output received from the EMEP model.

4.3 Development of policy and sensitivity scenarios

The scenarios and sensitivity cases are summarized in Table 4-1. The scenarios were developed for the period 2005-2050[27] and analysed for years 2005, 2020, 2025, 2030, 2040 and 2050, depending on the scenario. Sensitivity cases are variants of the Baseline, where specific elements are altered (emission factors for the condensable fraction of PM, methane emissions outside Europe), while all other scenario elements are kept unchanged, so that the effect of this particular alteration can be quantified.

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[27] For years prior to 2020, only the (statistical) Baseline scenario and its sensitivity cases were developed. For the year 2020, also the optimized ERC scenario was developed. All other scenarios are only developed for future years.

Table 4-1: Overview of the developed policy and sensitivity scenarios

Scenario name	Scenario description	Results for:
Baseline	Consistent with the projected evolution of the energy system in the 2040 climate target impact assessment[28]. It includes the latest EU and national legislation and plans.	2005 - 2050
MTFR	Maximum Technically Feasible Reduction (MTFR) scenario developed for the Baseline scenario.	2030 – 2050; (2020, 2025) (a)
ZPAP	A Zero Pollution Action Plan (ZPAP) scenario that allows to fulfil the target related to the ecosystem impacts of air pollution from the ZPAP(b); this is an optimized scenario.	2030
ERC	Optimized scenarios where the model would be forced to reach a situation where all MS meet all their 2020-29 emission reduction commitments (ERCs) in 2020 and 2025, and ERCs 2030 in 2030 and beyond to evaluate impacts compared to the baseline, and measures required to achieve compliance, providing results to inform the 2025 review of the NEC Directive.	2020 - 2050
ERC+ZPAP	Optimized scenario where both, ZPAP targets as well as compliance with ERCs in 2030 are assured.	2030
Sensitivity cases to Baseline		
Ref2_filter	Sensitivity case where only filterable PM from combustion sources is measured, i.e., excluding the condensable fraction. Emission factors originate from TNO Ref2 set.	2005 - 2050
High_C	Sensitivity case for condensable PM where 'high' emission factors originating from the study supported by Nordic Council of Ministers (Simpson et al. 2022b) are applied consistently to all countries.	2005 - 2050
Global MTFR (CH4 only)	A scenario implementing maximum technically feasible reductions on methane (CH_4) emission sources globally, while retaining Baseline on other ozone precursors (NOx, VOC, CO).	2040, 2050
Sensitivity case to MTFR		
Global MTFR (AP+CH4)	A scenario implementing maximum technically feasible reductions on all ozone precursors (NOx, VOC, CO, CH_4) globally.	2040, 2050

(a) The MTFR for 2020 and 2025 were calculated to develop the optimized scenarios achieving respective ERCs in 2020 and 2025.

(b) According to the analysis with the GAINS model, the ZPAP target on reducing premature deaths from air pollution is met in the baseline.

4.3.1 Key policy scenarios

The ***Baseline* scenario** assumptions have been discussed in Section 3.3; it creates a starting point for all other scenarios, i.e., all remaining policy scenarios are built/further developed starting from assumptions and setup of the *Baseline* scenario.

The ***MTFR*** (Maximum Technically Feasible Reduction) **scenario** implies the application of best available emission control technologies (conversely, achieving highest emission reductions) defined in the GAINS model considering achievable reduction rates and technological application limits. The latter refer to limitations due to the age structure of installations, their lifetimes, and capacity for uptake of mitigation technologies appropriate for a given source. Effectively, it means that over time more and more capacity can be controlled with low emission techniques and the pace and extent of penetration will be sector- and country-specific. While such technological constraints are taken into account, no financial constraints are assumed limiting

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[28] More specifically, it is consistent with the 'S3 scenario' of that impact assessment, which illustrates a pathway to meet the greenhouse gas emission reductions of the preferred target option.

installation or operation of any of the measures. Such a definition was also applied for the development of MTFR scenarios within the AAQD impact assessment as well as the CAO3.

For non-EU countries, current legislation was assumed in all scenarios. Energy projections in non-EU countries are consistent with recently completed EU projects; in particular for West Balkan, the Baseline contains climate mitigation action comparable to EU MIX55, as used in the EU4Green West Balkan project.

The ***ZPAP*** (Zero Pollution Action Plan) **scenario** is developed to address achievement of the ZPAP targets[29] for 2030. Since, according to GAINS model assessment, the health-related target is achieved in the Baseline, the focus is to achieve the target related to the ecosystem impacts of air pollution. Development of this scenario involved additional optimization runs with the GAINS model to identify a cost-effective solution achieving these objectives, provided they are feasible.

The ***ERC scenario*** was developed as a cost optimal scenario, where all MS meet all their 2020-29 emission reduction commitments in 2020 and 2025 (*ERC-20* and *ERC-25*, respectively), to evaluate impacts compared to the baseline, providing results to inform the 2025 review of the NEC Directive. A retrospective cost optimization in GAINS is a rather unusual exercise as the constraints regarding applicability limits for technologies depend on the time perspective (e.g., constraints for 2030 are stricter than for 2040). The assumptions on applicability (of measures beyond current legislation) constraints for the 2020 and 2025 optimization are set from a 2015 perspective. Furthermore, the ERC scenarios where compliance of the ERC for 2030 is assured were developed for 2030, 2040, and 2050.

*The **ERC+ZPAP scenario:*** Additionally, IIASA has developed a scenario for 2030 where both ZPAP and ERCs compliance is assured, provided attainment of both is feasible. This scenario is motivated by the fact that achieving ZPAP objectives does not assure compliance with ERCs and vice versa, achieving ERCs does not assure that all objectives of ZPAP are reached.

4.3.2 Inclusion of condensable PM

As shown in the CAO3, and also demonstrated in Figure 4-1 (from Simpson et al., 2022) below, the inclusion of the condensable fraction of PM can change PM emission estimates substantially, particularly for small combustion sources. Figure 4-1 shows the $PM_{2.5}$ emissions for small combustion for the year 2018 for cases excluding condensables (*Typical_solid*), including condensables (*Typical_total*), and an alternative case assuming higher emission factors (*HighEF_total*).

In recent years, the reporting of emissions with condensables has been improving. For several sectors, such as transport, condensables have long been included due to the established measurement methods and the availability of default emissions factors (e.g., those provided in the Guidebook). However, in the case of residential combustion of solid fuels (GNFR C), which is typically a key source of primary $PM_{2.5}$ emissions, reporting has been more inconsistent. This stems from challenges like a lack of data, differences in the methods used etc.

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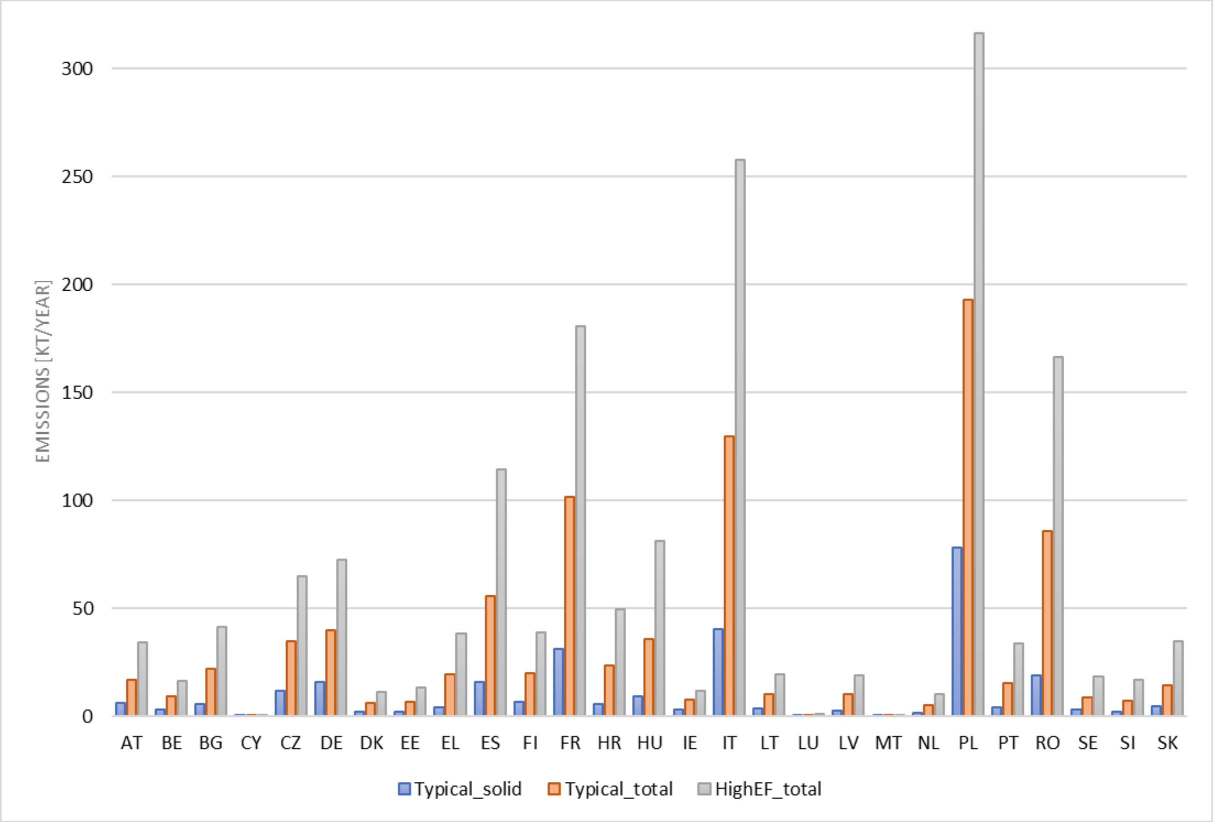
[29] https://ec.europa.eu/environment/strategy/zero-pollution-action-plan_en

Figure 4-1: Comparison of $PM_{2.5}$ emissions [kt/year] for small combustion for 2018 (Simpson et al., 2022)



The inclusion of condensables in official reporting has progressively improved, especially following the introduction of a set of emission factors in the Guidebook based on the work of Denier van der Gon et al. (2015). Despite this progress, some inconsistencies in reporting still persist due to, for example, (i) use of different emission factors *Tiers* from the Guidebook, where Tier 1 default factors account only for fuel type and not for type of combustion device, (ii) lack of data about combustion type structure and its development over time, (iii) quality of data or assumptions how to estimate fuel use and combustion practices, etc. To identify possible inconsistencies with respect to emission factors used, we have reviewed the 2023 reported emissions submissions using the following approach:

- Identified EU Member States that use Ref2 as a data source for $PM_{2.5}$ emissions in GNFR C for the EMEP status runs in 2023[30].
- Checked the descriptions of the Emission Factors (EFs) for GNFR C in the Informative Inventory Report (IIR) and any mention of condensables.
- When the inclusion of condensables was unclear, the implied emission factor was calculated based on NFR data. If the EF was less than approximately 100 g/GJ, it was assumed that condensables were not included, as the implied EF is expected to range between 500 and 800 g/GJ for traditional appliances when condensables are included[31]. Since the more advanced stoves have lower emission factors as illustrated in Simpson et al. (2022), the 100 g/GJ implied emission factor has been chosen as a safe limit below which condensables can be assumed to be excluded.

The analysis, as well as Baseline consultations with Member States, revealed that five countries (Table 4-2) have not incorporated condensables for residential (stationary) small combustion.

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[30] https://emep.int/publ/reports/2023/EMEP_Status_Report_1_2023.pdf

Table 4-2: EU countries where condensables are not included in the 2023 reporting

Country	Explanation
Austria	The IIR is not clearly explaining the inclusion, however, national experts confirmed during Baseline consultations that the condensables are not included. Furthermore, the assessment of implied EFs shows they are < 100 g/GJ, indicating that condensables are likely not included.
Estonia	IIR explicitly mentions that condensables are excluded (based on input of measurement team).
Germany	The IIR does not provide explicit information if condensables are included. However, during Baseline consultations, national experts confirmed that the submission did not include explicitly condensables. Furthermore, the assessment of implied EFs shows they are rather small and therefore condensables are likely not included.
Lithuania	IIR explicitly mentions that $PM_{2.5}$ condensables are not included in the national inventory.
Luxembourg	The IIR does not provide explicit information if condensables are included. However, during Baseline consultations, national experts confirmed that the national inventory did not include explicitly condensables. Assessment of implied EFs shows they are too small and therefore confirming that the condensables are likely not included.

In the Baseline, PM emission factors in the GAINS model are country specific and assume that condensable fraction is included, also for the five countries listed above (Table 4-2). The assumptions in GAINS have been also communicated to the Member States during the consultations that IIASA held with them (Section 3.4). A simple comparison of GAINS emission factors in CAO4, CAO3, vs national reporting is not directly possible, owing to different resolution of the model and the guidebook/national methods of estimating emissions. However, as illustrated in Section 3 of the Annex, GAINS and nationally reported residential sector emissions compare well for all countries that report condensable PM and differences for the remaining few (as listed above) were discussed and acknowledged by the Member States experts.

Comparing Ref2 scenarios with reported emissions

Reported emissions of $PM_{2.5}$ for GNFR C in 2019 were compared with the outcomes of the 2019 Ref2 scenarios for all Member States[31]. The *Ideal* and *Typical* scenarios are both based on the median of the full range of emission factors collected when developing *Ref2*, whereas the *HighEF* scenario is based on the median of the top 5 (or top 3 when less than 10 values were identified) emission factors found in the literature search. Both, the *Typical* and *HighEF* scenarios include “bad combustion” practices, such as burning wet wood, which increase emission factors (Simpson et al. 2022b).

The analysis of Figure 4-2 shows a diverse picture, with some countries with reported emissions lying between the Ideal and Typical scenarios, and thus lower than the Typical values that incorporate the impact of human behaviour and “bad combustion”, and some, such as Poland and France, with higher reported emissions, that come closer to the *HighEF* scenario. These variations highlight the lack of a consistent approach to incorporate condensables in the small combustion sector across Member States. As for the Member States that do not include condensables at all (as shown in Table 4-2), the EFs are much lower, even lower than the EFs based on the *Ideal* scenario, as can be expected.

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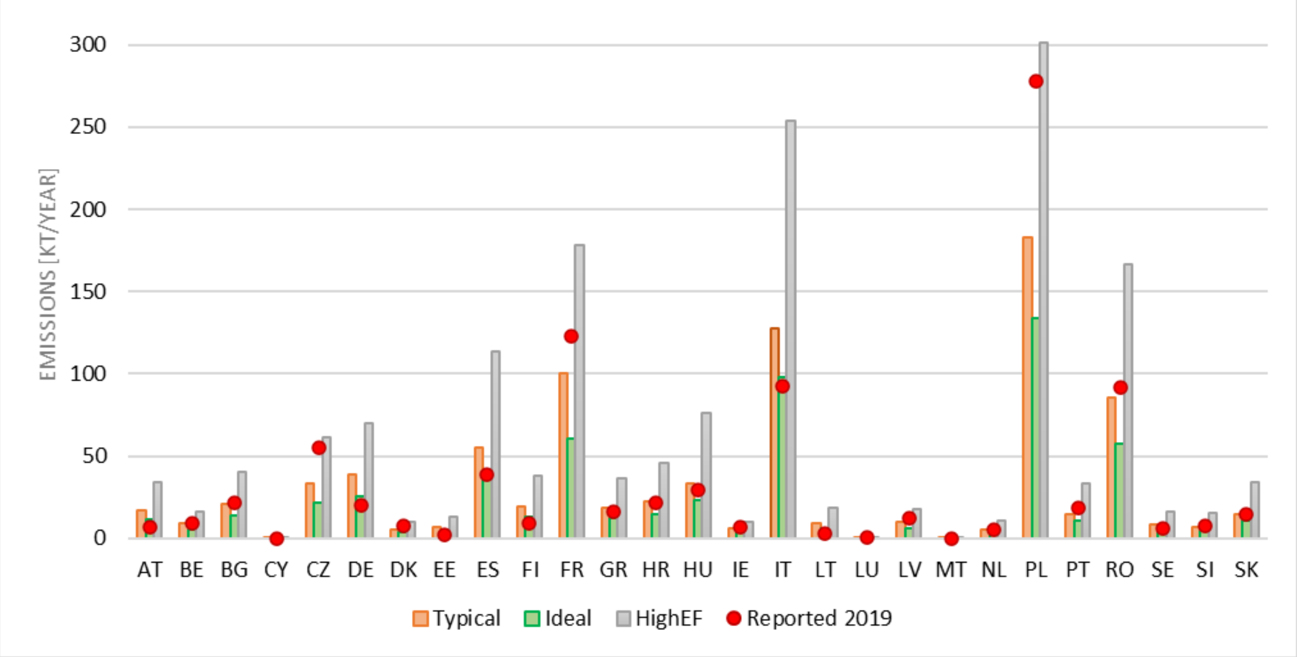
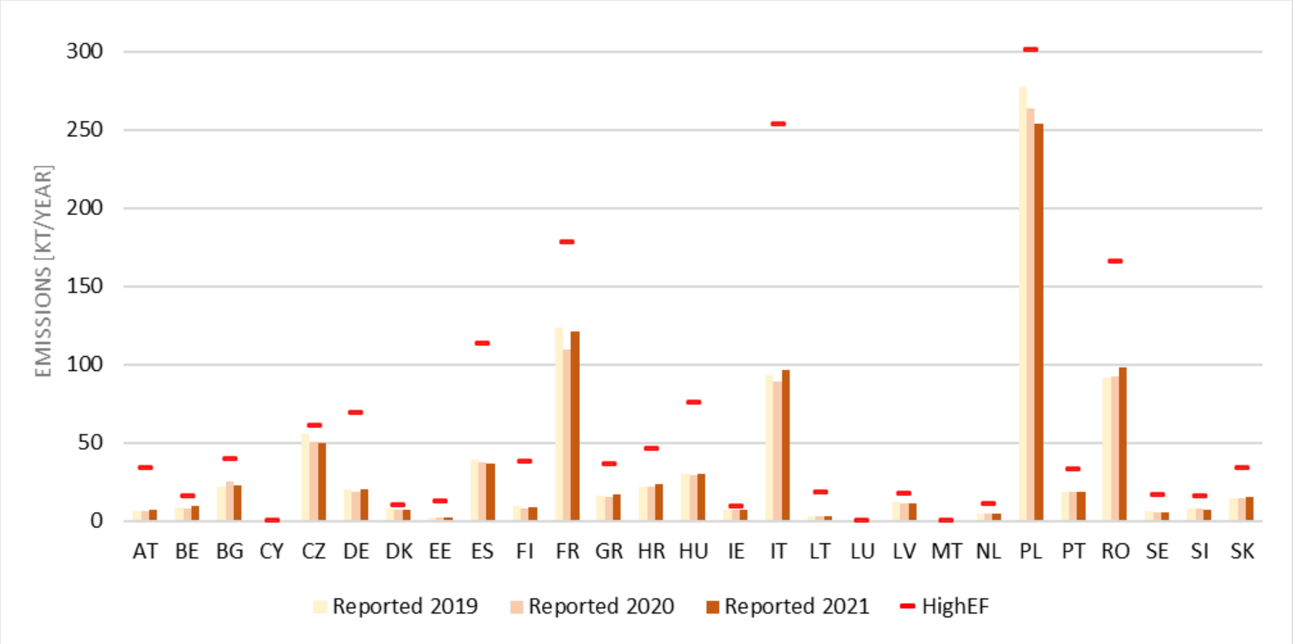
[31] Based on the 2023 submission (see https://www.ceip.at/webdab-emission-database/reported-emissiondata) extract reported small combustion emissions

Figure 4-2: Comparison of Ref2 scenarios to reported 2019 emissions, based on 2023 submission [kt $PM_{2.5}$]



The analysis of Figure 4-3 indicates that for all Member States, reported emissions for 2019 to 2021 are lower than the *HighEF* scenario, with some countries relatively lower than others. The variation of emissions from year to year is relatively limited. It can be attributed to a combination of changing activity data (meteorological variation combined with changes in the fuel mix) and emission factors (installation renewal). When drawing these comparisons, it is also important to keep in mind the impact of country-specific issues on emissions in this sector. Additionally, since 2020 and 2021 coincide with the COVID-19 pandemic, it is challenging to assess the extent to which the pandemic may have influenced emissions from small combustion sources.

Figure 4-3: Comparison of Ref2 scenario (HighEF) to reported emissions for 2019-2021, based on the 2023 submissions [kt $PM_{2.5}$]



Scenarios

To address the uncertainties and analyse impact of various assumptions (emission factors) for PM EFs for residential sector, we explore the impact on compliance and assess which of the assumption leads to improved representation of measured particles in the ambient air. For that purpose, we use the following assumptions about the condensable fraction of PM in the two analysed scenarios (these are sensitivity cases to the *Baseline*):

- ***Ref2_Filter***: We assume that the condensables in EFs for small combustion are **fully excluded**. The emission factor set relies on the fuel and combustion technology specific set of *Ref2* EFs without condensables, as reported in Simpson et al. (2022)
- ***High_C***: The second sensitivity scenario considers applying **higher emission factors for condensables.** These will be based on the high emission factor set from Simpson et al. (2022), *HighEF_total*, combined with national inventory information, if found necessary. Recent inventory submissions (2022/2023) by e.g., Poland and France suggested that the base scenario used in the *Ref2* study might underestimate actual emissions and some national emission factors might be even higher, i.e., close to those reported as *HighEF_total* estimated in the Simpson et al. (2022). Since the recently reported emission factors for these two countries were similar to *HighEF_total*, the scenario is relying on the consistent set of high emission factors as reported in the Simpson et al. (2022).

The results of these two sensitivity cases are compared against the *Baseline* scenario in view of achieving (in 2025 and 2030) the NEC Directive emission reduction commitments for $PM_{2.5}$ per Member State. This way, the sensitivity of the condensables issue with regard to meeting the reduction commitments can be assessed. Furthermore, the results will be evaluated against the newly available ambient measurements with the EMEP model.

4.3.3 Sensitivity to global reductions of methane and other ozone precursors

Sensitivity to changes in ***CH_4 emissions outside Europe***: Background concentrations of ozone are to some degree determined by emissions of methane as an ozone precursor. Due to the long lifetime of CH_4 in the atmosphere, this contribution is non-local and thus strongly influenced by emissions outside the EU. Sensitivity cases were constructed testing different assumptions for global CH_4 emissions, drawing from scenarios developed in the context of the Gothenburg Protocol review. Separate reduction cases of only CH_4 and combined with other precursors (NOx, VOCs, CO) were analysed. The configurations of sensitivity scenarios are shown in Table 4-3. The global MTFR mitigation case is very ambitious and assumes 50 % global CH_4 emission reductions and even higher reductions of the non-methane ozone precursors (NOx, NMVOC, CO) in 2050. The high reduction of non-methane ozone precursors at the global level is driven by the still available mitigation potential for non-EU countries, which is much higher compared to the EU (at the EU level, the MTFR case yields about 20-30% reduction beyond the Baseline) owing to existing policies and underlying energy scenario where strong decline of fossil fuels is projected.

Table 4-3: Setup of ozone precursor sensitivity scenarios

		CH_4		NOx, VOC, CO	
Scenario	Region	CLE	MTFR	CLE	MTFR
Global MTFR (CH4 only)	EU		√	√	
	Non-EU/World		√	√	
Global MTFR (AP+CH4)	EU		√		√
	Non-EU/World		√		√

4.4 Emissions and air quality under the scenarios

For each of the scenarios (Baseline and policy scenarios) the modelling results are provided and analysed for each Member State, for the EU as a whole and for at least the years 2025, 2030, 2040 and 2050. The description includes an explanation of key trends, differences of results between scenarios, and brief statement as to how CAO4 results compare to the CAO3.

4.4.1 Evolution of emissions

This section provides estimates of emissions of key air pollutants, including SO_2, NO_x, NMVOC, NH_3 $PM_{2.5}$, Black Carbon (BC), and methane (CH_4) for selected scenarios. The estimates are shown here as EU total, distributed by major source categories (aggregates of GNFR sectors).

Figure 4-4 through Figure 4-9 show the air pollutant emissions in the EU for the *Baseline* and selected scenarios, including *MTFR* (reflecting on the scope for further mitigation in 2030 and beyond) and scenarios that assure compliance with the ZPAP objectives as well as achieve the ERCs in the period 2020 through 2050.

At the EU level, emissions of all six pollutants have declined since 2005 by about 40% for $PM_{2.5}$ and NMVOC, over 50% for BC, nearly 60% for NOx and about 85% for SO_2. However, NH_3 declined by only 9%. Key contributors to this reduction are the power, industry, and transport sectors for SO_2, NOx, while for $PM_{2.5}$ residential sector is more important. For BC, over 70% of the achieved reduction originates from transport and about 20% from residential combustion. Further reductions are expected for most species owing to the continued renewal of installations that need to comply with more stringent emission limit values as well as envisaged decarbonization, consistent with the objectives of the European Green Deal.

Compared to 2005, emissions are expected to decline in the *Baseline* by 50 to 90% (depending on species) by 2030, except ammonia, which decline only by 11%, i.e., only 2 percentage points from 2025 level estimated in GAINS[32]. Overall, the key contribution to emission reduction comes from improved compliance with the IED, successful transition and implementation of policies in the transport sector, and an assumed decline in fuelwood use for residential heating. These transformations will have little impact on ammonia emissions and since the revised IED does not bring a significant increase in coverage and stringency, and other new environmental policies for agriculture are scarce, the expected change is rather small.

Despite significant success of current legislation, including the envisaged impacts of the EU climate policy, and an associated strong reduction of air pollutants, there are still technical means of reducing emissions further. This is demonstrated in the *MTFR* scenario as well as scenarios assuming full compliance with ZPAP objectives and ERCs. The GAINS model estimates that the *MTFR* scenario could bring, EU-wide, over 40% additional mitigation potential (compared to baseline) for SO_2 in 2030 and 2050, 25-30% for $PM_{2.5}$ (nearly 38% for BC), over 20% for NMVOC and NOx, and about 23% and 27% for NH_3 by 2030 and 2050, respectively. It is interesting to note that these estimates indicate a very similar further mitigation potential for all species, even for ammonia, that typically had a much smaller mitigation scope.

As evaluated further in the report, several Member States have not (in the past) and are not expected (according to GAINS calculation in the baseline) to be in compliance with the ERCs for some pollutants, especially NH_3. At EU level, the ZPAP objective for eutrophication is missed. The additional reductions to achieve compliance are typically not large from the perspective of the EU as a whole, as illustrated in the

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[32] This estimated decrease in GAINS is lower than the value given in the EEA Briefing which is based on Member States' reported emission inventories (https://www.eea.europa.eu/publications/national-emission-reduction-commitments-directive-2024) due to a lower estimate in GAINS for 2005. For 2020 the EEA and GAINS estimates agree well, whereas the number for 2022 by EEA based on Member States' reports EEA is lower than GAINS in 2025.

following figures. The exception is NH_3, for which more than half of the identified mitigation potential (at the EU level) would need to be mobilized to achieve ZPAP objectives.

Overall, the trends of all air pollutants mirror those assessed in CAO3. However, there are some systematic differences, which are either driven by updates of methodology, activity development outlook, or policy implementation. These include, for example:

- slightly higher NOx due to updates for soil NOx,
- updated emission factors, structure and outlook for residential sector driving up PM and BC, although further mitigation potential, especially in the longer term, remains pretty much the same,
- and higher 2030 NH_3 emissions since ambition of IED has been reduced.

Current estimates and trends for SO_2 and NMVOC are pretty much the same as CAO3.

Figure 4-4: Emissions of SO_2 in the baseline and selected scenarios, EU total.

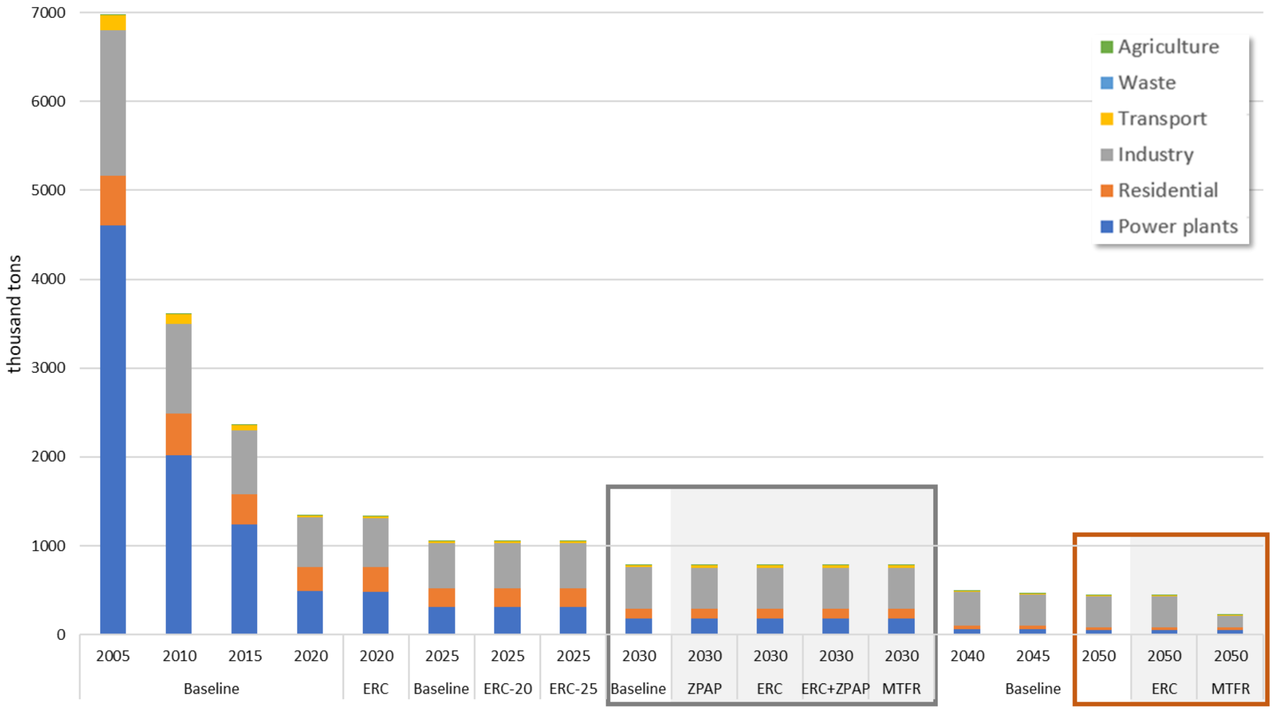


Figure 4-5: Emissions of NO_X (as NO_2) in the baseline and selected scenarios, EU total.

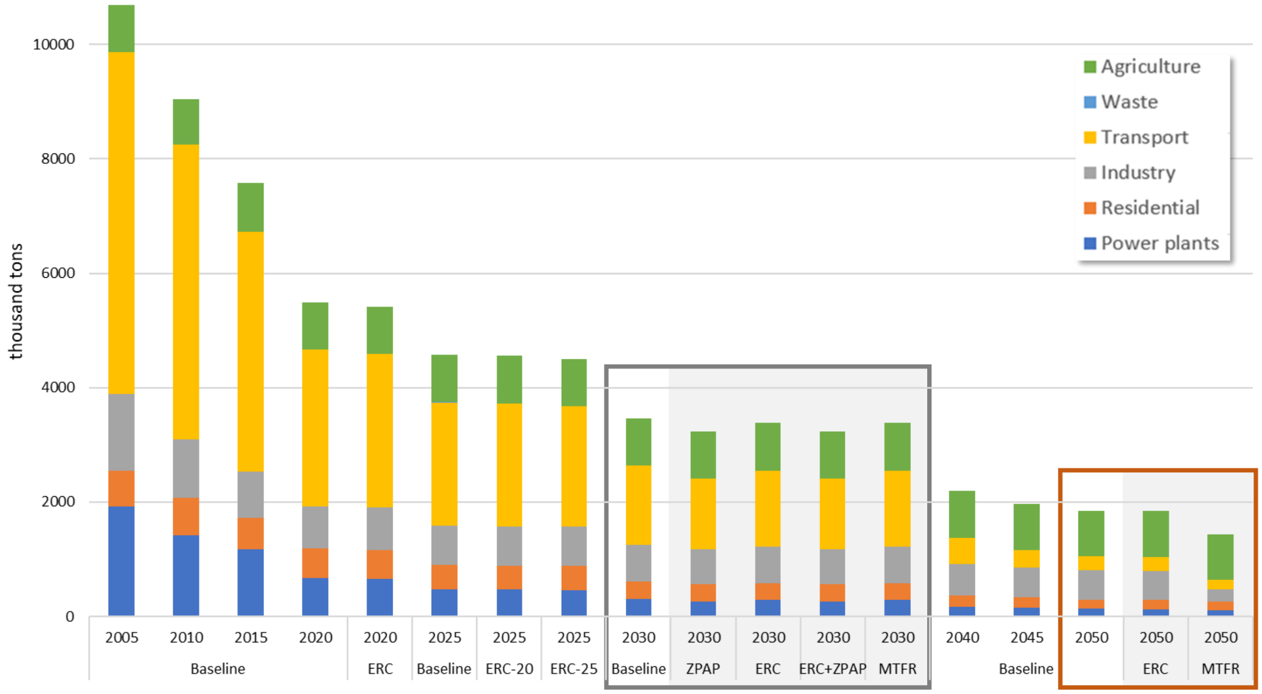


Figure 4-6: Emissions of $PM_{2.5}$ in the baseline and selected scenarios, EU total.

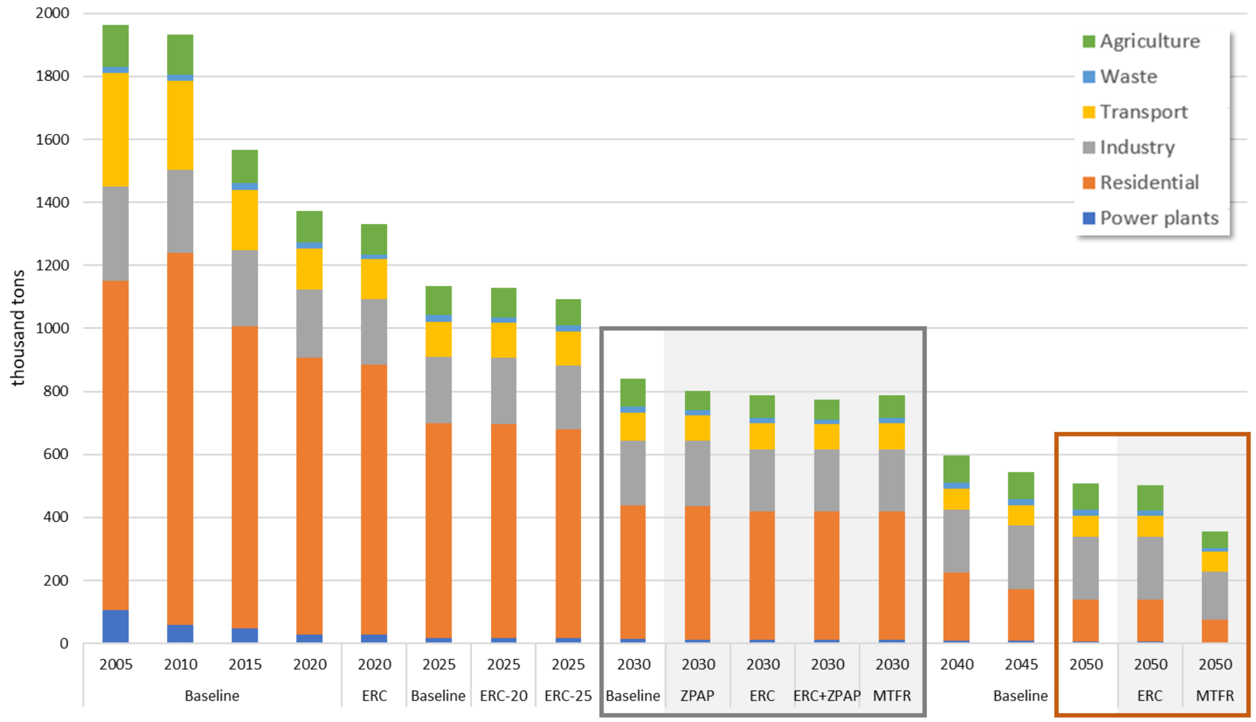


Figure 4-7: Emissions of NH_3 in the baseline and selected scenarios, EU total.

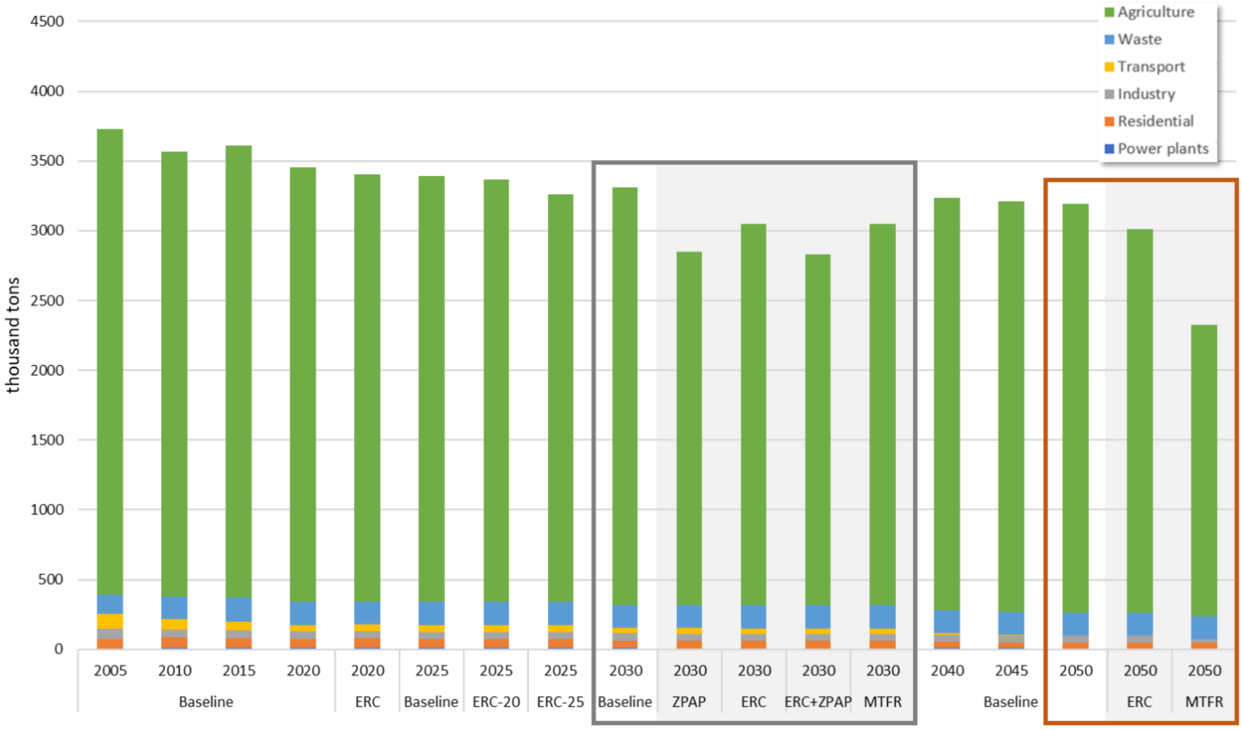
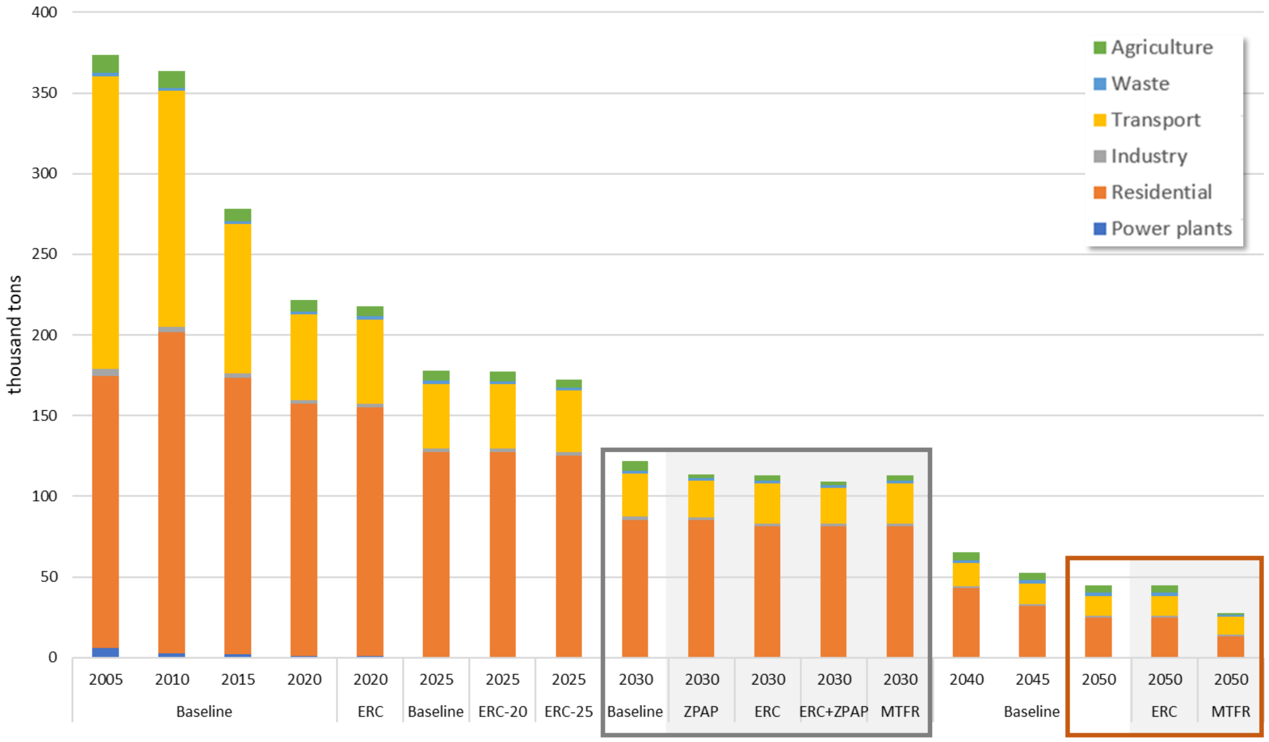


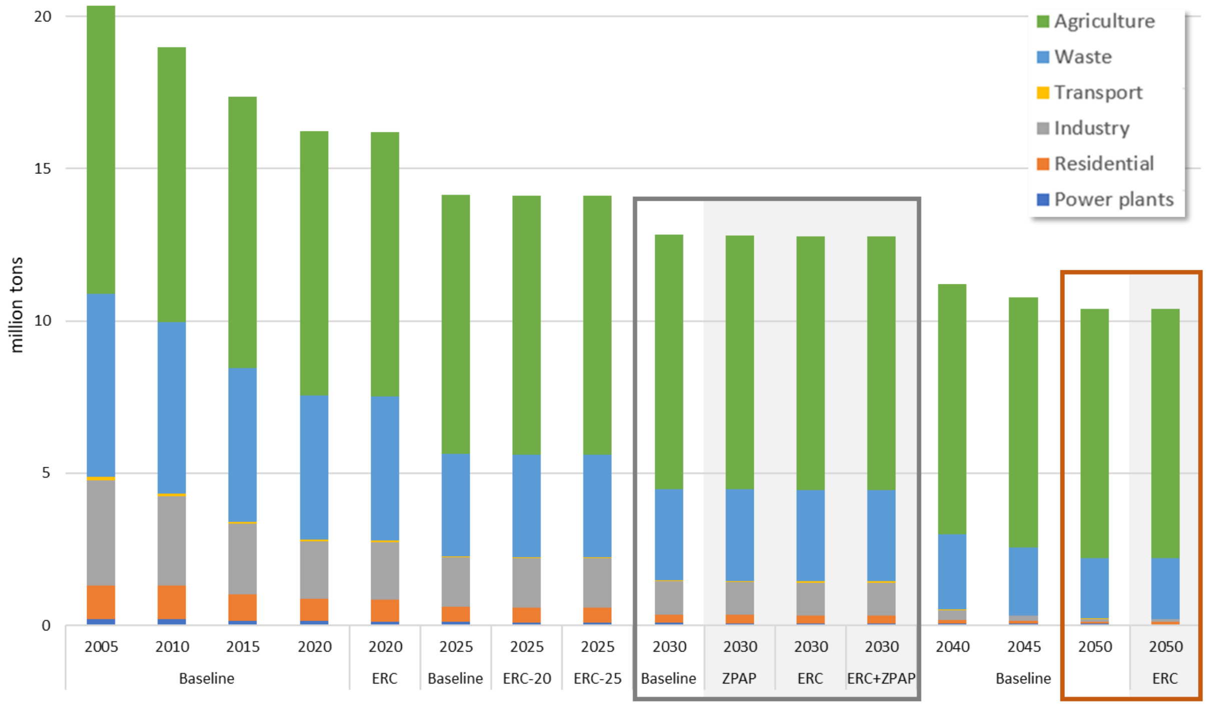
Figure 4-8: Emissions of NMVOC in the baseline and selected scenarios, EU total.

Figure 4-9: Emissions of black carbon (BC) in the baseline and selected scenarios, EU total.



Methane emissions for the developed scenarios have also been estimated (Figure 4-10). Emissions and future outlook are very similar to those presented in CAO3. Since 2005, emissions declined by over 30% and are expected to decline further reaching about 37% lower levels than estimated for 2005 by 2030. Compared to 2020, the expected reduction by 2030 is about 21%. Notably, the GAINS model underestimates the benefits of measures introduced in agriculture to achieve ZPAP targets (the impact of NH_3 dedicated housing and storage measures on CH_4 emissions is not considered in the current model formulation). By 2040, a reduction of 31% is estimated, compared to 2020, with key reductions from progressing decarbonization of economy and benefits of existing waste sector policies.

Figure 4-10: Emissions of CH_4 in the baseline and selected scenarios, EU total.



4.4.2 Compliance with the NEC Directive objectives

The following tables summarize for all NEC Directive pollutants and EU countries, the compliance with the NEC Directive ERCs for 2030 and 2050 for selected scenarios. The Annex (Section 6) provides analysis of compliance with the NEC Directive ERCs for 2020 and 2025 as well as assessment of the potential and feasibility for achieving them applying GAINS optimization to the 2020 and 2025 emissions.

For SO_2, the *Baseline* projections indicate that all countries will be in compliance in 2030 and beyond (Table 4-4).

Table 4-4: Comparison of % reductions achieved in 2030 and 2050, relative to 2005, in selected scenarios for SO_2.

	2030					2050		
Country	**2030 ERC**	**Baseline**	**ZPAP**	**ERC**	**MTFR**	**Baseline**	**ERC**	**MTFR**
Austria	41%	72%	72%	72%	76%	81%	81%	83%
Belgium	66%	83%	83%	83%	90%	87%	87%	95%
Bulgaria	88%	95%	95%	95%	98%	98%	98%	100%
Croatia	83%	92%	92%	92%	96%	93%	93%	97%
Cyprus	93%	96%	96%	96%	99%	97%	97%	99%
Czech Rep.	66%	86%	86%	86%	89%	95%	95%	97%
Denmark	59%	73%	73%	73%	78%	78%	78%	82%
Estonia	68%	98%	98%	98%	99%	99%	99%	100%
Finland	34%	82%	82%	82%	89%	87%	87%	92%
France	77%	85%	85%	85%	88%	89%	89%	93%
Germany	58%	67%	67%	67%	81%	82%	82%	90%
Greece	88%	97%	97%	97%	99%	98%	98%	99%
Hungary	73%	82%	82%	82%	88%	87%	87%	90%
Ireland	85%	94%	94%	94%	96%	96%	96%	98%
Italy	71%	85%	85%	85%	94%	90%	90%	95%
Latvia	46%	73%	73%	73%	77%	74%	74%	78%
Lithuania	60%	76%	76%	76%	90%	86%	86%	94%
Luxembourg	50%	71%	71%	71%	87%	76%	76%	90%
Malta	95%	99%	99%	99%	100%	100%	100%	100%
Netherlands	53%	80%	80%	80%	88%	83%	83%	90%
Poland	70%	85%	85%	85%	91%	95%	95%	98%
Portugal	83%	91%	91%	91%	96%	94%	94%	97%
Romania	88%	93%	93%	93%	97%	96%	96%	99%
Slovakia	82%	89%	89%	89%	97%	91%	91%	97%
Slovenia	92%	93%	93%	93%	95%	97%	97%	99%
Spain	88%	95%	95%	95%	98%	96%	96%	98%
Sweden	22%	68%	68%	68%	69%	77%	77%	77%
EU	78%	89%	89%	89%	94%	94%	94%	97%

For NOx, emissions of two countries were estimated above the ERCs for 2030, while all comply by 2050. Inclusion of soil NOx would lead to much more severe non-compliance (eight countries) with 2030 ERCs in 2030, but not in 2050 (Table 4-5).

Table 4-5: Comparison of % reductions achieved in 2030 and 2050, relative to 2005, in selected scenarios for NOx. Highlighted cells indicate non-attainment of the 2030 ERCs.

	2030						2050			
Country	2030 ERC	Baseline	Baseline+ Soil NOx	ZPAP	ERC	MTFR	Baseline	Baseline+ Soil NOx	ERC	MTFR
Austria	69%	78%	74%	80%	78%	84%	91%	86%	91%	95%
Belgium	59%	79%	74%	80%	79%	82%	92%	86%	92%	94%
Bulgaria	58%	69%	58%	73%	70%	80%	92%	79%	93%	96%
Croatia	57%	71%	65%	73%	71%	82%	86%	80%	86%	95%
Cyprus	55%	76%	73%	77%	76%	85%	87%	84%	88%	95%
Czech Rep.	64%	72%	64%	75%	74%	81%	90%	82%	91%	96%
Denmark	68%	75%	65%	76%	75%	79%	89%	79%	89%	91%
Estonia	30%	72%	63%	75%	72%	78%	89%	80%	90%	93%
Finland	47%	70%	66%	76%	70%	78%	86%	81%	86%	90%
France	69%	75%	68%	76%	75%	78%	92%	84%	92%	95%
Germany	65%	71%	66%	74%	72%	77%	88%	83%	89%	92%
Greece	55%	80%	77%	81%	80%	85%	90%	87%	90%	95%
Hungary	66%	67%	55%	70%	72%	78%	89%	75%	89%	93%
Ireland	69%	75%	61%	76%	75%	81%	90%	74%	91%	95%
Italy	65%	77%	74%	79%	77%	82%	90%	86%	90%	94%
Latvia	34%	55%	44%	62%	56%	67%	79%	66%	79%	88%
Lithuania	51%	57%	43%	61%	57%	70%	88%	73%	88%	94%
Luxembourg	83%	89%	88%	91%	90%	93%	95%	94%	95%	98%
Malta	79%	75%	74%	76%	79%	80%	91%	90%	91%	93%
Netherlands	61%	78%	73%	79%	78%	82%	89%	83%	89%	92%
Poland	39%	61%	54%	64%	61%	73%	87%	78%	87%	93%
Portugal	63%	74%	72%	78%	75%	84%	89%	86%	89%	95%
Romania	60%	56%	48%	65%	66%	75%	85%	73%	85%	93%
Slovakia	50%	66%	59%	69%	66%	81%	83%	76%	83%	94%
Slovenia	65%	70%	67%	73%	73%	76%	92%	88%	92%	95%
Spain	62%	79%	75%	81%	80%	86%	89%	85%	89%	93%
Sweden	66%	72%	65%	75%	72%	80%	86%	79%	86%	91%
EU	61%	73%	68%	76%	74%	80%	89%	83%	89%	93%

Nearly a third of Member States might be missing on compliance with the $PM_{2.5}$ ERCs in 2030 (Table 4-6), although several of these instances are rather small according to GAINS calculations, i.e., Cyprus, Denmark, Portugal, within 1% of ERCs. There exists mitigation potential that could be unlocked to achieve compliance. Compared to CAO3, the number of Member States, for which non-compliance with ERCs in 2030 is estimated, doubled, i.e. from 4 in CAO3 to 8 in CAO4. However, for Cyprus and Portugal the non-compliance is small, while for Czechia and Romania the difference is larger and driven by revised assessment of emissions for residential sector (Czechia and Romania) and also open burning of agricultural residue (Romania). The updates reflect new information and methods applied and are reflected in both the national inventories and GAINS for 2005 and 2030.

Table 4-6: Comparison of % reductions achieved in 2030 and 2050, relative to 2005, in selected scenarios for $PM_{2.5}$. Highlighted cells indicate non-attainment of the 2030 ERCs.

	2030						2050		
Country	2030 ERC	Baseline	Ref2_filter	High_C	ERC	MTFR	Baseline	ERC	MTFR
Austria	46%	66%	63%	66%	66%	77%	79%	79%	84%
Belgium	39%	62%	58%	63%	62%	72%	70%	70%	78%
Bulgaria	41%	65%	67%	61%	65%	75%	84%	84%	90%
Croatia	55%	74%	66%	77%	75%	83%	88%	90%	94%
Cyprus	70%	69%	70%	69%	70%	81%	69%	70%	80%
Czech Rep.	60%	54%	54%	43%	60%	66%	84%	84%	90%
Denmark	55%	55%	53%	53%	55%	68%	66%	66%	75%
Estonia	41%	75%	71%	74%	75%	84%	85%	85%	91%
Finland	34%	59%	63%	49%	59%	71%	72%	72%	81%
France	57%	63%	55%	72%	63%	73%	75%	75%	81%
Germany	43%	51%	50%	51%	51%	62%	61%	61%	68%
Greece	50%	70%	68%	72%	70%	78%	77%	77%	83%
Hungary	55%	43%	48%	38%	55%	57%	75%	76%	83%
Ireland	41%	73%	68%	74%	74%	80%	81%	81%	86%
Italy	40%	54%	56%	48%	54%	63%	70%	70%	79%
Latvia	43%	77%	67%	77%	77%	83%	88%	88%	92%
Lithuania	36%	62%	62%	64%	62%	76%	83%	83%	89%
Luxembourg	40%	71%	69%	71%	71%	74%	75%	75%	77%
Malta	50%	73%	74%	71%	77%	79%	74%	75%	80%
Netherlands	45%	50%	52%	46%	50%	61%	54%	54%	64%
Poland	58%	60%	59%	61%	60%	70%	84%	85%	90%
Portugal	53%	52%	48%	56%	53%	74%	67%	67%	84%
Romania	58%	39%	40%	32%	58%	61%	76%	76%	91%
Slovakia	49%	76%	74%	71%	76%	82%	86%	86%	90%
Slovenia	60%	41%	46%	40%	60%	61%	79%	79%	89%
Spain	50%	46%	43%	45%	50%	58%	55%	55%	65%
Sweden	19%	69%	64%	80%	69%	72%	70%	70%	73%
EU	50%	57%	55%	57%	60%	68%	74%	74%	82%

For $PM_{2.5}$, the comparison of attainment of ERCs also includes the two sensitivity scenarios where only filterable PM is included (Ref2_filter) and the scenario where high emission factors were used including condensables and bad combustion practices (High_C). Somewhat surprisingly, different variants do not change much the compliance issues. In fact, the case where high emission factors are used shows in some cases better ERC compliance; this is likely because the transformation towards cleaner residential heating installations in the baseline has the strongest impact on the very high condensable fraction of emissions which are reduced more efficiently than the solid fraction.

As indicated earlier, for NH_3, most Member States are estimated to be in non-compliance in 2030 as well as in 2050, under baseline assumptions (Table 4-7). Compliance with the IED and other currently implemented policies do not assure achieving necessary reductions in emissions. Interestingly, achievement of the ZPAP objective for eutrophication, shown here as a cost-optimal scenario, still leaves several Member States in projected non-compliance, though the situation would be much improved compared to the baseline. A dedicated scenario (ERC) shows it is feasible to meet the ammonia ERC in all Member States, apart from the Netherlands where GAINS does not identify enough mitigation potential to reach the ERC in 2030 or 2050 with technical measures. It appears that technical measures, which are already largely employed in the Netherlands, including application of measures on farms that are smaller than IED thresholds, are not sufficient. According to Dutch experts (from discussion during consultations), achievement of ERCs would necessitate structural changes in the agriculture system or behavioural changes which could help to achieve necessary reductions.

Table 4-7: Comparison of % reductions achieved in 2030 and 2050, relative to 2005, in selected scenarios for NH_3. Highlighted cells indicate non-attainment of the 2030 ERCs.

	2030					2050		
Country	**2030 ERC**	**Baseline**	**ZPAP**	**ERC**	**MTFR**	**Baseline**	**ERC**	**MTFR**
Austria	12%	11%	24%	12%	34%	16%	16%	40%
Belgium	13%	10%	19%	13%	25%	11%	13%	30%
Bulgaria	12%	6%	30%	12%	43%	7%	12%	49%
Croatia	25%	11%	33%	25%	48%	11%	25%	53%
Cyprus	20%	17%	27%	20%	32%	21%	21%	38%
Czech Rep.	22%	9%	19%	22%	22%	16%	22%	29%
Denmark	24%	20%	36%	24%	38%	25%	25%	45%
Estonia	1%	2%	13%	2%	18%	5%	5%	27%
Finland	20%	24%	33%	25%	37%	25%	25%	39%
France	13%	8%	20%	13%	28%	12%	13%	36%
Germany	29%	16%	25%	29%	31%	20%	29%	39%
Greece	10%	15%	25%	15%	32%	22%	22%	41%
Hungary	32%	11%	25%	32%	34%	18%	32%	41%
Ireland	5%	-7%	2%	5%	11%	-5%	5%	15%
Italy	16%	17%	28%	17%	35%	22%	22%	41%
Latvia	1%	-12%	-1%	1%	4%	-9%	1%	10%
Lithuania	10%	15%	23%	15%	28%	20%	20%	36%
Luxembourg	22%	8%	20%	22%	23%	16%	22%	32%
Malta	24%	26%	40%	26%	45%	27%	27%	51%
Netherlands	21%	12%	13%	13%	14%	12%	13%	14%
Poland	17%	5%	27%	17%	39%	0%	17%	39%
Portugal	15%	3%	17%	15%	26%	14%	15%	41%
Romania	25%	20%	29%	25%	33%	24%	25%	38%
Slovakia	30%	22%	42%	30%	45%	28%	30%	50%
Slovenia	15%	10%	20%	15%	31%	18%	18%	43%
Spain	16%	8%	23%	16%	39%	12%	16%	43%
Sweden	17%	14%	26%	17%	34%	13%	17%	37%
EU	19%	11%	24%	18%	32%	14%	19%	38%

Table 4-8: Comparison of % reductions achieved in 2030 and 2050, relative to 2005, in selected scenarios for NMVOC. Highlighted cells indicate non-attainment of the 2030 ERCs.

	2030					2050				
Country	2030 ERC	Baseline	Baseline+ Agr VOC	ZPAP	ERC	MTFR	Baseline	Baseline+ Agr VOC	ERC	MTFR
Austria	36%	58%	46%	58%	58%	67%	67%	52%	67%	75%
Belgium	35%	57%	50%	58%	57%	63%	66%	57%	66%	72%
Bulgaria	42%	50%	45%	53%	50%	63%	69%	63%	69%	79%
Croatia	48%	69%	65%	73%	69%	82%	78%	72%	79%	90%
Cyprus	50%	69%	63%	71%	69%	77%	77%	71%	77%	84%
Czech Rep.	50%	60%	56%	62%	64%	72%	80%	76%	80%	88%
Denmark	37%	62%	47%	66%	62%	77%	67%	52%	67%	82%
Estonia	28%	59%	52%	61%	60%	72%	63%	57%	63%	76%
Finland	48%	58%	54%	59%	58%	70%	72%	65%	72%	80%
France	52%	63%	55%	63%	63%	71%	70%	62%	70%	76%
Germany	28%	43%	37%	46%	43%	61%	51%	44%	51%	69%
Greece	62%	75%	72%	77%	75%	83%	82%	79%	82%	89%
Hungary	58%	56%	49%	58%	61%	67%	72%	61%	72%	79%
Ireland	32%	38%	23%	39%	38%	54%	40%	24%	40%	59%
Italy	46%	54%	48%	55%	54%	63%	64%	57%	64%	74%
Latvia	38%	52%	48%	53%	53%	70%	65%	59%	65%	83%
Lithuania	47%	46%	43%	51%	47%	61%	70%	62%	70%	82%
Luxembourg	42%	45%	34%	46%	45%	61%	55%	43%	55%	70%
Malta	27%	50%	47%	53%	52%	64%	63%	59%	63%	75%
Netherlands	15%	36%	25%	37%	36%	47%	47%	34%	47%	57%
Poland	26%	43%	38%	47%	43%	60%	59%	51%	59%	75%
Portugal	38%	49%	44%	53%	50%	63%	61%	55%	61%	72%
Romania	45%	49%	46%	57%	59%	67%	75%	68%	75%	87%
Slovakia	32%	54%	53%	57%	54%	70%	67%	65%	67%	82%
Slovenia	53%	49%	45%	51%	57%	65%	68%	62%	68%	79%
Spain	39%	40%	35%	41%	41%	54%	48%	42%	48%	61%
Sweden	36%	51%	45%	53%	51%	60%	60%	51%	60%	68%
EU	41%	52%	46%	54%	53%	65%	63%	55%	63%	74%

4.4.3 Indicators for exposure to $PM_{2.5}$

Ambient concentrations of $PM_{2.5}$ are modelled in GAINS using linear transfer coefficients to translate emissions of PM and precursor gases into ambient concentrations of $PM_{2.5}$ at a resolution of 0.1°. This includes a downscaling for PPM based on the uEMEP model which calculates the additional increment in population exposure arising from fine-scale (250×250m) local variation of $PM_{2.5}$ concentrations (Denby et al. 2024). In addition to the contributions from anthropogenic sources, concentrations of natural dust and sea salt modelled with the EMEP CTM are available in the model and are added for the purpose of producing maps of total $PM_{2.5}$. However, they are not included in the health impact calculations.

Consistent with CAO3, the GAINS model estimates health impact indicators following the health impact assessment methodology that has been recommended for Europe by the World Health Organization (WHO) in the HRAPIE project (WHO 2013) with updated concentration-response functions for $PM_{2.5}$ (Chen and Hoek 2020). The model quantifies risks from long-term exposure to $PM_{2.5}$

- for all-cause mortality,

- considering only population above 30 years age,
- employing long-term (annual mean) $PM_{2.5}$ levels that are typical for the exposure of a given population (e.g., $PM_{2.5}$ levels measured at urban background stations, but not at hot spots),
- applying a linear exposure-response function to all $PM_{2.5}$ caused by anthropogenic sources, and
- excluding exposure from natural sources of $PM_{2.5}$ (e.g., soil dust) in the assessment[33].

The systematic review undertaken for the 2021 WHO Air Quality Guidelines (Chen and Hoek 2020), which scrutinized a much wider range of epidemiological evidence than in 2013, confirmed the earlier findings of the HRAPIE project, suggesting that a linear relationship between concentration and relative risk for all-cause mortality from $PM_{2.5}$ gives the best fit. The recommended value for the risk ratio was increased to 1.08 per 10 $\mu g/m^3$ compared to 1.06 per 10 $\mu g/m^3$ found by HRAPIE.

Consistent with the previous Clean Air Outlooks, GAINS retains the principle to account – in its standard calculations presented in the main report – for all anthropogenic $PM_{2.5}$ for calculating health impacts. This is due to there being no conclusive evidence for a lower limit of $PM_{2.5}$ toxicity (or 'cut-off'). Natural $PM_{2.5}$ is excluded from the assessment, following the argument that natural $PM_{2.5}$ cannot be (significantly) influenced by policy measures. Thus, the local level of natural background $PM_{2.5}$ is used as a lower cut-off for the risk calculation.

Other assessments, notably the Impact Assessment for the AAQD, and the EEA Air Quality in Europe reports have employed a different approach and used the WHO Air Quality Guideline level (5 μgm^{-3}) as lower cutoff for health risk calculations, leading to lower total burden estimates. In order to allow for better comparability of the CAO4 results, a sensitivity analysis quantifying mortality for total $PM_{2.5}$ concentrations (including natural sources) above 5 μgm^{-3} is presented in the Annex (section 4.1.2). The GAINS analysis computes the following indicators for health impacts from $PM_{2.5}$:

- Mean population exposure to $PM_{2.5}$ in each Member State.
- Annual cases of premature deaths attributable to exposure to $PM_{2.5}$ are estimated assuming 2010 (i.e. static) population data, also for the future. Thereby, future demographic changes do not affect the distribution of mitigation efforts among Member States; this is also consistent with how the ZPAP targets were defined. However, the use of constant 2010 figures introduce inaccuracies in the assessment of future health benefits, which scale with the change in total population. Thus, the accompanying assessment monetizing the economic and health benefits from the policy scenarios employs dynamic population data that are projected for the different Member States. This is in line with the approach used in the previous Clean Air Outlooks.

GAINS also provides other indicators, specifically the loss of statistical life expectancy and Years of Life Lost (YOLLs, YLL). The definition of these indicators and respective results are reported in the section 4.1 of the Annex.

Figure 4-11 shows annual mean concentrations of $PM_{2.5}$ calculated with the GAINS model for the period 2005 to 2050 for selected scenarios. In 2005, there were several regions in the EU not complying with the EU legislation limit values (25 $\mu g/m^3$), but the concentrations keep declining and by 2030, there are very few areas exceeding 25 $\mu g/m^3$ (estimated less than 0.3 % of the EU population, Figure 4-12), with a further decline by 2050 when no areas exceeding 20 $\mu g/m^3$ are seen. At the same time, in 2030 and even in 2050, large areas (and populations, see Figure 4-12) are exposed to levels well above the current WHO air quality guideline of 5 $\mu g/m^3$.

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[33] While natural sources are excluded from the health impact assessment, they are included in figures showing total $PM_{2.5}$ concentrations (maps, exposure distribution).

Figure 4-11: Annual mean concentrations of $PM_{2.5}$ (including natural sources) in 2005, 2025, compliance with ERCs (within feasibility) and MTFR cases for 2030 and 2050.

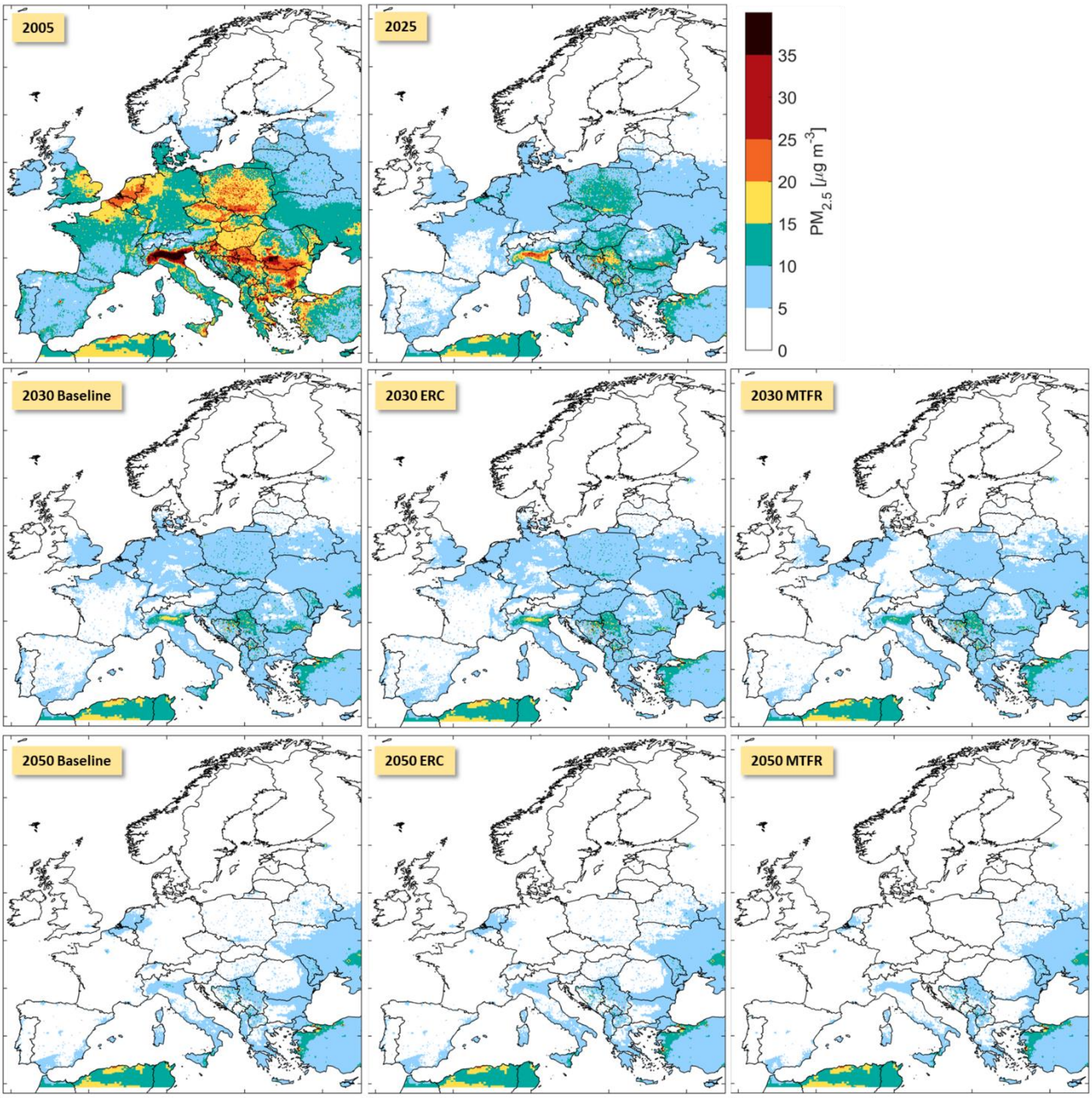


Figure 4-12 illustrates the impact of policies included in the *Baseline* and selected scenarios on the population exposed to various levels of $PM_{2.5}$. In 2005, less than 3 million people (or less than 1% of the EU population) enjoyed clean air (defined as per 2021 WHO recommendations) and a much larger number (about 66 million) was exposed to $PM_{2.5}$ levels exceeding the EU limit values at the time (25 µg/m^3). It is estimated that since 2005, air quality has improved significantly (illustrated by calculation for 2025), reducing exposure to levels above 15 µg/m^3. Close to two thirds of the EU population is exposed to levels below the WHO Interim Target 4 of 10 µg/m^3 (which is the new limit value introduced by the revised AAQD for 2030).

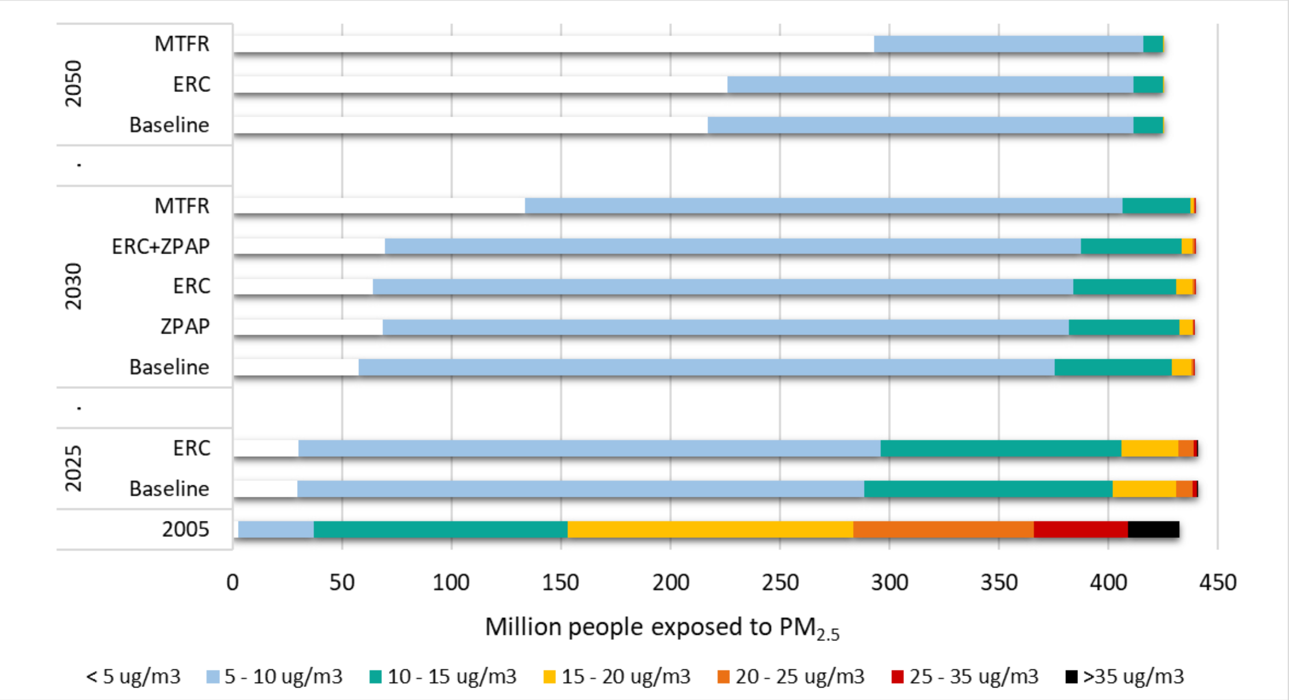
As discussed earlier, concentrations drop owing to successful introduction of air quality and decarbonization policies, although in 2030 nearly 15% of population would still be exposed to levels above 10 µg/m^3 if no further action is taken (but with all current legislation effectively enforced, including Fit for 55 package). Only

13% of EU population (or about 60 million persons) would live in areas where concentrations would be below the 2021 WHO recommendation (5 µg/m^3). This number would increase to 70 million (or 16% of EU population) assuming full compliance with the NEC Directive emission reduction commitments and the ZPAP targets in 2030. Implementation of the *MTFR* scenario could double the number of people exposed to levels below 5 µg/m^3 and reduce the number of those exposed to levels above 10 µg/m^3 also by nearly half to about 7% of total EU, compared to the Baseline.

Significant further improvements are expected by 2050, where in the Baseline more than half of the EU population (or nearly 220 million) would be exposed to levels below 5 µg/m^3 and only about 3% to levels above 10 µg/m^3. Further potential exists, as shown in the MTFR case for 2050.

Overall, the results for 2005, Baseline, and MTFR scenarios are comparable to CAO3 results, although for 2030, the CAO4 indicates that less population will be enjoying concentrations below 5 µg/m^3 in the Baseline as well as in the MTFR. For the Baseline, this is the result of higher $PM_{2.5}$ emissions from residential combustion sector in CAO4 (driven by slightly higher consumption of solid fuels, i.e., coal and biomass, revised data and assumptions on structure of installations, and consistent inclusion of condensable PM for all Member States) and lower ambition (compared to CAO3) for IED in agriculture since ammonia is a PM precursor. For the MTFR, major reason is a slightly less optimistic outlook for the feasible pace of upgrade of the solid fuel heating stoves and boilers in the residential sector.

Figure 4-12: Population in the EU exposed to different concentrations of $PM_{2.5}$ for selected key scenarios (total $PM_{2.5}$ including natural sources).



The picture is less homogenous for individual countries (Figure 4-13), foremost in 2005, where large differences in exposure distribution are visible (as was evident from the concentration maps), but also in pace of improvement over time. The strong decline in emissions of precursors of $PM_{2.5}$ in the last decades, especially in power plants, industry, and transport, is clearly visible in exposure change since 2005 for all EU countries. Currently, only small shares of population in some countries are exposed to $PM_{2.5}$ levels above 25 µg/m^3. However, there are also only a few countries (Estonia, Finland, Ireland, Sweden) where a majority of the population lives in areas with concentration levels consistent with the WHO AQG of 5 µg/m^3. Assuming effective implementation of existing and planned policies, concentrations are estimated to fall further in all countries in the *Baseline* scenario. While small number of people will face pollution levels in excess of 10-20 µg/m^3, most of the population in most of the EU countries will be still exposed to levels beyond 5 µg/m^3.

While there is scope for improvement in all Member States, in some countries, i.e., Malta, Italy, Romania, and Greece, GAINS results show that over 10% of population would be exposed in 2030 to $PM_{2.5}$ levels above 10 µg/m^3 even in the *MTFR* case, which in these countries does not allow to improve the exposure situation much beyond the *Baseline*. The reasons differ by country – for example Malta has high natural dust background levels, while Italy has high anthropogenic emissions in some regions (e.g., in Po-Valley) which cannot be eliminated by 2030 in GAINS optimisation due to model-built limitations on implementation rates of technologies and stock turnover. The distribution of exposure for the scenario where 2030 ERCs are achieved for all Member States and all PM precursors (within feasibility) shows slight improvement over *Baseline* at the EU level, with more pronounced improvements in some Member States such as Romania, Slovenia, Bulgaria. While the *MTFR* scenario, in 2030, shows further potential, it is not very large, indicating that there is only limited further technological potential available within a rather short time (less than a decade). As discussed earlier, further improvement is expected and possible, introducing also further structural changes in energy system and agriculture, however, in the longer term.

Figure 4-13: Share of population in the EU and MS exposed to different levels of $PM_{2.5}$ concentrations in 2005, currently (2025), and in 2030 in selected scenarios (total $PM_{2.5}$ including natural sources).

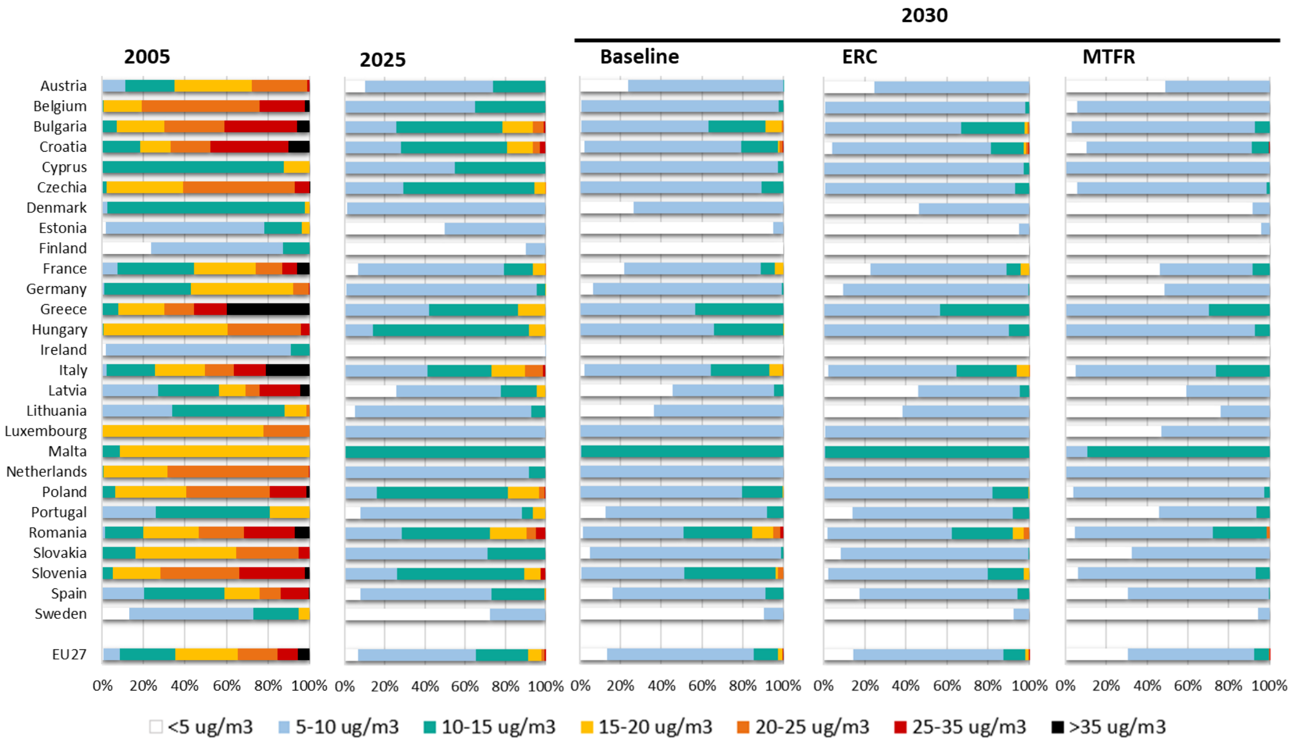


Figure 4-14 and Table 4-9 summarize the estimates of premature mortality from $PM_{2.5}$ using static population assumptions (constant population in 2010). The comparison shows for Baseline and ERC scenarios a decline in premature deaths (related to 2005) of about 62-75% in 2030 and 2050, and up to a 79% reduction by 2050 in the MTFR scenario. The ZPAP target of reducing premature deaths by 55% in 2030, compared to 2005, is achieved in the *Baseline*. This result demonstrates the impact and air quality benefits of the clean air and decarbonisation policies included in the *Baseline*, provided they are fully implemented.

A shown in Section 4.4.2, several Member States were not in compliance with ERCs for NEC Directive pollutants in 2020 and beyond, especially for NH_3, but in earlier years also for other precursors of ambient $PM_{2.5}$. A scenario was developed to estimate the benefit of full compliance with the ERCs in 2020, 2025, 2030 and beyond. This scenario is shown in Figure 4-14 as *ERC* assuring compliance with 2020 ERC for 2020, linear interpolation between 2020 and 2030 ERCs for 2025, and 2030 ERCs for 2030; and as *ERC 2020* where compliance with 2020 ERCs (rather than with the linear interpolation) for 2025 is enforced. The results indicate that in the period 2020 to 2030, about 1.6-3.3% of premature deaths (5,000 to 7,000, depending on the year) could have been avoided, except for 2025 in the *ERC 2020* case where the benefit would have been small (about 1,000).

Achieving ZPAP targets for eutrophication would result in the additional benefit (compared to the ERC scenario in 2030) of about 1400 avoided premature deaths while assuring also compliance with ERCs (ERC+ZPAP) could avoid nearly 5000 additional premature deaths, compared to the ERC (Table 4-9).

Figure 4-14: Comparison of the cases of premature deaths attributable to the exposure to total anthropogenic $PM_{2.5}$ in the EU, for the analysed scenarios. The marked 55% reduction of 2005 premature deaths refers to the ZPAP target.

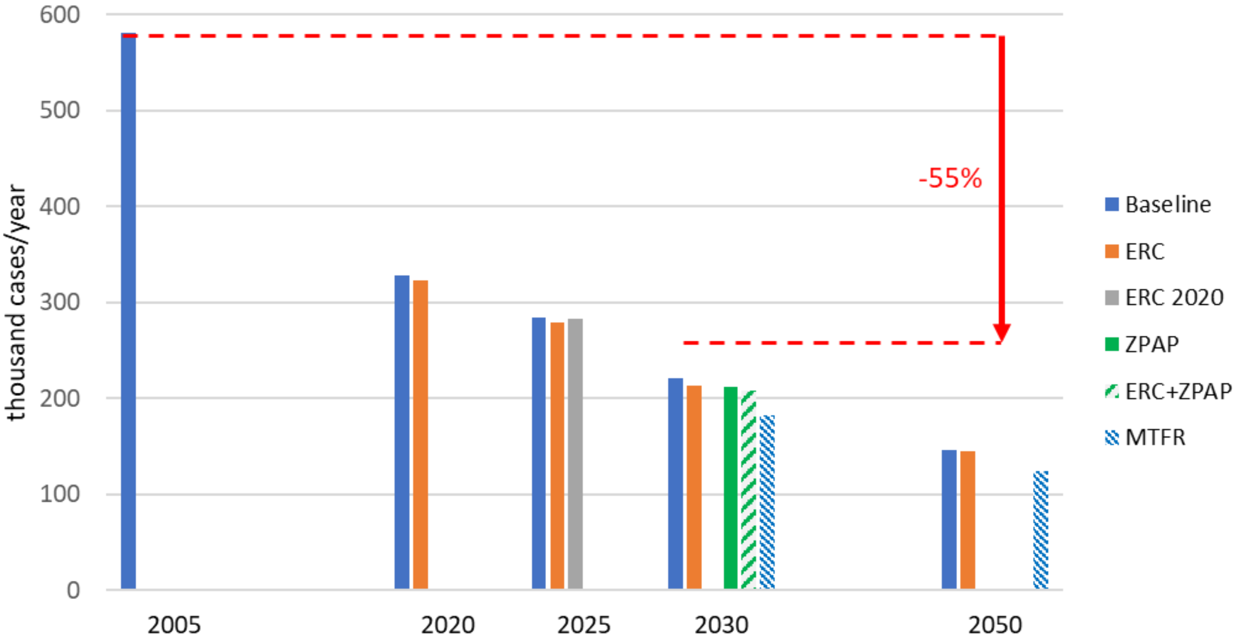


Table 4-9: Cases of premature death attributable to the exposure to $PM_{2.5}$ in the EU; thousand cases per year, using constant 2010 population data.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Premature deaths attributable to the exposure to total anthropogenic $PM_{2.5}$										
Baseline	581	507	412	329	284	221	182	163	153	147
ERC				323	279	213		160		145
ERC 2020					283					
ZPAP						212				
ERC+ZPAP						209				
MTFR						183		134		125

Table 4-10: Population-weighted $PM_{2.5}$ concentrations in the EU, incl. and excl. natural sources.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population-weighted $PM_{2.5}$ concentrations considering anthropogenic and natural sources (µg/m^3)										
Baseline	18.5	16.2	13.3	10.7	9.3	7.4	6.3	5.7	5.4	5.2
ERC				10.5	9.2	7.2		5.6		5.2
ERC 2020					9.3					
ZPAP						7.1				
ERC+ZPAP						7.				
MTFR						6.3		4.8		4.6
Population-weighted $PM_{2.5}$ concentrations considering anthropogenic only (µg/m^3)										
Baseline	17.8	15.5	12.6	10.0	8.7	6.7	5.6	5.0	4.7	4.5
ERC				9.8	8.5	6.5		4.9		4.5
ERC 2020					8.6					
ZPAP						6.5				
ERC+ZPAP						6.4				
MTFR						5.6		4.1		3.9

Further results for health indicators are provided in the section 4.1 of the Annex.

4.4.4 Indicators for exposure to ground-level ozone

Following the recommendation of the WHO/HRAPIE project, two impact indicators for ground-level ozone are provided:

- Annual cases of premature deaths attributable to ozone exposure (using constant 2010 population data), and
- The SOMO35 exposure indicator, calculated as the sum of the daily exceedances of maximum 8-hour ozone concentrations over 35 ppb threshold, summed over the whole year. SOMO35 indicator is calculated with a spatial resolution of 0.1×0.1° longitude/latitude and then multiplied by the population exposed in each of the grids.

Contrary to CAO3 report, the calculation of ozone concentrations has not been done with the GAINS model but with the EMEP model (as discussed earlier in the method section). The results for the Baseline and other scenarios for which EMEP model calculated ozone concentrations, have been prepared for the ALPHA-RiskPoll model, which was used to calculate ozone impacts, specifically premature deaths as shown in Figure 4-15 and Table 4-11. There is a steady reduction in estimated premature deaths reaching about 14% by 2030 in the Baseline, compared to 2005. The other scenarios, and even MTFR, do not achieve more than 18% reduction in premature deaths. These changes are similar to the trends calculated for SOMO35.

Compared to CAO3, the overall downward trends in SOMO35 and premature deaths are less pronounced than in CAO3, as a result of using EMEP model calculations of ozone in CAO4 rather than GAINS estimates. In CAO4, SOMO35 in future years is about 30% higher than in CAO3 (the same applies to premature death estimates), while for 2005 the CAO4 estimate of SOMO35 is lower than CAO3 by nearly 20%. These differences are primarily due to the interplay of three factors:

(i) An updated chemistry scheme implemented in the EMEP model after the generation of the transfer coefficients for GAINS used in CAO3, leading to higher ozone production rates and thus a (more or less constant) offset,

(ii) the assumptions about boundary conditions (inflow from the rest of the world) which are dynamic (changing over time) in the EMEP model simulations for CAO4 but were assumed constant in the source receptor runs for GAINS. Because O_3 inflow from the rest of the world increased from 2005 to 2020, the decrease in European O_3 between 2005 and 2020 is smaller in CAO4 than in CAO3.

(iii) the impact of non-linearity in ozone chemistry which is not reflected in the linear GAINS approach; this is most relevant for 2005 where the atmospheric composition is rather different from the 2030 baseline case for which the GAINS atmospheric coefficients were developed. In particular, titration (destruction of ozone by NO in the vicinity of strong NOx emission sources like cities) and its change over time cannot be represented well in a linear approach – the impact being that GAINS would tend to overestimate ozone in some highly populated areas, in the earlier years when NOx emissions are still relatively high, facilitating titration.

Figure 4-15: Cases of premature deaths attributable to the exposure to ground-level ozone in the EU.

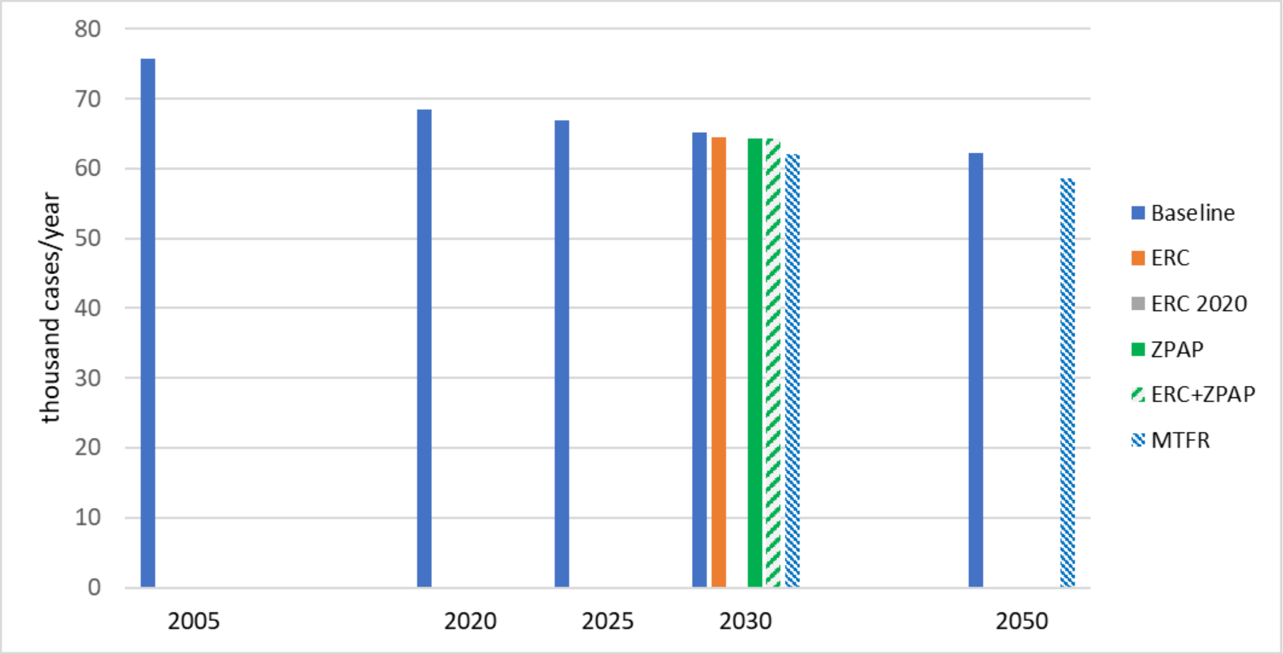


Figure 4-16: Population-weighted SOMO35 indicator (ppb days) in the EU.

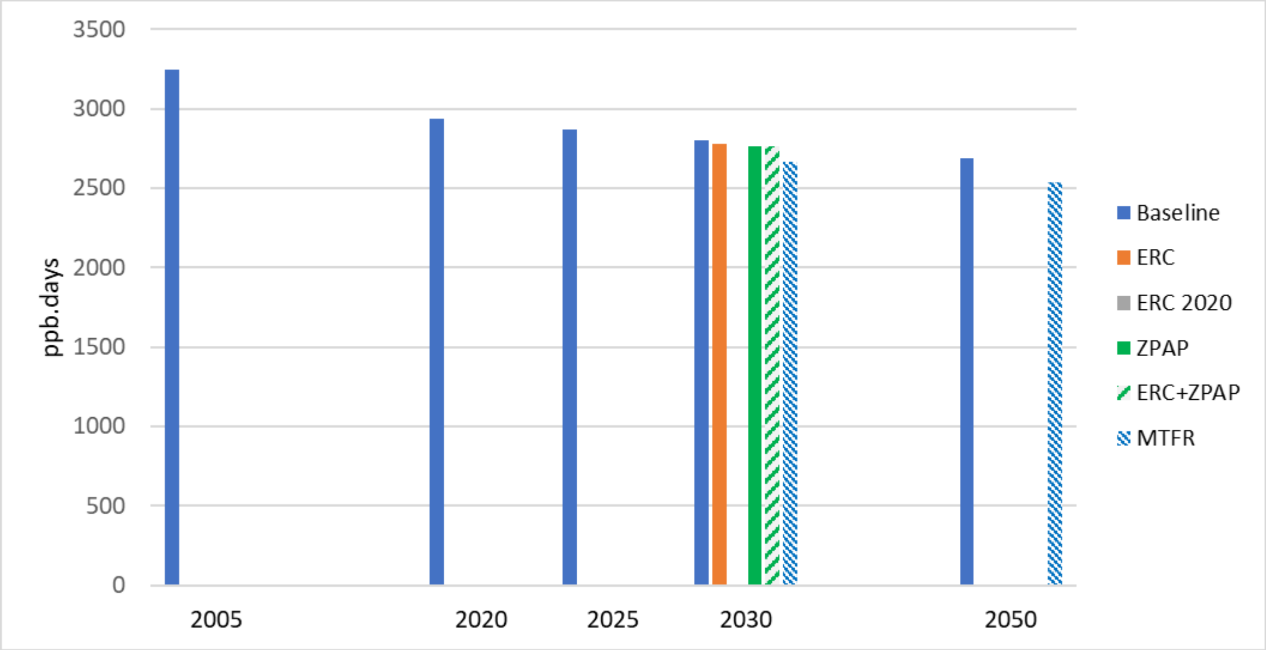


Table 4-11: Ground-level ozone-related health impact indicators for the EU.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Cases of premature deaths attributable to the exposure to ground-level ozone (thousand cases per year)										
Baseline	75.7			68.4	66.8	65.1		62.7		62.3
ERC						64.5				
ERC 2020										
ZPAP						64.3				
ERC+ZPAP						64.3				
MTFR						62.0		59.1		58.6
Population weighted SOMO35 (ppb.days)										
Baseline	3248			2937	2871	2801		2710		2694
ERC						2775				
ERC 2020										
ZPAP						2766				
ERC+ZPAP						2765				
MTFR						2666		2552		2536

4.4.5 Indicators for exposure to NO_2

Exposure to NO_2 has been associated with mortality and morbidity from a range of respiratory diseases. The systematic review undertaken for the 2021 WHO Air Quality Guidelines (Huangfu and Atkinson 2020) found evidence for a linear relationship between NO_2 concentration all-cause mortality with a relative risk of 1.02 per 10 μgm^{-3}. The calculation of NO_2 concentrations in GAINS relies on the atmospheric transfer coefficients that include downscaling, which approximates the calculations of the uEMEP model at 250m resolution (this update of the GAINS model, compared to CAO2, was discussed and applied already in the CAO3 work).

The 2021 WHO Air Quality Guideline has been set at 10 $\mu g/m^3$ annual mean NO_2, a value which is currently still exceeded widely in Europe (Figure 4-17). The guideline represents the lower limit of conclusive evidence but does not exclude health impacts below this value. For NO_2, the analysis presented below calculates health impacts considering the full concentration range without any cut-off. As a sensitivity analysis, results with a cut-off at the WHO Air Quality Guideline level are presented in the Annex.

The GAINS analysis computes the following indicators for health impacts from NO_2:

- Mean population exposure to NO_2 in each Member State.
- Annual cases of premature deaths attributable to exposure to NO_2 are estimated in a consistent manner with the approach used for $PM_{2.5}$. The numbers of attributable deaths from NO_2 and from $PM_{2.5}$ are calculated independently and are not additive due to the potential overlap of effects from both pollutants (more detailed discussion of that aspect has been provided in the Annex of the support to CAO3 report[34] (Klimont et al., 2022)).

Population exposure distribution has been estimated for 2005, current situation and future scenarios and is summarized in Figure 4-17.

In 2005, over 30% of the EU population (or about 135 million) were exposed to annual mean NO_2 concentrations below the current WHO air quality guideline value of 10 µg/m^3, however, about 20% of population (or nearly 90 million people) experiences levels above the current limit value of 40 µg/m^3. According to GAINS estimates, this has improved, reducing current exposure to levels above the current limit value to about 3% of population (or about 15 million) while nearly 60% are exposed to levels below WHO guidance in 2025.

Effective implementation of current and proposed policies (as assumed in the *Baseline*) is expected to bring significant further improvements leading to near elimination of exceedances of current limit values (remaining at about 1% of population in 2030 and less than 0.1% in 2050) and increasing population share exposed to levels below WHO AQG to about 72% and 97% in 2030 and 2050, respectively. Compliance with the ZPAP objectives as well as with the ERCs would result in additional reduction of exposure, bringing further 13 million people within exposure consistent with the WHO AQG by 2030. Some further potential to reduce emissions and consequently exposure is estimated for the *MTFR*. The *MTFR* scenario allows to slightly reduce exposure to concentrations above 40 µg/m^3 and a more pronounced change for increasing share of population enjoying concentrations below WHO guideline, i.e., to nearly 80% in 2030 and over 98%, or 417 million, by 2050.

These exposure distributions are comparable to the CAO3 results with a slightly larger share of population exposed to levels above 10 µg/m^3 in 2030, but a more optimistic outlook towards 2050 where even less population is exposed to levels above the WHO AQG.

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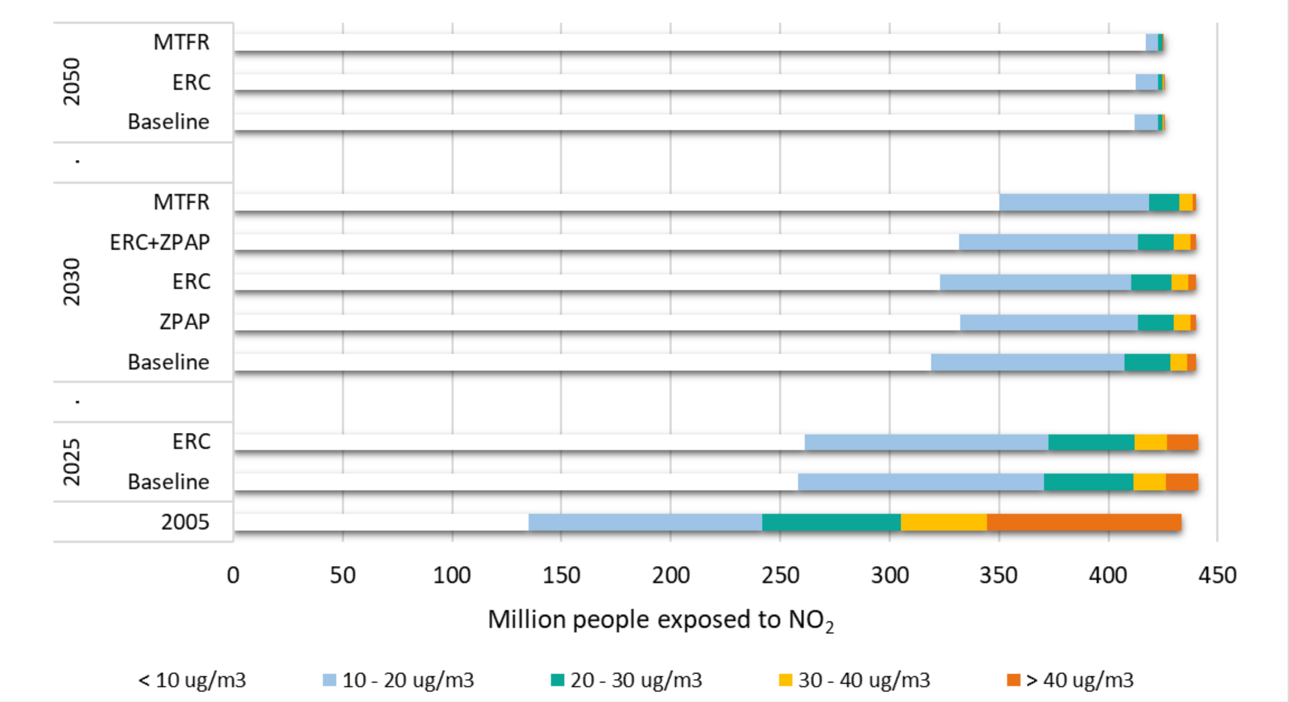
[34] https://environment.ec.europa.eu/topics/air/clean-air-outlook_en

Figure 4-17: Population in the EU exposed to different concentrations of NO_2 for selected key scenarios.



Compared to 2005, the number of premature deaths attributable to exposure to NO_2 is expected to decline in the *Baseline* by about 65% and 85%, considering total NO_2 from anthropogenic sources (Figure 4-18,Table 4-12). As discussed above for population exposure, the further mitigation potential (MTFR) exists and brings further improvement especially with respect to reduction of premature deaths attributable to exposure above 10 µg/m^3 (see Annex). In relative terms, compared to *Baseline*, further reductions could be in order of 17-37%, depending on the time period with declining additional benefits in the longer-term horizon, owing to strong decarbonization in the *Baseline* scenario.

Similarly to the assessment for population exposure, these results are comparable to CAO3 with higher number of premature deaths estimated for 2030, but a slightly more positive long-term outlook. The slight increase in 2030 (compared to CAO3) is likely linked to the revised estimates of soil NOx emissions and lesser impact of Euro 7 in 2030.

Figure 4-18: Comparison of the cases of premature deaths attributable to the exposure to total NO_2 (including all sources) in the EU, for the analysed scenarios.

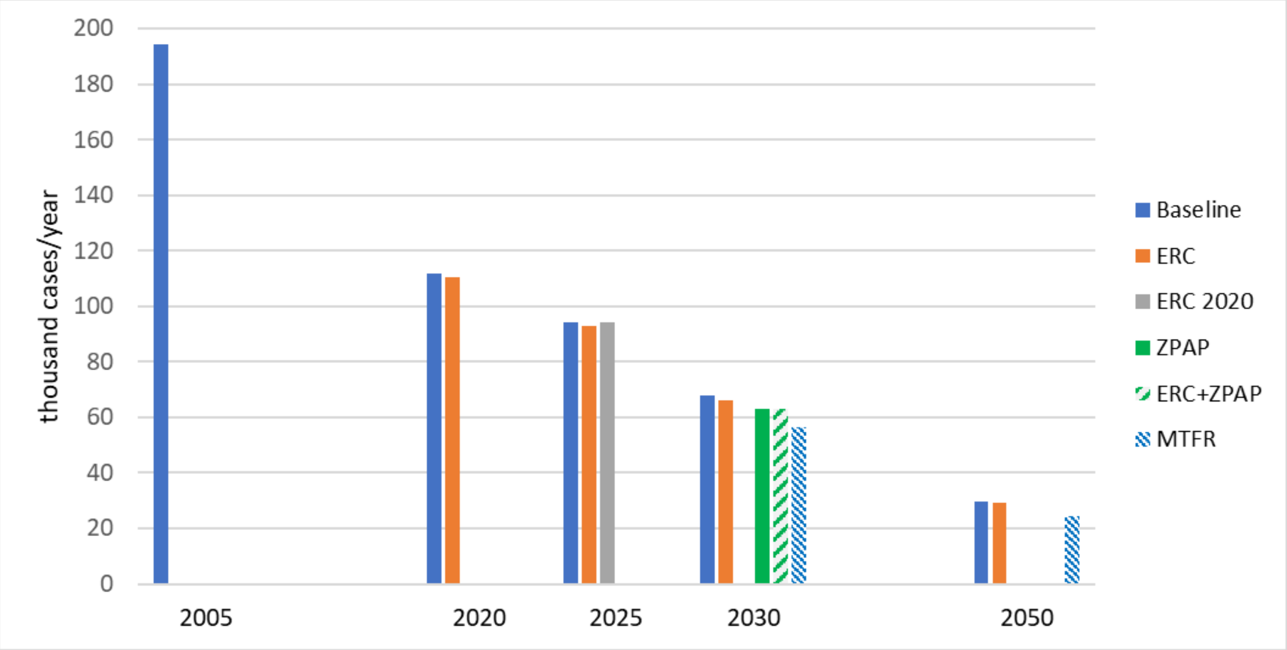


Table 4-12: Cases of premature death attributable to the exposure to NO_2 in the EU; thousand cases per year, using constant 2010 population data.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Premature deaths attributable to the exposure to total NO_2 originating from all sources, no cut-off										
Baseline	194.3		151.1	111.7	94.3	68.0		37.0		29.6
ERC				110.2	92.8	66.1				29.4
ERC 2020					94.0					
ZPAP						62.9				
ERC+ZPAP						62.9				
MTFR						56.5		29.8		24.3

Table 4-13: Population-weighted NO_2 concentrations in the EU; µg/m³.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population-weighted total NO_2 concentrations, no cut-off, all sources (µg/m³)										
Baseline	24.4		18.9	13.9	11.7	8.4		4.6		3.7
ERC				13.7	11.5	8.2				3.7
ERC 2020					11.7					
ZPAP						7.8				
ERC+ZPAP						7.8				
MTFR						7.0		3.7		3.0

4.4.6 Ecosystem impact indicators

Consistent with the previous Clean Air Outlook reports, this section provides evolution of the selected ecosystem impacts indicators for the key scenarios. The assessment relies on the most recent critical load (CL) data on eutrophication and acidification[35] (updated in 2021 and used in CAO3 study). This dataset relies on the submissions by the Member States and non-EU countries that were evaluated and accepted by the Coordination Centre for Effects (CCE) of the Working Group on Effects (WGE) under the Air Convention (UNECE LRTAP Convention).

For calculating ozone concentrations, AOT40 (accumulated ozone exposure above a threshold of 40 ppb), and phytotoxic ozone doses (PODs), the EMEP chemical transport model was run for Europe on a resolution of 0.1° × 0.1°, using the relevant emission scenarios as input. These results were used to calculate ozone effects on ecosystems as well as effects on agricultural yields.

In particular, the following indicators are presented here:

- The total ecosystems area in the EU where acid deposition exceeds the critical loads for acidification (in km^2 and as percentage of the total ecosystem area in the EU).
- The total ecosystems area in the EU where nitrogen deposition exceeds the critical loads for eutrophication (in km^2 and as percentage of the total ecosystem area in the EU).
- The total area of *Natura2000* ecosystem protection zones where N deposition exceeds CL for eutrophication.
- The forest area at risk from ozone quantified as the area with AOT40 levels exceeding the critical exposure level of 10,000 $\mu g/m^3$ h, as defined in the Manual on Mapping Critical Levels for Vegetation[36] by the International Cooperative Programme on Effects of Air Pollution on Natural Vegetation and Crops (ICP-Vegetation) of the UNECE Air Convention's Working Group on Effects. Effects on forest yield and carbon sequestration have been calculated with the ALPHA-RiskPoll model using POD. These are shown only for the Baseline and methane sensitivity scenarios for 2040 and 2050; see section 4.4.8.
- Effects on agricultural yields have been calculated from PODs suitable for integrated assessment modelling (i.e., POD3IAM metrics, see Simpson et al. (2022a)). The POD values will be combined with spatially resolved data on crop yields and exposure-yield relationships from the literature to estimate yield losses at least for wheat.

Ecosystem impact assessment shows a significant improvement in the *Baseline* with respect to exceedance of CL for acidification (Figure 4-19, Table 4-14) but much less improvement for eutrophication (Figure 4-20, Table 4-15). More detail for the protection of *Natura2000* areas is shown in the Annex and the results for ozone impacts on vegetation (via the AOT40 indicator) are reported in Section 4.4.8.

The share of ecosystems with excess acid deposition drops by 2030 to below 3% of ecosystem area in the EU in the *Baseline*; compared to 2005 the affected area is reduced by over 80% and declines further to below 2% in 2050 (Table 4-14). Scenarios aiming at achievement of goals outlined by ZPAP for reducing eutrophication and MTFR bring further reduction in excess deposition resulting in still significant relative improvements (25 to 45%, compared to the level in the *Baseline*), although the overall level of excess deposition is already rather low across most areas.

These results are very similar to the assessment presented in CAO3.

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[35] For natural terrestrial and freshwater ecosystems

[36] https://unece.org/fileadmin/DAM/env/documents/2017/AIR/EMEP/Final__new_Chapter_3_v2__August_2017_.pdf

Figure 4-19: Ecosystem area in the EU where the critical loads for acidification are exceeded.

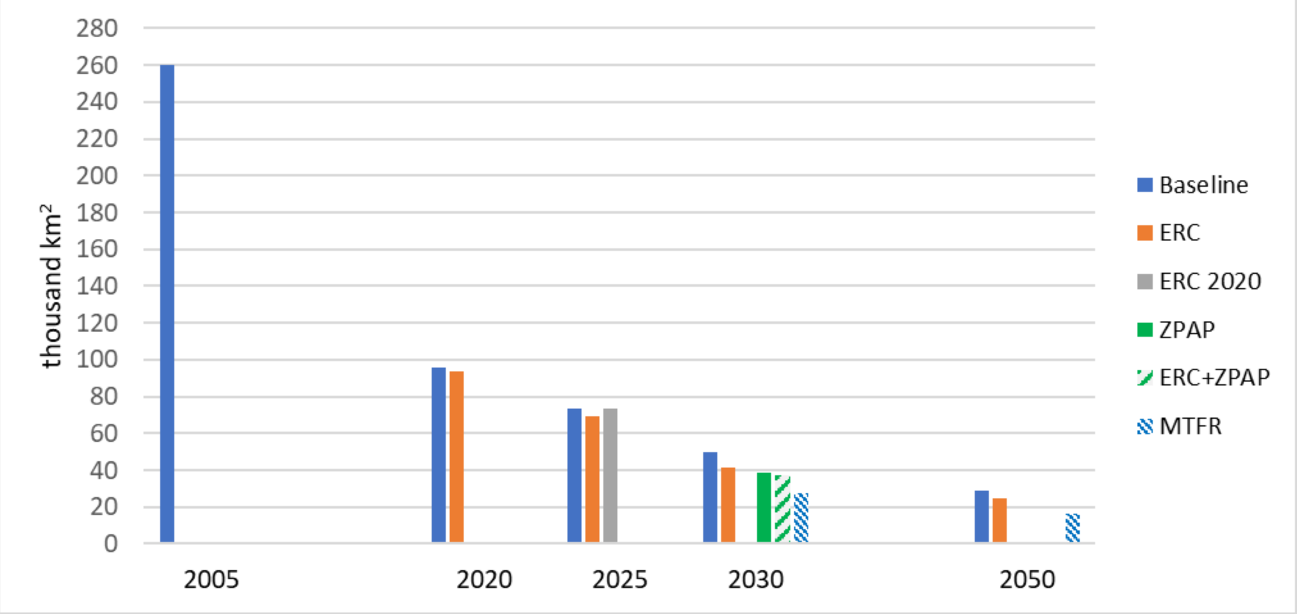


Table 4-14: Ecosystem area in the EU where the critical loads for acidification are exceeded.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Ecosystem area with acid deposition exceeding critical loads for acidification (1000 km²)										
Baseline	260.3	195.1	155.1	95.6	73.5	49.5	36.8	32.3	30.0	28.8
ERC				93.4	69.3	41.7		27.4		25.0
ERC 2020					73.2					
ZPAP						38.5				
ERC+ZPAP						37.5				
MTFR						27.4		17.9		16.4
Ecosystem area with acid deposition exceeding critical loads for acidification (% of total ecosystem area)										
Baseline	15.1	11.4	9.0	5.6	4.3	2.9	2.1	1.9	1.7	1.7
ERC				5.4	4.0	2.4		1.6		1.5
ERC 2020					4.3					
ZPAP						2.2				
ERC+ZPAP						2.2				
MTFR						1.6		1.0		1.0

The status and progress in reducing eutrophication is much less optimistic than that for acidification. Nearly 70% of ecosystems remain affected by eutrophication in 2030. While this is a reduction by about 19 %, compared to 2005, it comes short of the ZPAP target of 25% (Figure 4-20, Table 4-15). The 25 % reduction, compared to 2005, of the EU ecosystems area with nitrogen deposition exceeding the critical loads for eutrophication is achieved by 2030 in the *ZPAP* and *MTFR* scenarios, where for the latter a reduction of 31 % are estimated by 2030. At the same time, even in the *MTFR* case, only about 41 % of the EU ecosystems area are protected from eutrophication in 2030. In a longer term, further improvements are achieved in all scenarios, however, even in the *MTFR* case for 2050, about 52 % of ecosystem area remains unprotected from eutrophication. Similar, although slightly more optimistic, outlook is assessed for *Nature2000* nature protection areas where in the Baseline a 23 % reduction is achieved, close to the 25 % target. In the ZPAP scenario that reduction is nearly 30 %; for detailed results see section 4.2 of the Annex.

Overall, the CAO4 outlook is similar to the assessment in CAO3, however, for 2030 as well as in the longer term, the *Baseline* shows 1.5-3 % (or up to 50,000 km^2) more area where CLs for eutrophication are exceeded. Also the MTFR reduction potential for 2030 is few percent points lower than in CAO3, which is partly due to the reduced ambition of IED defining a slightly different Baseline; the difference for MTFR becomes smaller in 2050.

Figure 4-20: Ecosystem area in the EU where the critical loads for eutrophication are exceeded. The marked 25% reduction of 2005 area with N deposition exceeding CLs refers to the ZPAP target.

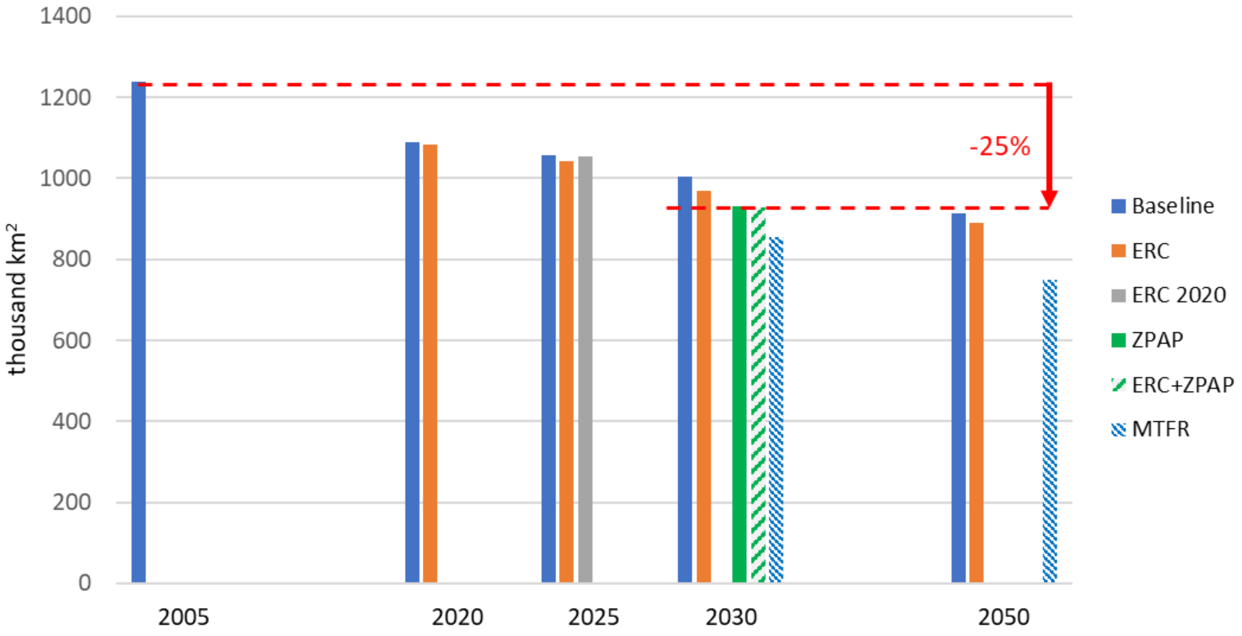


Table 4-15: Ecosystem area in the EU where the critical loads for eutrophication are exceeded.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Ecosystem area with nitrogen deposition exceeding critical loads for eutrophication (1000 km^2)										
Baseline	1239.	1200.	1167.	1089.	1056.	1003.	964.7	939.1	921.7	914.2
ERC				1082.	1041.	968.4		904.4		889.6
ERC 2020					1053.					
ZPAP						931.0				
ERC+ZPAP						928.9				
MTFR						856.3		769.8		748.7
Ecosystem area with nitrogen deposition exceeding critical loads for eutrophication (% of all ecosystems)										
Baseline	85.7	83.0	80.8	75.4	73.1	69.4	66.7	65.0	63.8	63.2
ERC				74.9	72.0	67.0		62.6		61.5
ERC 2020					72.9					
ZPAP						64.4				
ERC+ZPAP						64.3				
MTFR						59.2		53.2		51.8

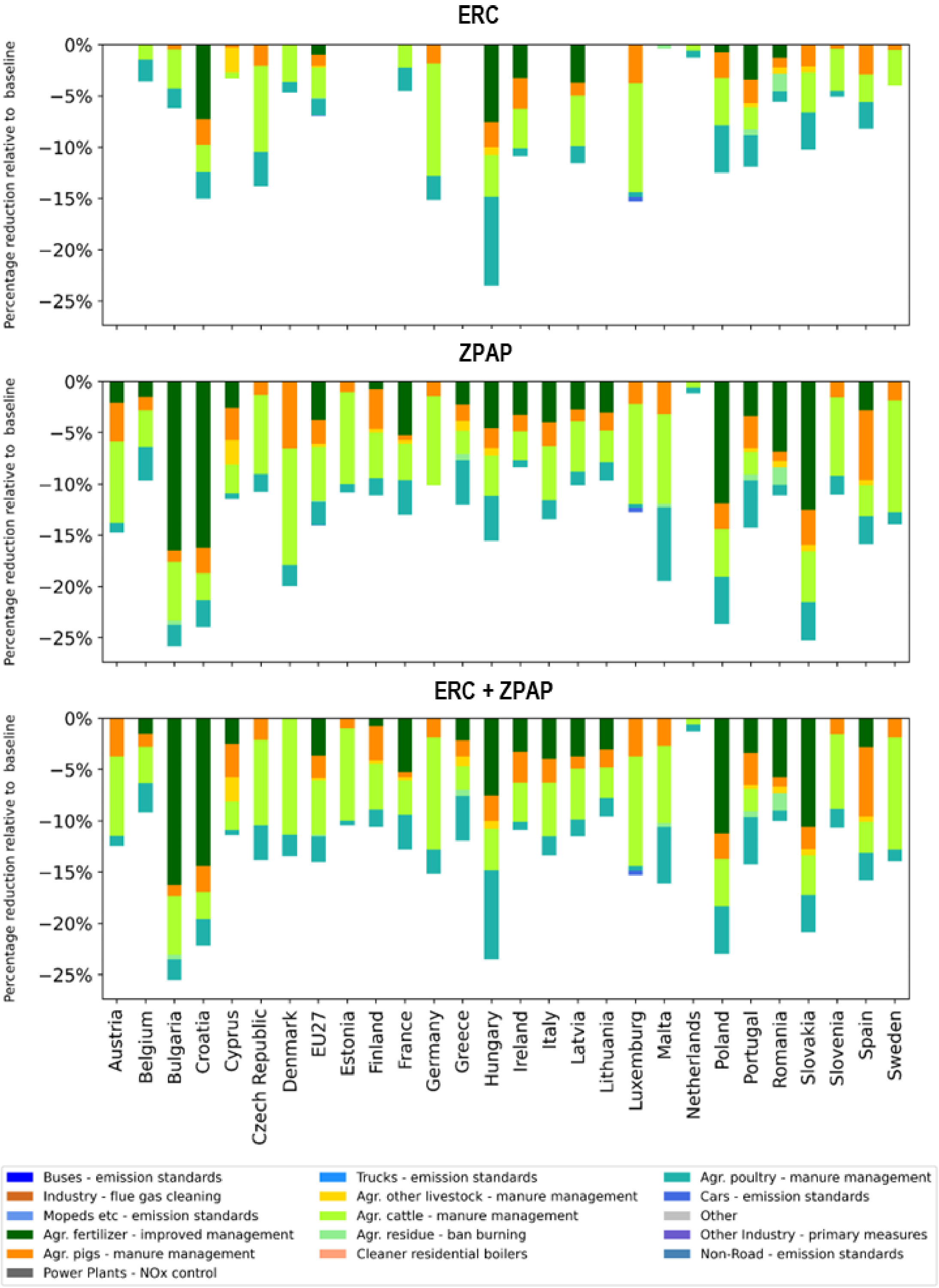
To assess further steps necessary to achieve the EU ZPAP ecosystem target, a dedicated scenario was developed where a cost-effective set of measures results from the GAINS model optimisation to reach the 25% reduction of ecosystems area where CLs for eutrophication are exceeded by 2030. The distribution of mitigation efforts, compared to the *Baseline*, by source category and Member State are shown in Figure 4-21. The overall NH_3 reduction at the EU level, is estimated at about 14% compared to the *Baseline*, with majority achieved via measures addressing emissions from cattle, followed by measures towards mitigation of emissions from application of mineral fertilizers, breeding of pigs, and poultry. Among these four groups, most of the emission reduction is associated with measures addressing on-field application of organic manures and mineral fertilizers, which jointly provide over 70% of total mitigation achieved in the *ZPAP* scenario, while about 25% reduction is achieved by low emission animal housing and improved storage of manures.

Since exceedance of critical loads for eutrophication is rather widespread, all of the Member States would need to introduce further measures to reduce ammonia emissions (Figure 4-21), typically (21 Member States) providing between 8-15% NH_3 reduction, with few exceptions (5 Member States) where more ambition is needed to meet ZPAP target and reductions vary from 16% to 24%. These additional reductions represent more than half of the total mitigation potential identified in the *MTFR* scenario for 2030 at the EU level. In fact, only two countries would need to mobilize less than 50% of their mitigation potential estimated for the MTFR case, while most (21 MS) need to exploit 50-70% of that potential.

We have also analysed the measures needed to comply with the ERCs in 2030, since many countries are estimated to head towards no compliance (see section 4.4.2, Figure 4-7). This analysis shows that, while the ZPAP objectives are not achieved (compare the combination of both targets shown also in Figure 4-21 as *ERC+ZPAP* scenario) in the ERC case, many Member States need to pursue further mitigation with the same type of cost optimal set of measures as calculated for ZPAP case.

Finally, the enforcement of ZPAP targets would also result in some additional mitigation of other pollutants than ammonia, especially NOx, but there is also small feedback on other pollutants; this is shown in the Annex (Section 4.3). That section shows also mitigation necessary to achieve ERCs, and full compliance with both ERCs and ZPAP (*ERC+ZPAP* scenario) for all pollutants across EU Member States by key categories of measures.

Figure 4-21: Distribution of further NH_3 reductions in the ERCs compliant and ZPAP scenario, compared to Baseline, in 2030.



4.4.7 Condensable PM sensitivity

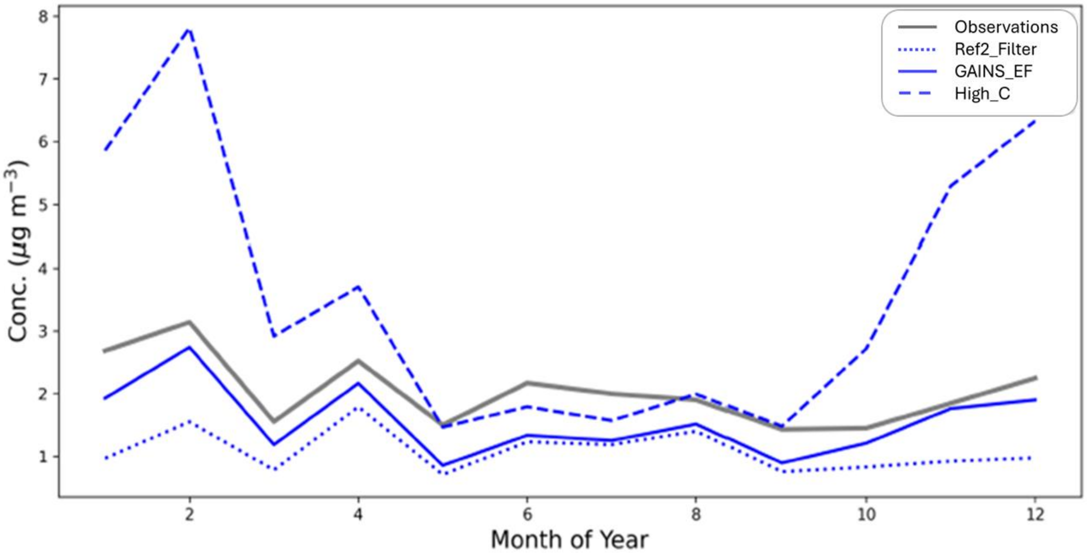
The quantitative and qualitative analysis, for each Member State, of the impacts that various consideration of the condensable PM could have on the achievement of the NEC Directive reduction commitments has been shown in Section 4.4.2. However, both the amount and characteristics of the condensable compounds are very uncertain. A further sensitivity has been conducted. In these additional tests, both the amount of emissions, and the assumptions concerning volatility have been varied, and the results have been compared to the latest available data for ambient measurements of organic carbon, in order to determine the best set of assumptions and to validate the emission factors used in GAINS in the Baseline and the policy scenarios.

Due to the complexity of the analysis and the need for dedicated EMEP model simulations, the analysis is limited to the two defined Baseline sensitivity scenarios, as described in Section 4.3.2.

IIASA and TNO developed the emission factor sets and implemented these in GAINS, producing new sets of chemically speciated particle emissions that were gridded, speciated (distinguishing BC and OC as well as size distribution) and used in the EMEP model. Beyond the central emission factors set that is further referred to as ‘GAINS_EF’ and represents emission factors used in the Baseline and policy scenarios in CAO4, the ‘Ref2_Filter’ and ‘High_C’ sets representing filterable PM only and high EFs with condensable PM, respectively, were used in this analysis (see also section 4.3 and Table 4-1).

Figure 4-22 shows the model agreement with OC (in $PM_{2.5}$) measurements in 2019, averaged across all sites, for the three model runs using respective emission factors and assuming that all condensable PM emissions are non-volatile (for further details see Section 4.4 in the Annex). Of these three runs, only the central estimate (*GAINS_EF*) shows a satisfactory agreement with the observations. This is expected since the *Ref2_Filter* case omits the known condensable PM contributions, and the *High_C* case assumes both high emission factors and that condensable PM are non-volatile.

Figure 4-22: All-site comparison of modelled OC (in $PM_{2.5}$) versus observations, 2019, non-volatile tests.



The results of the analysis show that OC modelling is very sensitive to the emission factors used, and to the assumptions concerning volatility used in the modelling (see Annex, Section 4.4, for more discussion). Although the results for the default non-volatile setup with central emission factors (*GAINS_EF*) were not quite as good as the more complex setups with higher emission factors and volatility assumptions, the results were rather similar and compared well with observations in any case. Although we know that the assumption that condensable PM is non-volatile is incorrect, it is also the simplest assumption we can make, and both the model results presented here, and other studies (see Simpson et al, 2022, for references) confirm that such an approach generates OC levels consistent with much more complex approaches.

Thus, for EMEP regional scale modelling the non-volatile approach with central emission factors still seems to represent the best approach. The high case (*High_C*) consistently overestimates measured concentrations, while using emission factors representing filterable PM only (*Ref2_Filter*) shows rather consistent, and sometimes significant, underestimation. These results show that the emission factors (including condensable PM) used in GAINS and currently recommended by the EEA/EMEP Guidebook as well used by most Member States in their reporting, appear to represent well the PM emissions.

Further details and additional results of modelling where various assumptions about volatility as well as about total emissions (2015 vs 2020) are made, are presented in the Annex (Section 4.4).

4.4.8 Sensitivity to methane emission reductions

The purpose of this sensitivity analysis is to assess how various levels of methane emission reduction (in the EU and / or through reducing emissions arriving from outside the EU) would contribute to the fulfilment of the air quality standard set for ozone as envisaged in the revised Ambient Air Quality Directive[37]. The model runs estimated the maximum daily 8-hour mean (MD8M) and AOT40. These simulations also included assumptions on the projected emissions of ozone precursors other than methane, as specified in Section 4.3.3. The model runs were performed for the period 2005 to 2050, but the specific simulation of methane mitigation impacts was estimated for the years 2040 and 2050.

The atmospheric calculations were done with the EMEP MSC-W chemical transport model (also used in the impact assessment for the revision of the Ambient Air Quality Directive). The analysis involves global model simulations combining global scenarios developed by IIASA within the discussion of the revision of the Gothenburg Protocol and updating them with the latest *Baseline* from this project for the EU and EU4Green project outcomes for the West Balkan.

Concentrations of CH_4 in ambient air were estimated using a reduced complexity Earth System Model emulator, as described in detail in van Caspel et al. (2024), assuming a uniform distribution of CH_4 over the globe. These CH_4 concentrations were implemented in the global EMEP model and the effect on the background levels of ozone was estimated, as well as the impact on ozone on European scale.

The outcomes from this modelling work are shown for indicators relevant for assessing compliance with the ozone target values in the current AAQD as well as the revised version which will apply from 2030. For the protection of human health, the AAQD specifies a target value of 120μgm^{-3} for MD8M, which is not to be exceeded for more than 25 days (current AAQD) / 18 days (revised AAQD) per year (averaged over 3 years). For the protection of the environment, the Directive specifies a target value for AOT40 of 18,000 $\mu gm^{-3}h$ (averaged for May to July over 5 years), and a long-term objective of 6,000 $\mu gm^{-3}h$.

Figure 4-23 shows how the 26th highest MD8M concentration, indicating compliance with the current target value, changes from 2005 in the *Baseline* up to 2050, and then impacts of the two *Global MTFR* mitigation cases for 2050: in both cases methane is mitigated globally while the non-methane ozone precursors are either at baseline policy ("*only CH4*") or are also controlled with maximum mitigation potential ("*AP+CH4*") globally, not only in the EU. The last row provides the 19th highest MD8M estimated for the mitigation cases for 2050, indicating achievement of the revised AAQD target value. The results for both metrics are very similar although naturally, the '26th highest' indicator shows less exceedances.

The current policies are expected to bring improved compliance (all blue and white areas, i.e., below indicator value of 120 $\mu g/m^3$) in most regions of the EU but hot spots in Italy, Portugal, Greece, parts of Spain, and parts

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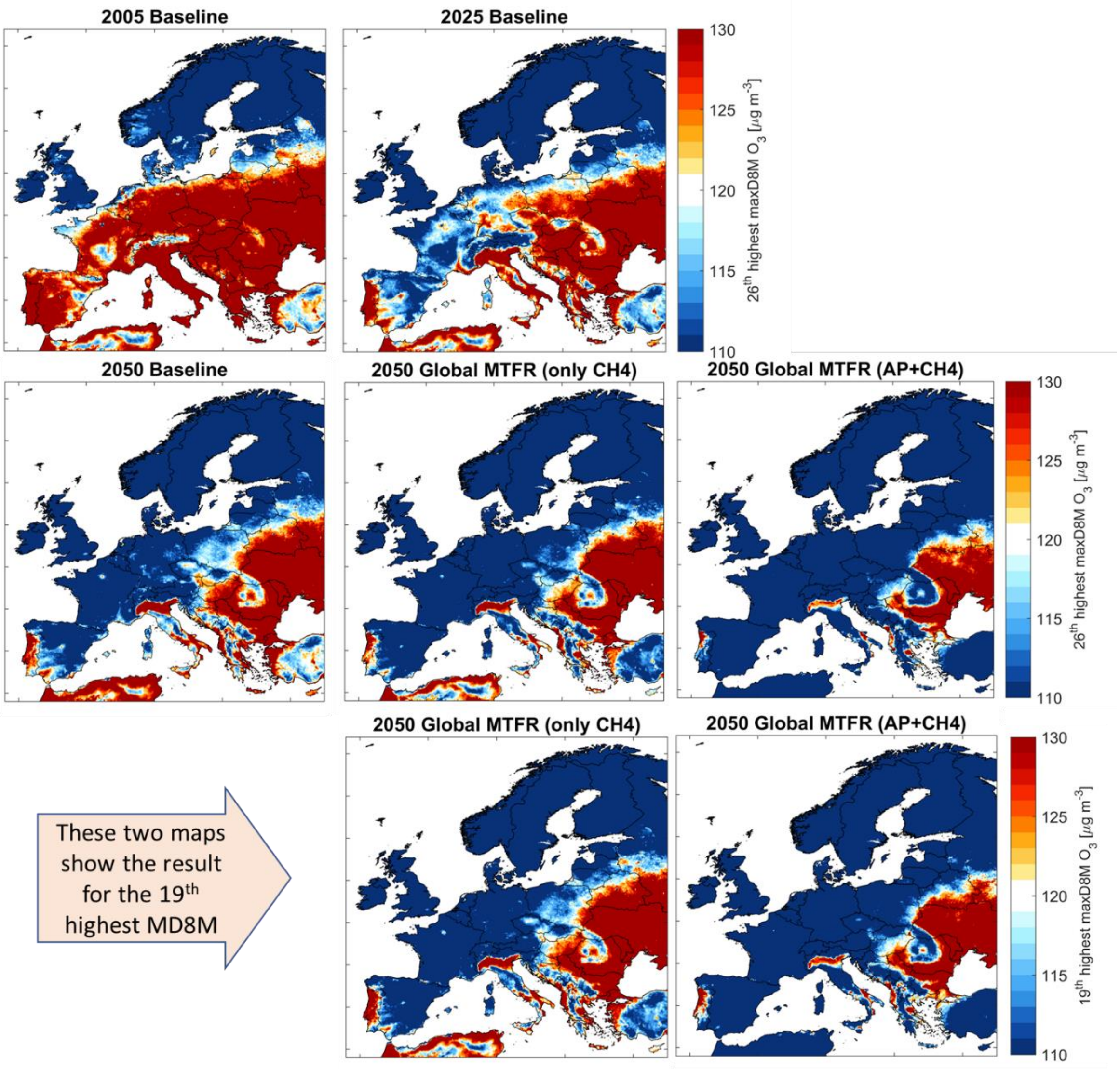
[37] Directive (EU) 2024/2881

of Eastern Europe remain. The mitigation cases bring some further reductions but not allowing for full compliance, independent if only methane or both methane and non-methane ozone precursors are controlled. The response is stronger for additional reduction of non-methane ozone precursors (NOx, NMVOC, CO) on top of the additional methane mitigation, i.e., 'Global MTFR (AP+CH4)' case vs 'Global MTFR (only CH4)' (Figure 4-23).

Figure 4-23: Spatial distribution of ozone concentrations for the 26th highest MD8M (two top rows) and for the 19th highest MD8M. Two mitigation cases for 2050 assume MTFR for CH_4 and either CLE (Global MTFR – only CH_4) or MTFR (Global MTFR – AP+CH_4) for non-methane precursors.



These two maps show the result for the 19th highest MD8M

The impact of methane mitigation in Europe alone has been also analysed (not shown) but it is very small, contributing only about 1% of the overall reduction. This is not surprising since the baseline already shows a decline in CH_4 emissions and further potential is rather small when considering technical measures only. In order to reduce methane emissions further, a set of transformational policies, e.g., dietary changes, would be needed as agriculture remains the largest source and among the most challenging to control.

The analysed sensitivity cases are further illustrated in Figure 4-24, showing the spatial distribution of *peak season average* MD8M for 2005, 2025, 2050 *Baseline* and the two mitigation cases for 2050 described above.

Although not used in the health impact calculations in this report, peak season ozone (defined as the average MD8M over the highest consecutive six months) is an exposure metric associated with mortality from long-term exposure to ozone (Huangfu and Atkinson, 2020). The most significant change in peak-season ozone is estimated in the Baseline scenario where, especially in Southern Europe, peak season concentrations decline strongly by 2050. Further mitigation of methane (Global MTFR – only CH_4) and other ozone precursors (Global MTFR – AP+CH_4) brings further important benefits, including for northern and central Europe. The impact of the latter seems more pronounced and in this case most of the areas (except Po Valley) are below 90 ug/m^3.

A similar response is seen for AOT40 (Figure 4-25) where mitigation of methane beyond Baseline results in reduction of AOT40 indicator but rather limited impact on compliance with the target value of 18,000µgm^{-3}h, leaving parts of Spain, Italy, Greece, Bulgaria in non-compliance (dark brown), while near compliance appears to be achieved in several central and eastern EU countries. The big change comes with the further and global mitigation of non-methane ozone precursors (Global MTFR – AP+CH_4) where most of EU, with exception of Po Valley and southern Romania, would be in compliance. This scenario brings also markable improvement outside EU. Still, even in this most ambitious sensitivity case, there is widespread non-achievement of the much stricter long-term objective for the protection of vegetation of 6,000 µgm^{-3}h specified in the revised AAQD.

Figure 4-24: Spatial distribution of peak season average MD8M ozone concentrations. Two mitigation cases for 2050 assume MTFR for CH_4 and either CLE (Global MTFR – only CH_4) or MTFR (Global MTFR – AP+CH_4) for non-methane precursors.

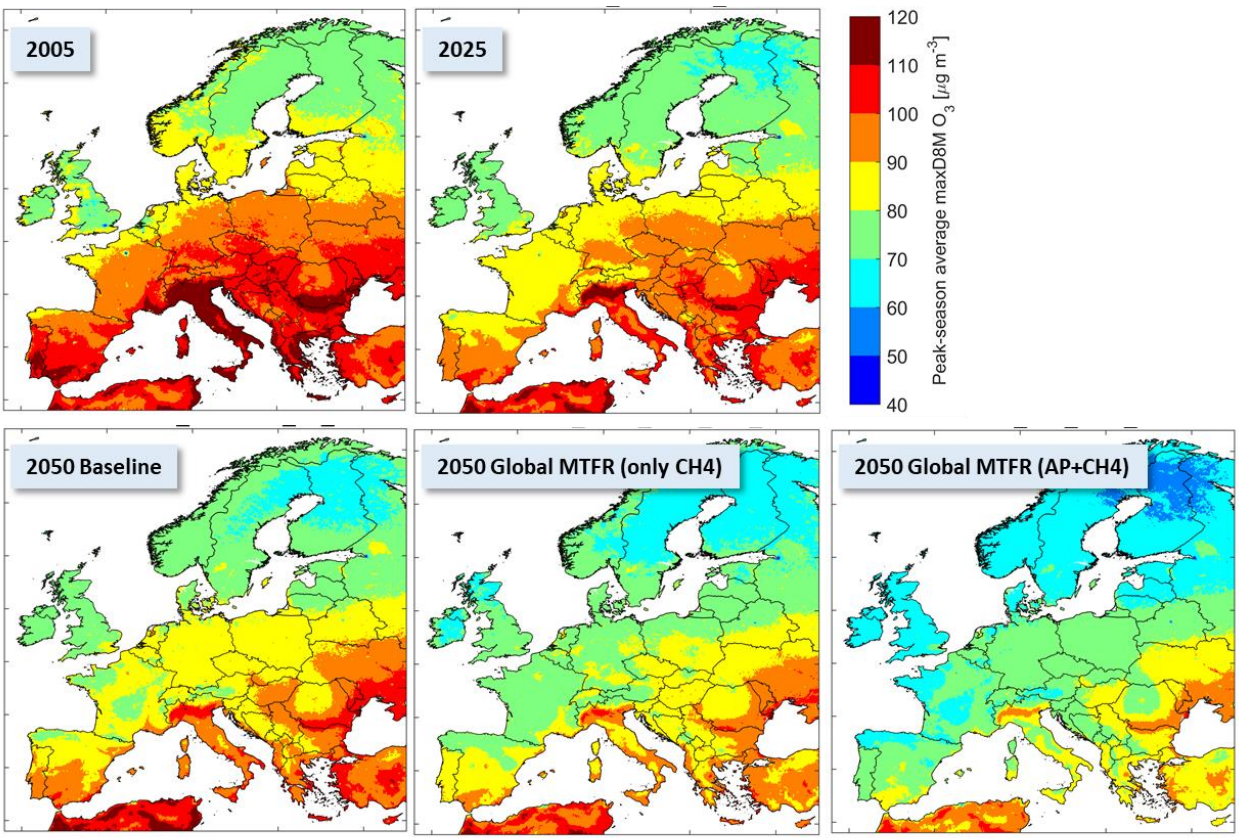
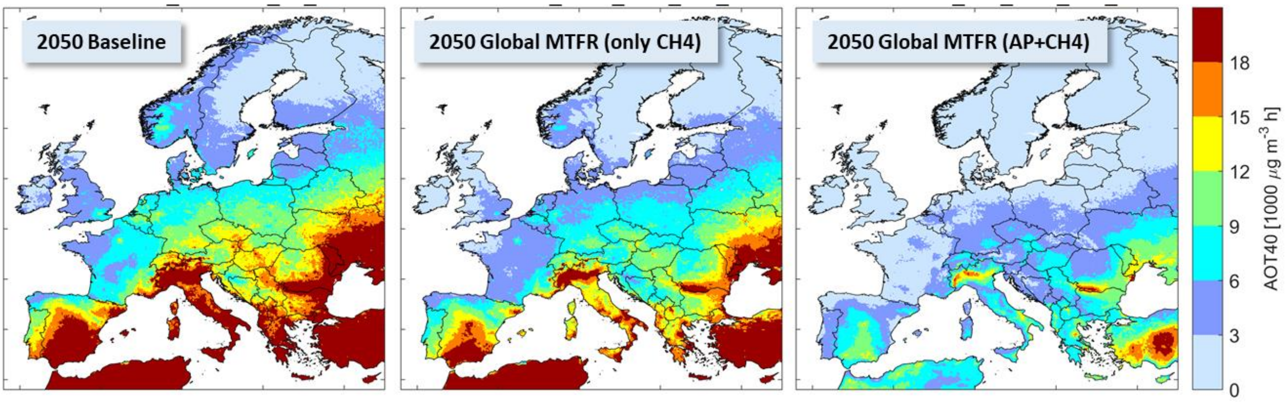


Figure 4-25: Spatial distribution of AOT40 indicator for 2050. Two mitigation cases for 2050 assume MTFR for CH_4 and either CLE (Global MTFR – only CH_4) or MTFR (Global MTFR – AP+CH_4) for non-methane precursors.



Finally, Figure 4-26 provides a comparison of compliance with the current (26th highest MD8M) and revised (19th highest MD8M) target values for MD8M at the monitoring stations in the EU. We compare baseline scenario (missing for 2030[38]), MTFR case (NOx, VOC, CO are further controlled but only in the EU), and the two methane sensitivity cases as described above.

As expected, the compliance continues to improve over time and with added mitigation in the MTFR cases. The improvement for the case when global methane mitigation is added (yellow line) over the EU MTFR case is comparable to the change observed (for 2050) between the Baseline and MTFR case (only EU non methane ozone precursors are controlled further), i.e., the difference between the blue and the red line. A much larger benefit is expected from mitigation of NOx, VOC, and CO globally (violet line); it is not so large for 2030 (short time frame to implement measures) but very significant for 2040, bringing a large number of additional stations in compliance with the target value compared to the scenario variants of acting in the EU only (MTFR) and of reducing only methane globally. The impact in 2050 is also large, although somehow smaller than in 2040 owing to continued reductions of emissions in many regions and growing response from the reduction of methane.

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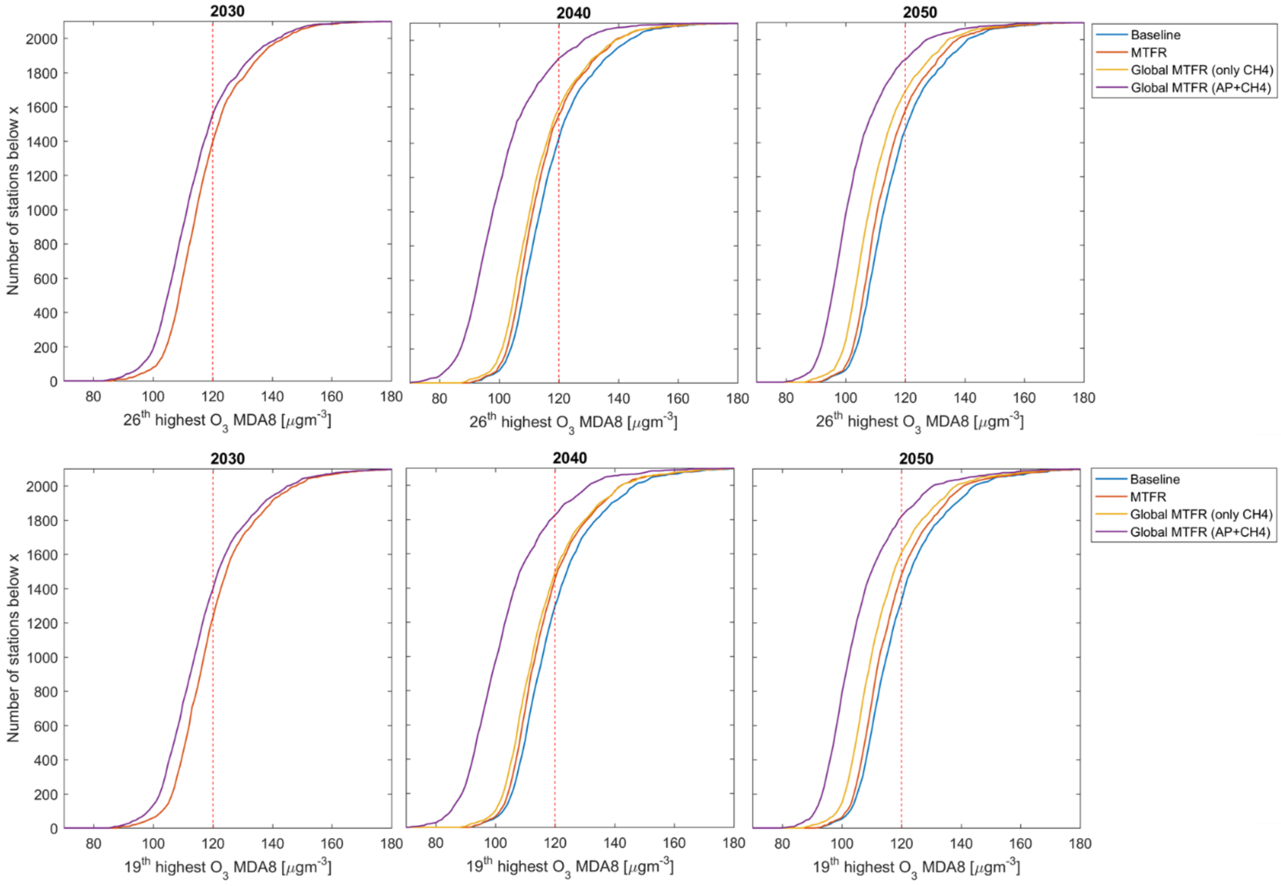
[38] The respective 26th and 19th MD8M indicators were not calculated with the EMEP model for the Baseline 2030 as the focus of the methane sensitivity runs was set on 2040 and 2050.

Figure 4-26: Assessment of compliance with the current and proposed ozone legislation, showing 26th highest MD8M (top row) and for the 19th highest MD8M (bottom row) for the Baseline and three MTFR cases for 2030, 2040, 2050.



4.5 Cross-border effects of pollution and pollution reduction

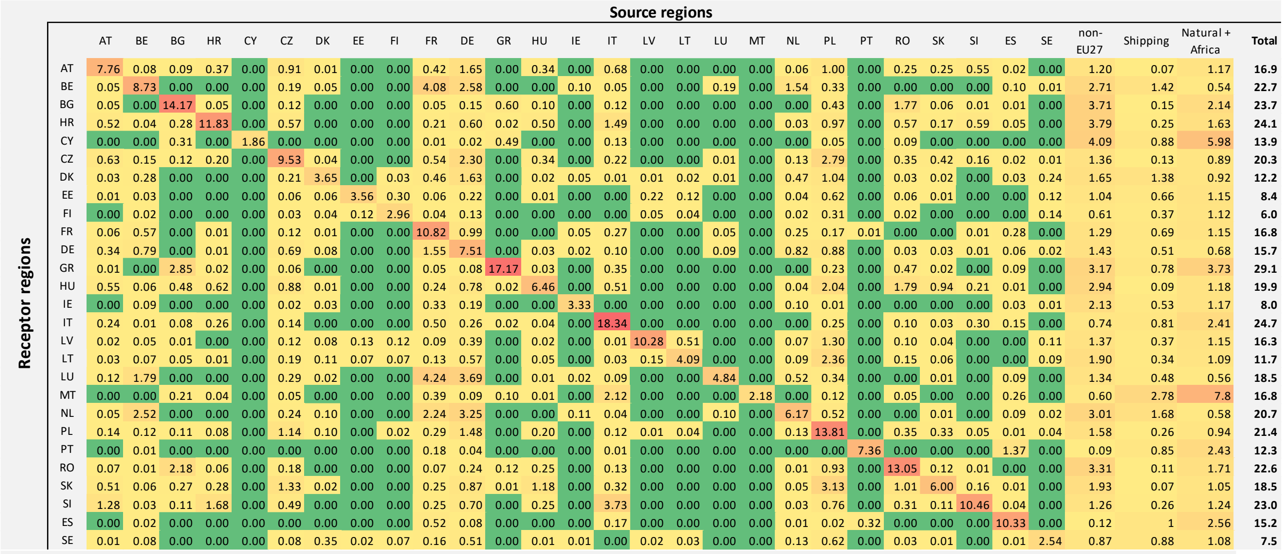
IIASA has employed its GAINS model to estimate in all EU Member States the contributions from different source regions (same country, other EU Member States, non-EU) to ambient $PM_{2.5}$ concentrations, and to the changes in $PM_{2.5}$ concentrations between different scenario years. Although the presentation of results does not highlight the Western Balkans explicitly (included in the non-EU region in the following Figures), in neighbouring regions the non-EU contribution can be linked to the developments in the Western Balkan as a dominating contributor. This can be seen in Figure 4-31 for e.g. Croatia and Hungary, where after 2020 more significant $PM_{2.5}$ concentration reductions occur. These are driven by the expected decline in precursor emissions (especially in the power sector) in the Western Balkan countries' baselines, assuming effective implementation of emission controls and strong decline in coal use, consistent with decarbonization policy and other air pollution regulations.

4.5.1 Import-export budgets

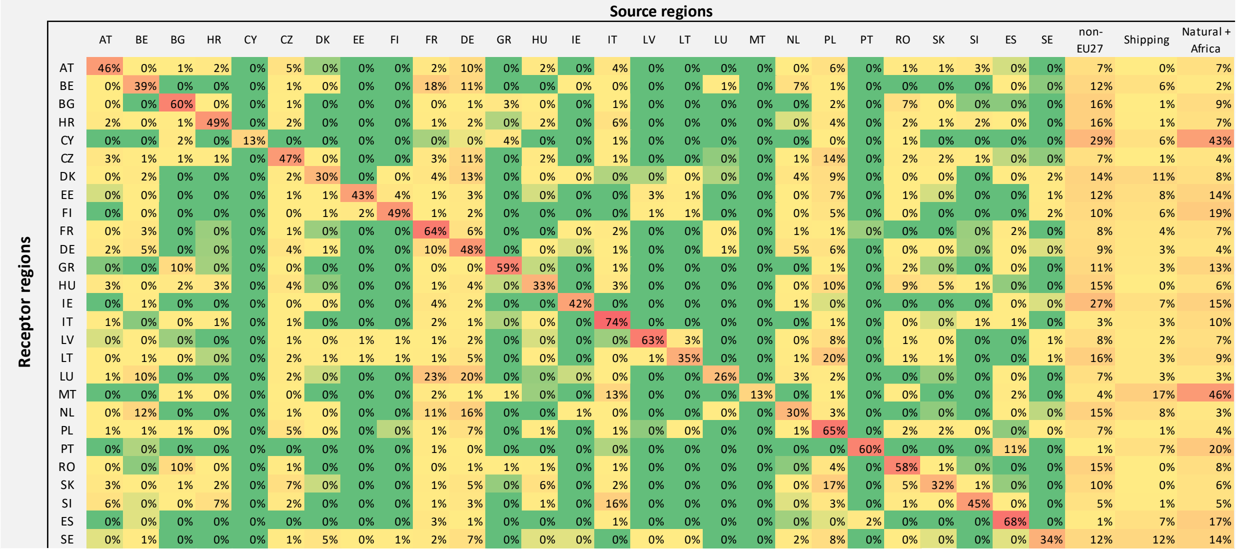
A series of figures in this section illustrates first the contribution of domestic pollution sources as opposed to those from other sources (other Member States, non-EU countries and natural sources) to the population-weighted mean concentration of $PM_{2.5}$ in 2005 in a given Member State. The results are presented as back-to-back tables showing absolute values ($\mu g/m^3$) and in relative terms (% of total concentration). These so-called 'import-export' matrices illustrate how the contributions change over time in the *Baseline* scenario (2015, 2030, and 2050 are shown) where, owing to the structure of pollution sources and economic development, the progress in reduction of particular species might vary, affecting pollutant concentrations in the country itself and in its neighbours. The impact depends on both primary PM precursors ($PM_{2.5}$) and precursors of secondary PM, including SO_2, NO_x, NH_3, NMVOC, and their reduction will vary from measure to measure, i.e., flue gas desulphurization on a power plant, new efficient stove, new animal house, etc. will reduce different pollutants and to a varying degree.

Such matrices can inform about the implications of different local and international policy showing how the contribution from different regions (or even sectors, although not shown here) could change. For example, the results presented here for the *Baseline* scenario show how, in several Member State where the local contribution dominated in 2005-2020 (e.g. Bulgaria, France, Italy, Poland, Portugal, Spain), over time their own contribution drops by about half because of implementation of national and EU policies. Some other countries, especially those with lower concentrations and away from larger industrialized Member States, like Finland or Sweden, see much smaller improvements in $PM_{2.5}$ concentrations. One rather common feature is that, owing to continued reduction of Member State emissions in the *Baseline* scenario, the role of emissions from the non-EU countries as well as from natural sources becomes more prominent.

Figure 4-27: Origin of population-weighted $PM_{2.5}$ background concentrations in each Member State computed for 2005 in µg/m³ [top] and as percent of total background concentrations [bottom].

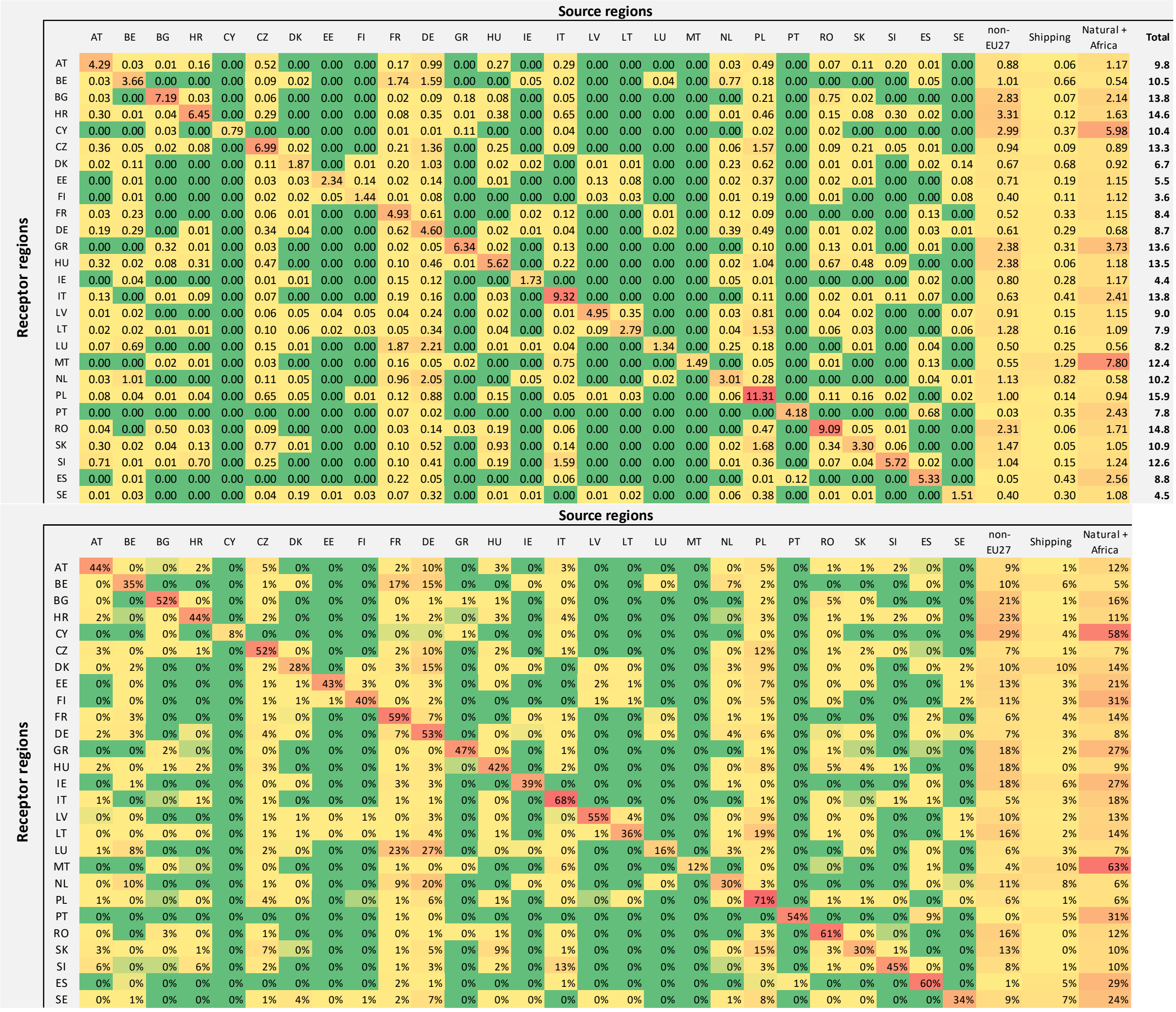


Receptor regions	Source regions																														
	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa	**Total**
AT	7.76	0.08	0.09	0.37	0.00	0.91	0.01	0.00	0.00	0.42	1.65	0.00	0.34	0.00	0.68	0.00	0.00	0.00	0.00	0.06	1.00	0.00	0.25	0.25	0.55	0.02	0.00	1.20	0.07	1.17	**16.9**
BE	0.05	8.73	0.00	0.00	0.00	0.19	0.05	0.00	0.00	4.08	2.58	0.00	0.00	0.10	0.05	0.00	0.00	0.19	0.00	1.54	0.33	0.00	0.00	0.00	0.00	0.10	0.01	2.71	1.42	0.54	**22.7**
BG	0.05	0.00	14.17	0.05	0.00	0.12	0.00	0.00	0.00	0.05	0.15	0.60	0.10	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.43	0.00	1.77	0.06	0.01	0.01	0.00	3.71	0.15	2.14	**23.7**
HR	0.52	0.04	0.28	11.83	0.00	0.57	0.00	0.00	0.00	0.21	0.60	0.02	0.50	0.00	1.49	0.00	0.00	0.00	0.00	0.03	0.97	0.00	0.57	0.17	0.59	0.05	0.00	3.79	0.25	1.63	**24.1**
CY	0.00	0.00	0.31	0.00	1.86	0.00	0.00	0.00	0.00	0.01	0.02	0.49	0.00	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.09	0.00	0.00	0.00	0.00	4.09	0.88	5.98	**13.9**
CZ	0.63	0.15	0.12	0.20	0.00	9.53	0.04	0.00	0.00	0.54	2.30	0.00	0.34	0.00	0.22	0.00	0.00	0.01	0.00	0.13	2.79	0.00	0.35	0.42	0.16	0.02	0.01	1.36	0.13	0.89	**20.3**
DK	0.03	0.28	0.00	0.00	0.00	0.21	3.65	0.00	0.03	0.46	1.63	0.00	0.02	0.05	0.01	0.01	0.02	0.01	0.00	0.47	1.04	0.00	0.03	0.02	0.00	0.03	0.24	1.65	1.38	0.92	**12.2**
EE	0.01	0.03	0.00	0.00	0.00	0.06	0.06	3.56	0.30	0.06	0.22	0.00	0.01	0.00	0.00	0.22	0.12	0.00	0.00	0.04	0.62	0.00	0.06	0.01	0.00	0.00	0.12	1.04	0.66	1.15	**8.4**
FI	0.00	0.02	0.00	0.00	0.00	0.03	0.04	0.12	2.96	0.04	0.13	0.00	0.00	0.00	0.00	0.05	0.04	0.00	0.00	0.02	0.31	0.00	0.02	0.00	0.00	0.00	0.14	0.61	0.37	1.12	**6.0**
FR	0.06	0.57	0.00	0.01	0.00	0.12	0.01	0.00	0.00	10.82	0.99	0.00	0.00	0.05	0.27	0.00	0.00	0.05	0.00	0.25	0.17	0.01	0.00	0.00	0.01	0.28	0.00	1.29	0.69	1.15	**16.8**
DE	0.34	0.79	0.00	0.01	0.00	0.69	0.08	0.00	0.00	1.55	7.51	0.00	0.03	0.02	0.10	0.00	0.00	0.09	0.00	0.82	0.88	0.00	0.03	0.03	0.01	0.06	0.02	1.43	0.51	0.68	**15.7**
GR	0.01	0.00	2.85	0.02	0.00	0.06	0.00	0.00	0.00	0.05	0.08	17.17	0.03	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.23	0.00	0.47	0.02	0.00	0.09	0.00	3.17	0.78	3.73	**29.1**
HU	0.55	0.06	0.48	0.62	0.00	0.88	0.01	0.00	0.00	0.24	0.78	0.02	6.46	0.00	0.51	0.00	0.00	0.00	0.00	0.04	2.04	0.00	1.79	0.94	0.21	0.01	0.00	2.94	0.09	1.18	**19.9**
IE	0.00	0.09	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.33	0.19	0.00	0.00	3.33	0.00	0.00	0.00	0.00	0.00	0.10	0.01	0.00	0.00	0.00	0.00	0.03	0.01	2.13	0.53	1.17	**8.0**
IT	0.24	0.01	0.08	0.26	0.00	0.14	0.00	0.00	0.00	0.50	0.26	0.02	0.04	0.00	18.34	0.00	0.00	0.00	0.00	0.00	0.25	0.00	0.10	0.03	0.30	0.15	0.00	0.74	0.81	2.41	**24.7**
LV	0.02	0.05	0.01	0.00	0.00	0.12	0.08	0.13	0.12	0.09	0.39	0.00	0.02	0.00	0.01	10.28	0.51	0.00	0.00	0.07	1.30	0.00	0.10	0.04	0.00	0.00	0.11	1.37	0.37	1.15	**16.3**
LT	0.03	0.07	0.05	0.01	0.00	0.19	0.11	0.07	0.07	0.13	0.57	0.00	0.05	0.00	0.03	0.15	4.09	0.00	0.00	0.09	2.36	0.00	0.15	0.06	0.00	0.00	0.09	1.90	0.34	1.09	**11.7**
LU	0.12	1.79	0.00	0.00	0.00	0.29	0.02	0.00	0.00	4.24	3.69	0.00	0.01	0.02	0.09	0.00	0.00	4.84	0.00	0.52	0.34	0.00	0.00	0.01	0.00	0.09	0.00	1.34	0.48	0.56	**18.5**
MT	0.00	0.00	0.21	0.04	0.00	0.05	0.00	0.00	0.00	0.39	0.09	0.10	0.01	0.00	2.12	0.00	0.00	0.00	2.18	0.00	0.12	0.00	0.05	0.00	0.00	0.26	0.00	0.60	2.78	7.8	**16.8**
NL	0.05	2.52	0.00	0.00	0.00	0.24	0.10	0.00	0.00	2.24	3.25	0.00	0.00	0.11	0.04	0.00	0.00	0.10	0.00	6.17	0.52	0.00	0.00	0.01	0.00	0.09	0.02	3.01	1.68	0.58	**20.7**
PL	0.14	0.12	0.11	0.08	0.00	1.14	0.10	0.00	0.02	0.29	1.48	0.00	0.20	0.00	0.12	0.01	0.04	0.00	0.00	0.13	13.81	0.00	0.35	0.33	0.05	0.01	0.04	1.58	0.26	0.94	**21.4**
PT	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.04	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	7.36	0.00	0.00	0.00	1.37	0.00	0.09	0.85	2.43	**12.3**
RO	0.07	0.01	2.18	0.06	0.00	0.18	0.00	0.00	0.00	0.07	0.24	0.12	0.25	0.00	0.13	0.00	0.00	0.00	0.00	0.01	0.93	0.00	13.05	0.12	0.01	0.00	0.00	3.31	0.11	1.71	**22.6**
SK	0.51	0.06	0.27	0.28	0.00	1.33	0.02	0.00	0.00	0.25	0.87	0.01	1.18	0.00	0.32	0.00	0.00	0.00	0.00	0.05	3.13	0.00	1.01	6.00	0.16	0.01	0.00	1.93	0.07	1.05	**18.5**
SI	1.28	0.03	0.11	1.68	0.00	0.49	0.00	0.00	0.00	0.25	0.70	0.00	0.25	0.00	3.73	0.00	0.00	0.00	0.00	0.03	0.76	0.00	0.31	0.11	10.46	0.04	0.00	1.26	0.26	1.24	**23.0**
ES	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.08	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.01	0.02	0.32	0.00	0.00	0.00	10.33	0.00	0.12	1	2.56	**15.2**
SE	0.01	0.08	0.00	0.00	0.00	0.08	0.35	0.02	0.07	0.16	0.51	0.00	0.01	0.01	0.00	0.02	0.03	0.00	0.00	0.13	0.62	0.00	0.03	0.01	0.00	0.01	2.54	0.87	0.88	1.08	**7.5**



Receptor regions	Source regions																													
	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa
AT	46%	0%	1%	2%	0%	5%	0%	0%	0%	2%	10%	0%	2%	0%	4%	0%	0%	0%	0%	0%	6%	0%	1%	1%	3%	0%	0%	7%	0%	7%
BE	0%	39%	0%	0%	0%	1%	0%	0%	0%	18%	11%	0%	0%	0%	0%	0%	0%	1%	0%	7%	1%	0%	0%	0%	0%	0%	0%	12%	6%	2%
BG	0%	0%	60%	0%	0%	1%	0%	0%	0%	0%	1%	3%	0%	0%	1%	0%	0%	0%	0%	0%	2%	0%	7%	0%	0%	0%	0%	16%	1%	9%
HR	2%	0%	1%	49%	0%	2%	0%	0%	0%	1%	2%	0%	2%	0%	6%	0%	0%	0%	0%	0%	4%	0%	2%	1%	2%	0%	0%	16%	1%	7%
CY	0%	0%	2%	0%	13%	0%	0%	0%	0%	0%	0%	4%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	29%	6%	43%
CZ	3%	1%	1%	1%	0%	47%	0%	0%	0%	3%	11%	0%	2%	0%	1%	0%	0%	0%	0%	1%	14%	0%	2%	2%	1%	0%	0%	7%	1%	4%
DK	0%	2%	0%	0%	0%	2%	30%	0%	0%	4%	13%	0%	0%	0%	0%	0%	0%	0%	0%	4%	9%	0%	0%	0%	0%	0%	2%	14%	11%	8%
EE	0%	0%	0%	0%	0%	1%	1%	43%	4%	1%	3%	0%	0%	0%	0%	3%	1%	0%	0%	0%	7%	0%	1%	0%	0%	0%	1%	12%	8%	14%
FI	0%	0%	0%	0%	0%	0%	1%	2%	49%	1%	2%	0%	0%	0%	0%	1%	1%	0%	0%	0%	5%	0%	0%	0%	0%	0%	2%	10%	6%	19%
FR	0%	3%	0%	0%	0%	1%	0%	0%	0%	64%	6%	0%	0%	0%	2%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	2%	0%	8%	4%	7%
DE	2%	5%	0%	0%	0%	4%	1%	0%	0%	10%	48%	0%	0%	0%	1%	0%	0%	1%	0%	5%	6%	0%	0%	0%	0%	0%	0%	9%	3%	4%
GR	0%	0%	10%	0%	0%	0%	0%	0%	0%	0%	0%	59%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	2%	0%	0%	0%	0%	11%	3%	13%
HU	3%	0%	2%	3%	0%	4%	0%	0%	0%	1%	4%	0%	33%	0%	3%	0%	0%	0%	0%	0%	10%	0%	9%	5%	1%	0%	0%	15%	0%	6%
IE	0%	1%	0%	0%	0%	0%	0%	0%	0%	4%	2%	0%	0%	42%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	27%	7%	15%
IT	1%	0%	0%	1%	0%	1%	0%	0%	0%	2%	1%	0%	0%	0%	74%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	1%	0%	3%	3%	10%
LV	0%	0%	0%	0%	0%	1%	0%	1%	1%	1%	2%	0%	0%	0%	0%	63%	3%	0%	0%	0%	8%	0%	1%	0%	0%	0%	1%	8%	2%	7%
LT	0%	1%	0%	0%	0%	2%	1%	1%	1%	1%	5%	0%	0%	0%	0%	1%	35%	0%	0%	1%	20%	0%	1%	1%	0%	0%	1%	16%	3%	9%
LU	1%	10%	0%	0%	0%	2%	0%	0%	0%	23%	20%	0%	0%	0%	0%	0%	0%	26%	0%	3%	2%	0%	0%	0%	0%	0%	0%	7%	3%	3%
MT	0%	0%	1%	0%	0%	0%	0%	0%	0%	2%	1%	1%	0%	0%	13%	0%	0%	0%	13%	0%	1%	0%	0%	0%	0%	2%	0%	4%	17%	46%
NL	0%	12%	0%	0%	0%	1%	0%	0%	0%	11%	16%	0%	0%	1%	0%	0%	0%	0%	0%	30%	3%	0%	0%	0%	0%	0%	0%	15%	8%	3%
PL	1%	1%	1%	0%	0%	5%	0%	0%	0%	1%	7%	0%	1%	0%	1%	0%	0%	0%	0%	1%	65%	0%	2%	2%	0%	0%	0%	7%	1%	4%
PT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	60%	0%	0%	0%	11%	0%	1%	7%	20%
RO	0%	0%	10%	0%	0%	1%	0%	0%	0%	0%	1%	1%	1%	0%	1%	0%	0%	0%	0%	0%	4%	0%	58%	1%	0%	0%	0%	15%	0%	8%
SK	3%	0%	1%	2%	0%	7%	0%	0%	0%	1%	5%	0%	6%	0%	2%	0%	0%	0%	0%	0%	17%	0%	5%	32%	1%	0%	0%	10%	0%	6%
SI	6%	0%	0%	7%	0%	2%	0%	0%	0%	1%	3%	0%	1%	0%	16%	0%	0%	0%	0%	0%	3%	0%	1%	0%	45%	0%	0%	5%	1%	5%
ES	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	68%	0%	1%	7%	17%
SE	0%	1%	0%	0%	0%	1%	5%	0%	1%	2%	7%	0%	0%	0%	0%	0%	0%	0%	0%	2%	8%	0%	0%	0%	0%	0%	34%	12%	12%	14%

Figure 4-28: Origin of population-weighted PM$_{2.5}$ background concentrations in each Member State computed for 2020 in µg/m^3 [top] and as percent of total background concentrations [bottom].



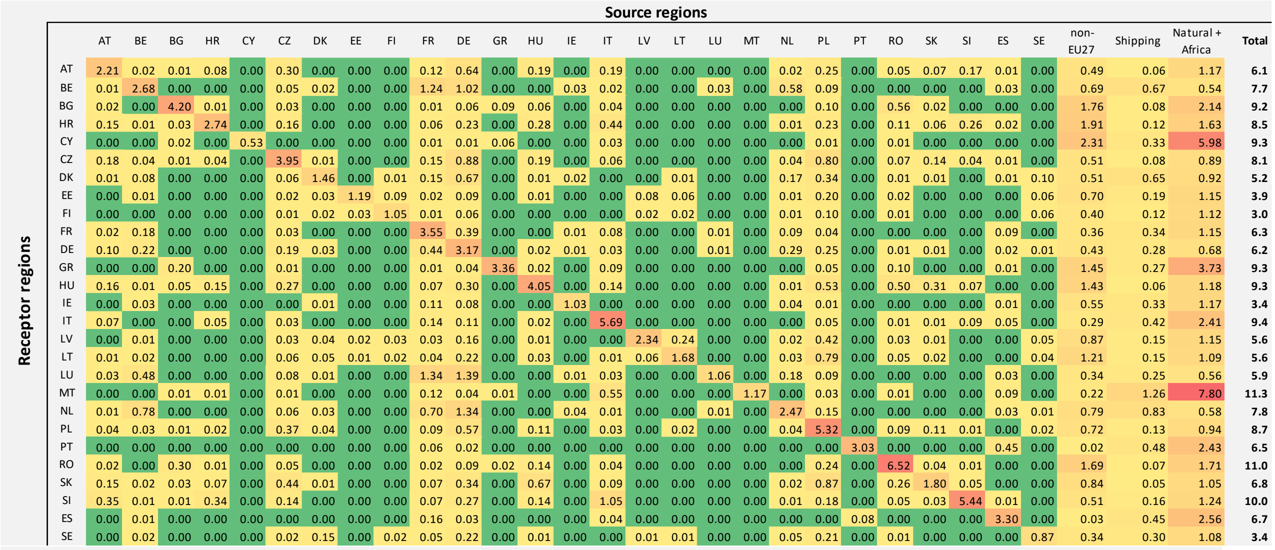
Source regions

Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa	**Total**
AT	4.29	0.03	0.01	0.16	0.00	0.52	0.00	0.00	0.00	0.17	0.99	0.00	0.27	0.00	0.29	0.00	0.00	0.00	0.00	0.03	0.49	0.00	0.07	0.11	0.20	0.01	0.00	0.88	0.06	1.17	**9.8**
BE	0.03	3.66	0.00	0.00	0.00	0.09	0.02	0.00	0.00	1.74	1.59	0.00	0.00	0.05	0.02	0.00	0.00	0.04	0.00	0.77	0.18	0.00	0.00	0.00	0.00	0.05	0.00	1.01	0.66	0.54	**10.5**
BG	0.03	0.00	7.19	0.03	0.00	0.06	0.00	0.00	0.00	0.02	0.09	0.18	0.08	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.75	0.02	0.00	0.00	0.00	2.83	0.07	2.14	**13.8**
HR	0.30	0.01	0.04	6.45	0.00	0.29	0.00	0.00	0.00	0.08	0.35	0.01	0.38	0.00	0.65	0.00	0.00	0.00	0.00	0.01	0.46	0.00	0.15	0.08	0.30	0.02	0.00	3.31	0.12	1.63	**14.6**
CY	0.00	0.00	0.03	0.00	0.79	0.00	0.00	0.00	0.00	0.01	0.01	0.11	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.00	0.00	2.99	0.37	5.98	**10.4**
CZ	0.36	0.05	0.02	0.08	0.00	6.99	0.02	0.00	0.00	0.21	1.36	0.00	0.25	0.00	0.09	0.00	0.00	0.00	0.00	0.06	1.57	0.00	0.09	0.21	0.05	0.01	0.00	0.94	0.09	0.89	**13.3**
DK	0.02	0.11	0.00	0.00	0.00	0.11	1.87	0.00	0.01	0.20	1.03	0.00	0.02	0.02	0.00	0.01	0.01	0.00	0.00	0.23	0.62	0.00	0.01	0.01	0.00	0.02	0.14	0.67	0.68	0.92	**6.7**
EE	0.00	0.01	0.00	0.00	0.00	0.03	0.03	2.34	0.14	0.02	0.14	0.00	0.01	0.00	0.00	0.13	0.08	0.00	0.00	0.02	0.37	0.00	0.02	0.01	0.00	0.00	0.08	0.71	0.19	1.15	**5.5**
FI	0.00	0.01	0.00	0.00	0.00	0.02	0.02	0.05	1.44	0.01	0.08	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.01	0.19	0.00	0.01	0.00	0.00	0.00	0.08	0.40	0.11	1.12	**3.6**
FR	0.03	0.23	0.00	0.00	0.00	0.06	0.01	0.00	0.00	4.93	0.61	0.00	0.00	0.02	0.12	0.00	0.00	0.01	0.00	0.12	0.09	0.00	0.00	0.00	0.00	0.13	0.00	0.52	0.33	1.15	**8.4**
DE	0.19	0.29	0.00	0.01	0.00	0.34	0.04	0.00	0.00	0.62	4.60	0.00	0.02	0.01	0.04	0.00	0.00	0.02	0.00	0.39	0.49	0.00	0.01	0.02	0.00	0.03	0.01	0.61	0.29	0.68	**8.7**
GR	0.00	0.00	0.32	0.01	0.00	0.03	0.00	0.00	0.00	0.02	0.05	6.34	0.02	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.13	0.01	0.00	0.01	0.00	2.38	0.31	3.73	**13.6**
HU	0.32	0.02	0.08	0.31	0.00	0.47	0.00	0.00	0.00	0.10	0.46	0.01	5.62	0.00	0.22	0.00	0.00	0.00	0.00	0.02	1.04	0.00	0.67	0.48	0.09	0.00	0.00	2.38	0.06	1.18	**13.5**
IE	0.00	0.04	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.15	0.12	0.00	0.00	1.73	0.00	0.00	0.00	0.00	0.00	0.05	0.01	0.00	0.00	0.00	0.00	0.02	0.00	0.80	0.28	1.17	**4.4**
IT	0.13	0.00	0.01	0.09	0.00	0.07	0.00	0.00	0.00	0.19	0.16	0.00	0.03	0.00	9.32	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.02	0.01	0.11	0.07	0.00	0.63	0.41	2.41	**13.8**
LV	0.01	0.02	0.00	0.00	0.00	0.06	0.05	0.04	0.05	0.04	0.24	0.00	0.02	0.00	0.01	4.95	0.35	0.00	0.00	0.03	0.81	0.00	0.04	0.02	0.00	0.00	0.07	0.91	0.15	1.15	**9.0**
LT	0.02	0.02	0.01	0.01	0.00	0.10	0.06	0.02	0.03	0.05	0.34	0.00	0.04	0.00	0.02	0.09	2.79	0.00	0.00	0.04	1.53	0.00	0.06	0.03	0.00	0.00	0.06	1.28	0.16	1.09	**7.9**
LU	0.07	0.69	0.00	0.00	0.00	0.15	0.01	0.00	0.00	1.87	2.21	0.00	0.01	0.01	0.04	0.00	0.00	1.34	0.00	0.25	0.18	0.00	0.00	0.01	0.00	0.04	0.00	0.50	0.25	0.56	**8.2**
MT	0.00	0.00	0.02	0.01	0.00	0.03	0.00	0.00	0.00	0.16	0.05	0.02	0.00	0.00	0.75	0.00	0.00	0.00	1.49	0.00	0.05	0.00	0.01	0.00	0.00	0.13	0.00	0.55	1.29	7.80	**12.4**
NL	0.03	1.01	0.00	0.00	0.00	0.11	0.05	0.00	0.00	0.96	2.05	0.00	0.00	0.05	0.02	0.00	0.00	0.02	0.00	3.01	0.28	0.00	0.00	0.00	0.00	0.04	0.01	1.13	0.82	0.58	**10.2**
PL	0.08	0.04	0.01	0.04	0.00	0.65	0.05	0.00	0.01	0.12	0.88	0.00	0.15	0.00	0.05	0.01	0.03	0.00	0.00	0.06	11.31	0.00	0.11	0.16	0.02	0.00	0.02	1.00	0.14	0.94	**15.9**
PT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.18	0.00	0.00	0.00	0.68	0.00	0.03	0.35	2.43	**7.8**
RO	0.04	0.00	0.50	0.03	0.00	0.09	0.00	0.00	0.00	0.03	0.14	0.03	0.19	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.47	0.00	9.09	0.05	0.01	0.00	0.00	2.31	0.06	1.71	**14.8**
SK	0.30	0.02	0.04	0.13	0.00	0.77	0.01	0.00	0.00	0.10	0.52	0.00	0.93	0.00	0.14	0.00	0.00	0.00	0.00	0.02	1.68	0.00	0.34	3.30	0.06	0.00	0.00	1.47	0.05	1.05	**10.9**
SI	0.71	0.01	0.01	0.70	0.00	0.25	0.00	0.00	0.00	0.10	0.41	0.00	0.19	0.00	1.59	0.00	0.00	0.00	0.00	0.01	0.36	0.00	0.07	0.04	5.72	0.02	0.00	1.04	0.15	1.24	**12.6**
ES	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.05	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.01	0.12	0.00	0.00	0.00	5.33	0.00	0.05	0.43	2.56	**8.8**
SE	0.01	0.03	0.00	0.00	0.00	0.04	0.19	0.01	0.03	0.07	0.32	0.00	0.01	0.01	0.00	0.01	0.02	0.00	0.00	0.06	0.38	0.00	0.01	0.01	0.00	0.00	1.51	0.40	0.30	1.08	**4.5**

Source regions

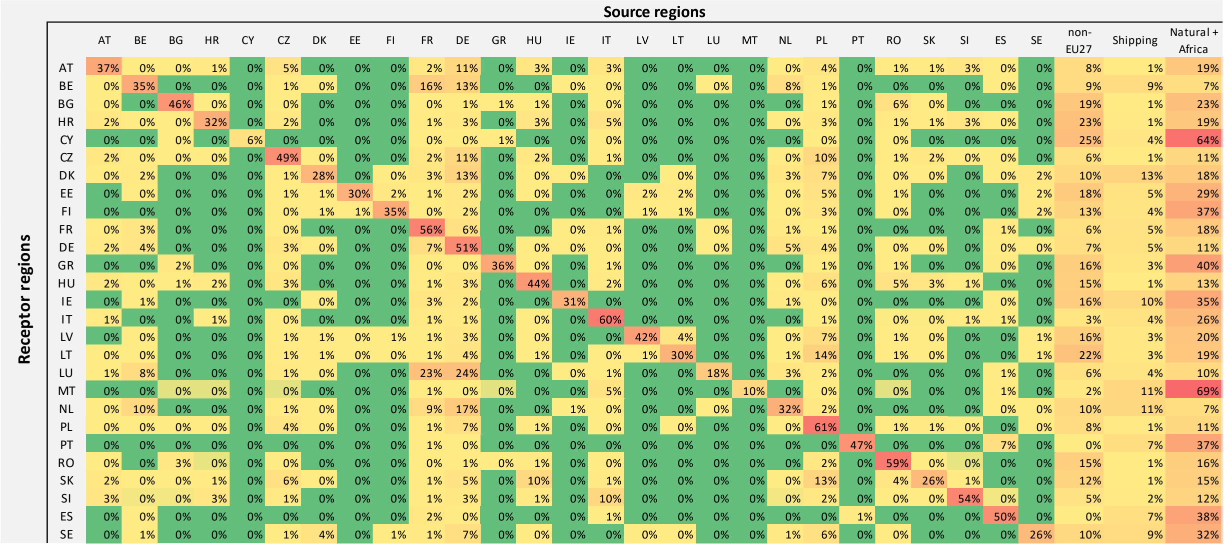
Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa
AT	44%	0%	0%	2%	0%	5%	0%	0%	0%	2%	10%	0%	3%	0%	3%	0%	0%	0%	0%	0%	5%	0%	1%	1%	2%	0%	0%	9%	1%	12%
BE	0%	35%	0%	0%	0%	1%	0%	0%	0%	17%	15%	0%	0%	0%	0%	0%	0%	0%	0%	7%	2%	0%	0%	0%	0%	0%	0%	10%	6%	5%
BG	0%	0%	52%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	2%	0%	5%	0%	0%	0%	0%	21%	1%	16%
HR	2%	0%	0%	44%	0%	2%	0%	0%	0%	1%	2%	0%	3%	0%	4%	0%	0%	0%	0%	0%	3%	0%	1%	1%	2%	0%	0%	23%	1%	11%
CY	0%	0%	0%	0%	8%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	29%	4%	58%
CZ	3%	0%	0%	1%	0%	52%	0%	0%	0%	2%	10%	0%	2%	0%	1%	0%	0%	0%	0%	0%	12%	0%	1%	2%	0%	0%	0%	7%	1%	7%
DK	0%	2%	0%	0%	0%	2%	28%	0%	0%	3%	15%	0%	0%	0%	0%	0%	0%	0%	0%	3%	9%	0%	0%	0%	0%	0%	2%	10%	10%	14%
EE	0%	0%	0%	0%	0%	1%	1%	43%	3%	0%	3%	0%	0%	0%	0%	2%	1%	0%	0%	0%	7%	0%	0%	0%	0%	0%	1%	13%	3%	21%
FI	0%	0%	0%	0%	0%	1%	1%	1%	40%	0%	2%	0%	0%	0%	0%	1%	1%	0%	0%	0%	5%	0%	0%	0%	0%	0%	2%	11%	3%	31%
FR	0%	3%	0%	0%	0%	1%	0%	0%	0%	59%	7%	0%	0%	0%	1%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	2%	0%	6%	4%	14%
DE	2%	3%	0%	0%	0%	4%	0%	0%	0%	7%	53%	0%	0%	0%	0%	0%	0%	0%	0%	4%	6%	0%	0%	0%	0%	0%	0%	7%	3%	8%
GR	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	47%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	18%	2%	27%
HU	2%	0%	1%	2%	0%	3%	0%	0%	0%	1%	3%	0%	42%	0%	2%	0%	0%	0%	0%	0%	8%	0%	5%	4%	1%	0%	0%	18%	0%	9%
IE	0%	1%	0%	0%	0%	0%	0%	0%	0%	3%	3%	0%	0%	39%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	18%	6%	27%
IT	1%	0%	0%	1%	0%	1%	0%	0%	0%	1%	1%	0%	0%	0%	68%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	1%	0%	5%	3%	18%
LV	0%	0%	0%	0%	0%	1%	1%	0%	1%	0%	3%	0%	0%	0%	0%	55%	4%	0%	0%	0%	9%	0%	0%	0%	0%	0%	1%	10%	2%	13%
LT	0%	0%	0%	0%	0%	1%	1%	0%	0%	1%	4%	0%	1%	0%	0%	1%	36%	0%	0%	1%	19%	0%	1%	0%	0%	0%	1%	16%	2%	14%
LU	1%	8%	0%	0%	0%	2%	0%	0%	0%	23%	27%	0%	0%	0%	0%	0%	0%	16%	0%	3%	2%	0%	0%	0%	0%	0%	0%	6%	3%	7%
MT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	6%	0%	0%	0%	12%	0%	0%	0%	0%	0%	0%	1%	0%	4%	10%	63%
NL	0%	10%	0%	0%	0%	1%	0%	0%	0%	9%	20%	0%	0%	0%	0%	0%	0%	0%	0%	30%	3%	0%	0%	0%	0%	0%	0%	11%	8%	6%
PL	1%	0%	0%	0%	0%	4%	0%	0%	0%	1%	6%	0%	1%	0%	0%	0%	0%	0%	0%	0%	71%	0%	1%	1%	0%	0%	0%	6%	1%	6%
PT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	54%	0%	0%	0%	9%	0%	0%	5%	31%
RO	0%	0%	3%	0%	0%	1%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	3%	0%	61%	0%	0%	0%	0%	16%	0%	12%
SK	3%	0%	0%	1%	0%	7%	0%	0%	0%	1%	5%	0%	9%	0%	1%	0%	0%	0%	0%	0%	15%	0%	3%	30%	1%	0%	0%	13%	0%	10%
SI	6%	0%	0%	6%	0%	2%	0%	0%	0%	1%	3%	0%	2%	0%	13%	0%	0%	0%	0%	0%	3%	0%	1%	0%	45%	0%	0%	8%	1%	10%
ES	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	1%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	60%	0%	1%	5%	29%
SE	0%	1%	0%	0%	0%	1%	4%	0%	1%	2%	7%	0%	0%	0%	0%	0%	0%	0%	0%	1%	8%	0%	0%	0%	0%	0%	34%	9%	7%	24%

Figure 4-29: Origin of population-weighted $PM_{2.5}$ background concentrations in each Member State computed for 2030 *Baseline* scenario in µg/m³ [top] and as percent of total background concentrations [bottom].



Source regions

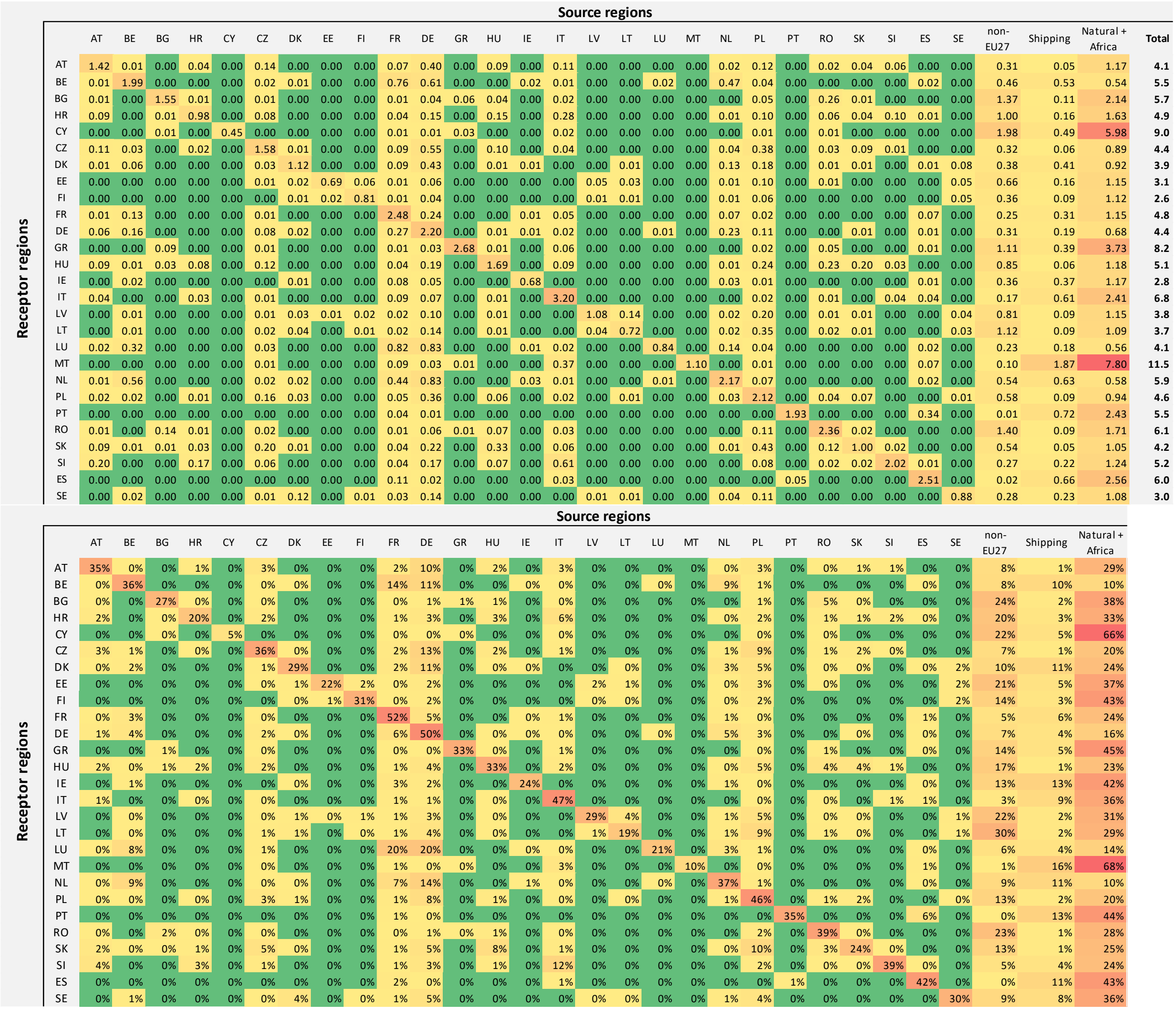
Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa	**Total**
AT	2.21	0.02	0.01	0.08	0.00	0.30	0.00	0.00	0.00	0.12	0.64	0.00	0.19	0.00	0.19	0.00	0.00	0.00	0.00	0.02	0.25	0.00	0.05	0.07	0.17	0.01	0.00	0.49	0.06	1.17	**6.1**
BE	0.01	2.68	0.00	0.00	0.00	0.05	0.02	0.00	0.00	1.24	1.02	0.00	0.00	0.03	0.02	0.00	0.00	0.03	0.00	0.58	0.09	0.00	0.00	0.00	0.00	0.03	0.00	0.69	0.67	0.54	**7.7**
BG	0.02	0.00	4.20	0.01	0.00	0.03	0.00	0.00	0.00	0.01	0.06	0.09	0.06	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.56	0.02	0.00	0.00	0.00	1.76	0.08	2.14	**9.2**
HR	0.15	0.01	0.03	2.74	0.00	0.16	0.00	0.00	0.00	0.06	0.23	0.00	0.28	0.00	0.44	0.00	0.00	0.00	0.00	0.01	0.23	0.00	0.11	0.06	0.26	0.02	0.00	1.91	0.12	1.63	**8.5**
CY	0.00	0.00	0.02	0.00	0.53	0.00	0.00	0.00	0.00	0.01	0.01	0.06	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	2.31	0.33	5.98	**9.3**
CZ	0.18	0.04	0.01	0.04	0.00	3.95	0.01	0.00	0.00	0.15	0.88	0.00	0.19	0.00	0.06	0.00	0.00	0.00	0.00	0.04	0.80	0.00	0.07	0.14	0.04	0.01	0.00	0.51	0.08	0.89	**8.1**
DK	0.01	0.08	0.00	0.00	0.00	0.06	1.46	0.00	0.01	0.15	0.67	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.17	0.34	0.00	0.01	0.01	0.00	0.01	0.10	0.51	0.65	0.92	**5.2**
EE	0.00	0.01	0.00	0.00	0.00	0.02	0.03	1.19	0.09	0.02	0.09	0.00	0.01	0.00	0.00	0.08	0.06	0.00	0.00	0.01	0.20	0.00	0.02	0.00	0.00	0.00	0.06	0.70	0.19	1.15	**3.9**
FI	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	1.05	0.01	0.06	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.01	0.10	0.00	0.01	0.00	0.00	0.00	0.06	0.40	0.12	1.12	**3.0**
FR	0.02	0.18	0.00	0.00	0.00	0.03	0.00	0.00	0.00	3.55	0.39	0.00	0.00	0.01	0.08	0.00	0.00	0.01	0.00	0.09	0.04	0.00	0.00	0.00	0.00	0.09	0.00	0.36	0.34	1.15	**6.3**
DE	0.10	0.22	0.00	0.00	0.00	0.19	0.03	0.00	0.00	0.44	3.17	0.00	0.02	0.01	0.03	0.00	0.00	0.01	0.00	0.29	0.25	0.00	0.01	0.01	0.00	0.02	0.01	0.43	0.28	0.68	**6.2**
GR	0.00	0.00	0.20	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.04	3.36	0.02	0.00	0.09	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.10	0.00	0.00	0.01	0.00	1.45	0.27	3.73	**9.3**
HU	0.16	0.01	0.05	0.15	0.00	0.27	0.00	0.00	0.00	0.07	0.30	0.00	4.05	0.00	0.14	0.00	0.00	0.00	0.00	0.01	0.53	0.00	0.50	0.31	0.07	0.00	0.00	1.43	0.06	1.18	**9.3**
IE	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.11	0.08	0.00	0.00	1.03	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.55	0.33	1.17	**3.4**
IT	0.07	0.00	0.00	0.05	0.00	0.03	0.00	0.00	0.00	0.14	0.11	0.00	0.02	0.00	5.69	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.01	0.01	0.09	0.05	0.00	0.29	0.42	2.41	**9.4**
LV	0.00	0.01	0.00	0.00	0.00	0.03	0.04	0.02	0.03	0.03	0.16	0.00	0.01	0.00	0.00	2.34	0.24	0.00	0.00	0.02	0.42	0.00	0.03	0.01	0.00	0.00	0.05	0.87	0.15	1.15	**5.6**
LT	0.01	0.02	0.00	0.00	0.00	0.06	0.05	0.01	0.02	0.04	0.22	0.00	0.03	0.00	0.01	0.06	1.68	0.00	0.00	0.03	0.79	0.00	0.05	0.02	0.00	0.00	0.04	1.21	0.15	1.09	**5.6**
LU	0.03	0.48	0.00	0.00	0.00	0.08	0.01	0.00	0.00	1.34	1.39	0.00	0.00	0.01	0.03	0.00	0.00	1.06	0.00	0.18	0.09	0.00	0.00	0.00	0.00	0.03	0.00	0.34	0.25	0.56	**5.9**
MT	0.00	0.00	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.12	0.04	0.01	0.00	0.00	0.55	0.00	0.00	0.00	1.17	0.00	0.03	0.00	0.01	0.00	0.00	0.09	0.00	0.22	1.26	7.80	**11.3**
NL	0.01	0.78	0.00	0.00	0.00	0.06	0.03	0.00	0.00	0.70	1.34	0.00	0.00	0.04	0.01	0.00	0.00	0.01	0.00	2.47	0.15	0.00	0.00	0.00	0.00	0.03	0.01	0.79	0.83	0.58	**7.8**
PL	0.04	0.03	0.01	0.02	0.00	0.37	0.04	0.00	0.00	0.09	0.57	0.00	0.11	0.00	0.03	0.00	0.02	0.00	0.00	0.04	5.32	0.00	0.09	0.11	0.01	0.00	0.02	0.72	0.13	0.94	**8.7**
PT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.03	0.00	0.00	0.00	0.45	0.00	0.02	0.48	2.43	**6.5**
RO	0.02	0.00	0.30	0.01	0.00	0.05	0.00	0.00	0.00	0.02	0.09	0.02	0.14	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.24	0.00	6.52	0.04	0.01	0.00	0.00	1.69	0.07	1.71	**11.0**
SK	0.15	0.02	0.03	0.07	0.00	0.44	0.01	0.00	0.00	0.07	0.34	0.00	0.67	0.00	0.09	0.00	0.00	0.00	0.00	0.02	0.87	0.00	0.26	1.80	0.05	0.00	0.00	0.84	0.05	1.05	**6.8**
SI	0.35	0.01	0.01	0.34	0.00	0.14	0.00	0.00	0.00	0.07	0.27	0.00	0.14	0.00	1.05	0.00	0.00	0.00	0.00	0.01	0.18	0.00	0.05	0.03	5.44	0.01	0.00	0.51	0.16	1.24	**10.0**
ES	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.03	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.00	0.00	3.30	0.00	0.03	0.45	2.56	**6.7**
SE	0.00	0.02	0.00	0.00	0.00	0.02	0.15	0.00	0.02	0.05	0.22	0.00	0.01	0.00	0.00	0.01	0.01	0.00	0.00	0.05	0.21	0.00	0.01	0.00	0.00	0.00	0.87	0.34	0.30	1.08	**3.4**



Source regions

Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa
AT	37%	0%	0%	1%	0%	5%	0%	0%	0%	2%	11%	0%	3%	0%	3%	0%	0%	0%	0%	0%	4%	0%	1%	1%	3%	0%	0%	8%	1%	19%
BE	0%	35%	0%	0%	0%	1%	0%	0%	0%	16%	13%	0%	0%	0%	0%	0%	0%	0%	0%	8%	1%	0%	0%	0%	0%	0%	0%	9%	9%	7%
BG	0%	0%	46%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%	6%	0%	0%	0%	0%	19%	1%	23%
HR	2%	0%	0%	32%	0%	2%	0%	0%	0%	1%	3%	0%	3%	0%	5%	0%	0%	0%	0%	0%	3%	0%	1%	1%	3%	0%	0%	23%	1%	19%
CY	0%	0%	0%	0%	6%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	25%	4%	64%
CZ	2%	0%	0%	0%	0%	49%	0%	0%	0%	2%	11%	0%	2%	0%	1%	0%	0%	0%	0%	0%	10%	0%	1%	2%	0%	0%	0%	6%	1%	11%
DK	0%	2%	0%	0%	0%	1%	28%	0%	0%	3%	13%	0%	0%	0%	0%	0%	0%	0%	0%	3%	7%	0%	0%	0%	0%	0%	2%	10%	13%	18%
EE	0%	0%	0%	0%	0%	1%	1%	30%	2%	1%	2%	0%	0%	0%	0%	2%	2%	0%	0%	0%	5%	0%	1%	0%	0%	0%	2%	18%	5%	29%
FI	0%	0%	0%	0%	0%	0%	1%	1%	35%	0%	2%	0%	0%	0%	0%	1%	1%	0%	0%	0%	3%	0%	0%	0%	0%	0%	2%	13%	4%	37%
FR	0%	3%	0%	0%	0%	0%	0%	0%	0%	56%	6%	0%	0%	0%	1%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%	1%	0%	6%	5%	18%
DE	2%	4%	0%	0%	0%	3%	0%	0%	0%	7%	51%	0%	0%	0%	0%	0%	0%	0%	0%	5%	4%	0%	0%	0%	0%	0%	0%	7%	5%	11%
GR	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	36%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	16%	3%	40%
HU	2%	0%	1%	2%	0%	3%	0%	0%	0%	1%	3%	0%	44%	0%	2%	0%	0%	0%	0%	0%	6%	0%	5%	3%	1%	0%	0%	15%	1%	13%
IE	0%	1%	0%	0%	0%	0%	0%	0%	0%	3%	2%	0%	0%	31%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	16%	10%	35%
IT	1%	0%	0%	1%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	60%	0%	0%	0%	0%	0%	1%	0%	0%	0%	1%	1%	0%	3%	4%	26%
LV	0%	0%	0%	0%	0%	1%	1%	0%	1%	1%	3%	0%	0%	0%	0%	42%	4%	0%	0%	0%	7%	0%	1%	0%	0%	0%	1%	16%	3%	20%
LT	0%	0%	0%	0%	0%	1%	1%	0%	0%	1%	4%	0%	1%	0%	0%	1%	30%	0%	0%	1%	14%	0%	1%	0%	0%	0%	1%	22%	3%	19%
LU	1%	8%	0%	0%	0%	1%	0%	0%	0%	23%	24%	0%	0%	0%	1%	0%	0%	18%	0%	3%	2%	0%	0%	0%	0%	1%	0%	6%	4%	10%
MT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	5%	0%	0%	0%	10%	0%	0%	0%	0%	0%	0%	1%	0%	2%	11%	69%
NL	0%	10%	0%	0%	0%	1%	0%	0%	0%	9%	17%	0%	0%	1%	0%	0%	0%	0%	0%	32%	2%	0%	0%	0%	0%	0%	0%	10%	11%	7%
PL	0%	0%	0%	0%	0%	4%	0%	0%	0%	1%	7%	0%	1%	0%	0%	0%	0%	0%	0%	0%	61%	0%	1%	1%	0%	0%	0%	8%	1%	11%
PT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	47%	0%	0%	0%	7%	0%	0%	7%	37%
RO	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	2%	0%	59%	0%	0%	0%	0%	15%	1%	16%
SK	2%	0%	0%	1%	0%	6%	0%	0%	0%	1%	5%	0%	10%	0%	1%	0%	0%	0%	0%	0%	13%	0%	4%	26%	1%	0%	0%	12%	1%	15%
SI	3%	0%	0%	3%	0%	1%	0%	0%	0%	1%	3%	0%	1%	0%	10%	0%	0%	0%	0%	0%	2%	0%	0%	0%	54%	0%	0%	5%	2%	12%
ES	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	50%	0%	0%	7%	38%
SE	0%	1%	0%	0%	0%	1%	4%	0%	1%	1%	7%	0%	0%	0%	0%	0%	0%	0%	0%	1%	6%	0%	0%	0%	0%	0%	26%	10%	9%	32%

Figure 4-30: Origin of population-weighted $PM_{2.5}$ background concentrations in each Member State computed for 2050 *Baseline* scenario in µg/m³ [top] and as percent of total background concentrations [bottom].



Source regions

Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa	Total
AT	1.42	0.01	0.00	0.04	0.00	0.14	0.00	0.00	0.00	0.07	0.40	0.00	0.09	0.00	0.11	0.00	0.00	0.00	0.00	0.02	0.12	0.00	0.02	0.04	0.06	0.00	0.00	0.31	0.05	1.17	**4.1**
BE	0.01	1.99	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.76	0.61	0.00	0.00	0.02	0.01	0.00	0.00	0.02	0.00	0.47	0.04	0.00	0.00	0.00	0.00	0.02	0.00	0.46	0.53	0.54	**5.5**
BG	0.01	0.00	1.55	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.04	0.06	0.04	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.26	0.01	0.00	0.00	0.00	1.37	0.11	2.14	**5.7**
HR	0.09	0.00	0.01	0.98	0.00	0.08	0.00	0.00	0.00	0.04	0.15	0.00	0.15	0.00	0.28	0.00	0.00	0.00	0.00	0.01	0.10	0.00	0.06	0.04	0.10	0.01	0.00	1.00	0.16	1.63	**4.9**
CY	0.00	0.00	0.01	0.00	0.45	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	1.98	0.49	5.98	**9.0**
CZ	0.11	0.03	0.00	0.02	0.00	1.58	0.01	0.00	0.00	0.09	0.55	0.00	0.10	0.00	0.04	0.00	0.00	0.00	0.00	0.04	0.38	0.00	0.03	0.09	0.01	0.00	0.00	0.32	0.06	0.89	**4.4**
DK	0.01	0.06	0.00	0.00	0.00	0.03	1.12	0.00	0.00	0.09	0.43	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.13	0.18	0.00	0.01	0.01	0.00	0.01	0.08	0.38	0.41	0.92	**3.9**
EE	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.69	0.06	0.01	0.06	0.00	0.00	0.00	0.00	0.05	0.03	0.00	0.00	0.01	0.10	0.00	0.01	0.00	0.00	0.00	0.05	0.66	0.16	1.15	**3.1**
FI	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.81	0.01	0.04	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.01	0.06	0.00	0.00	0.00	0.00	0.00	0.05	0.36	0.09	1.12	**2.6**
FR	0.01	0.13	0.00	0.00	0.00	0.01	0.00	0.00	0.00	2.48	0.24	0.00	0.00	0.01	0.05	0.00	0.00	0.00	0.00	0.07	0.02	0.00	0.00	0.00	0.00	0.07	0.00	0.25	0.31	1.15	**4.8**
DE	0.06	0.16	0.00	0.00	0.00	0.08	0.02	0.00	0.00	0.27	2.20	0.00	0.01	0.01	0.02	0.00	0.00	0.01	0.00	0.23	0.11	0.00	0.00	0.01	0.00	0.01	0.00	0.31	0.19	0.68	**4.4**
GR	0.00	0.00	0.09	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.03	2.68	0.01	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.05	0.00	0.00	0.01	0.00	1.11	0.39	3.73	**8.2**
HU	0.09	0.01	0.03	0.08	0.00	0.12	0.00	0.00	0.00	0.04	0.19	0.00	1.69	0.00	0.09	0.00	0.00	0.00	0.00	0.01	0.24	0.00	0.23	0.20	0.03	0.00	0.00	0.85	0.06	1.18	**5.1**
IE	0.00	0.02	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.08	0.05	0.00	0.00	0.68	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.36	0.37	1.17	**2.8**
IT	0.04	0.00	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.09	0.07	0.00	0.01	0.00	3.20	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.01	0.00	0.04	0.04	0.00	0.17	0.61	2.41	**6.8**
LV	0.00	0.01	0.00	0.00	0.00	0.01	0.03	0.01	0.02	0.02	0.10	0.00	0.01	0.00	0.00	1.08	0.14	0.00	0.00	0.02	0.20	0.00	0.01	0.01	0.00	0.00	0.04	0.81	0.09	1.15	**3.8**
LT	0.00	0.01	0.00	0.00	0.00	0.02	0.04	0.00	0.01	0.02	0.14	0.00	0.01	0.00	0.00	0.04	0.72	0.00	0.00	0.02	0.35	0.00	0.02	0.01	0.00	0.00	0.03	1.12	0.09	1.09	**3.7**
LU	0.02	0.32	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.82	0.83	0.00	0.00	0.01	0.02	0.00	0.00	0.84	0.00	0.14	0.04	0.00	0.00	0.00	0.00	0.02	0.00	0.23	0.18	0.56	**4.1**
MT	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.09	0.03	0.01	0.00	0.00	0.37	0.00	0.00	0.00	1.10	0.00	0.01	0.00	0.00	0.00	0.00	0.07	0.00	0.10	1.87	7.80	**11.5**
NL	0.01	0.56	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.44	0.83	0.00	0.00	0.03	0.01	0.00	0.00	0.01	0.00	2.17	0.07	0.00	0.00	0.00	0.00	0.02	0.00	0.54	0.63	0.58	**5.9**
PL	0.02	0.02	0.00	0.01	0.00	0.16	0.03	0.00	0.00	0.05	0.36	0.00	0.06	0.00	0.02	0.00	0.01	0.00	0.00	0.03	2.12	0.00	0.04	0.07	0.00	0.00	0.01	0.58	0.09	0.94	**4.6**
PT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.93	0.00	0.00	0.00	0.34	0.00	0.01	0.72	2.43	**5.5**
RO	0.01	0.00	0.14	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.06	0.01	0.07	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.11	0.00	2.36	0.02	0.00	0.00	0.00	1.40	0.09	1.71	**6.1**
SK	0.09	0.01	0.01	0.03	0.00	0.20	0.01	0.00	0.00	0.04	0.22	0.00	0.33	0.00	0.06	0.00	0.00	0.00	0.00	0.01	0.43	0.00	0.12	1.00	0.02	0.00	0.00	0.54	0.05	1.05	**4.2**
SI	0.20	0.00	0.00	0.17	0.00	0.06	0.00	0.00	0.00	0.04	0.17	0.00	0.07	0.00	0.61	0.00	0.00	0.00	0.00	0.00	0.08	0.00	0.02	0.02	2.02	0.01	0.00	0.27	0.22	1.24	**5.2**
ES	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.02	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	2.51	0.00	0.02	0.66	2.56	**6.0**
SE	0.00	0.02	0.00	0.00	0.00	0.01	0.12	0.00	0.01	0.03	0.14	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.04	0.11	0.00	0.00	0.00	0.00	0.00	0.88	0.28	0.23	1.08	**3.0**

Source regions

Receptor regions	AT	BE	BG	HR	CY	CZ	DK	EE	FI	FR	DE	GR	HU	IE	IT	LV	LT	LU	MT	NL	PL	PT	RO	SK	SI	ES	SE	non-EU27	Shipping	Natural + Africa
AT	35%	0%	0%	1%	0%	3%	0%	0%	0%	2%	10%	0%	2%	0%	3%	0%	0%	0%	0%	0%	3%	0%	0%	1%	1%	0%	0%	8%	1%	29%
BE	0%	36%	0%	0%	0%	0%	0%	0%	0%	14%	11%	0%	0%	0%	0%	0%	0%	0%	0%	9%	1%	0%	0%	0%	0%	0%	0%	8%	10%	10%
BG	0%	0%	27%	0%	0%	0%	0%	0%	0%	0%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%	5%	0%	0%	0%	0%	24%	2%	38%
HR	2%	0%	0%	20%	0%	2%	0%	0%	0%	1%	3%	0%	3%	0%	6%	0%	0%	0%	0%	0%	2%	0%	1%	1%	2%	0%	0%	20%	3%	33%
CY	0%	0%	0%	0%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	22%	5%	66%
CZ	3%	1%	0%	0%	0%	36%	0%	0%	0%	2%	13%	0%	2%	0%	1%	0%	0%	0%	0%	1%	9%	0%	1%	2%	0%	0%	0%	7%	1%	20%
DK	0%	2%	0%	0%	0%	1%	29%	0%	0%	2%	11%	0%	0%	0%	0%	0%	0%	0%	0%	3%	5%	0%	0%	0%	0%	0%	2%	10%	11%	24%
EE	0%	0%	0%	0%	0%	0%	1%	22%	2%	0%	2%	0%	0%	0%	0%	2%	1%	0%	0%	0%	3%	0%	0%	0%	0%	0%	2%	21%	5%	37%
FI	0%	0%	0%	0%	0%	0%	0%	1%	31%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	0%	2%	14%	3%	43%
FR	0%	3%	0%	0%	0%	0%	0%	0%	0%	52%	5%	0%	0%	0%	1%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	1%	0%	5%	6%	24%
DE	1%	4%	0%	0%	0%	2%	0%	0%	0%	6%	50%	0%	0%	0%	0%	0%	0%	0%	0%	5%	3%	0%	0%	0%	0%	0%	0%	7%	4%	16%
GR	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	33%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	14%	5%	45%
HU	2%	0%	1%	2%	0%	2%	0%	0%	0%	1%	4%	0%	33%	0%	2%	0%	0%	0%	0%	0%	5%	0%	4%	4%	1%	0%	0%	17%	1%	23%
IE	0%	1%	0%	0%	0%	0%	0%	0%	0%	3%	2%	0%	0%	24%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	13%	13%	42%
IT	1%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	47%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	3%	9%	36%
LV	0%	0%	0%	0%	0%	0%	1%	0%	1%	1%	3%	0%	0%	0%	0%	29%	4%	0%	0%	1%	5%	0%	0%	0%	0%	0%	1%	22%	2%	31%
LT	0%	0%	0%	0%	0%	1%	1%	0%	0%	1%	4%	0%	0%	0%	0%	1%	19%	0%	0%	1%	9%	0%	1%	0%	0%	0%	1%	30%	2%	29%
LU	0%	8%	0%	0%	0%	1%	0%	0%	0%	20%	20%	0%	0%	0%	0%	0%	0%	21%	0%	3%	1%	0%	0%	0%	0%	0%	0%	6%	4%	14%
MT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	3%	0%	0%	0%	10%	0%	0%	0%	0%	0%	0%	1%	0%	1%	16%	68%
NL	0%	9%	0%	0%	0%	0%	0%	0%	0%	7%	14%	0%	0%	1%	0%	0%	0%	0%	0%	37%	1%	0%	0%	0%	0%	0%	0%	9%	11%	10%
PL	0%	0%	0%	0%	0%	3%	1%	0%	0%	1%	8%	0%	1%	0%	0%	0%	0%	0%	0%	1%	46%	0%	1%	2%	0%	0%	0%	13%	2%	20%
PT	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	35%	0%	0%	0%	6%	0%	0%	13%	44%
RO	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%	0%	2%	0%	39%	0%	0%	0%	0%	23%	1%	28%
SK	2%	0%	0%	1%	0%	5%	0%	0%	0%	1%	5%	0%	8%	0%	1%	0%	0%	0%	0%	0%	10%	0%	3%	24%	0%	0%	0%	13%	1%	25%
SI	4%	0%	0%	3%	0%	1%	0%	0%	0%	1%	3%	0%	1%	0%	12%	0%	0%	0%	0%	0%	2%	0%	0%	0%	39%	0%	0%	5%	4%	24%
ES	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%	42%	0%	0%	11%	43%
SE	0%	1%	0%	0%	0%	0%	4%	0%	0%	1%	5%	0%	0%	0%	0%	0%	0%	0%	0%	1%	4%	0%	0%	0%	0%	0%	30%	9%	8%	36%

4.5.2 Origin of $PM_{2.5}$ in each Member State

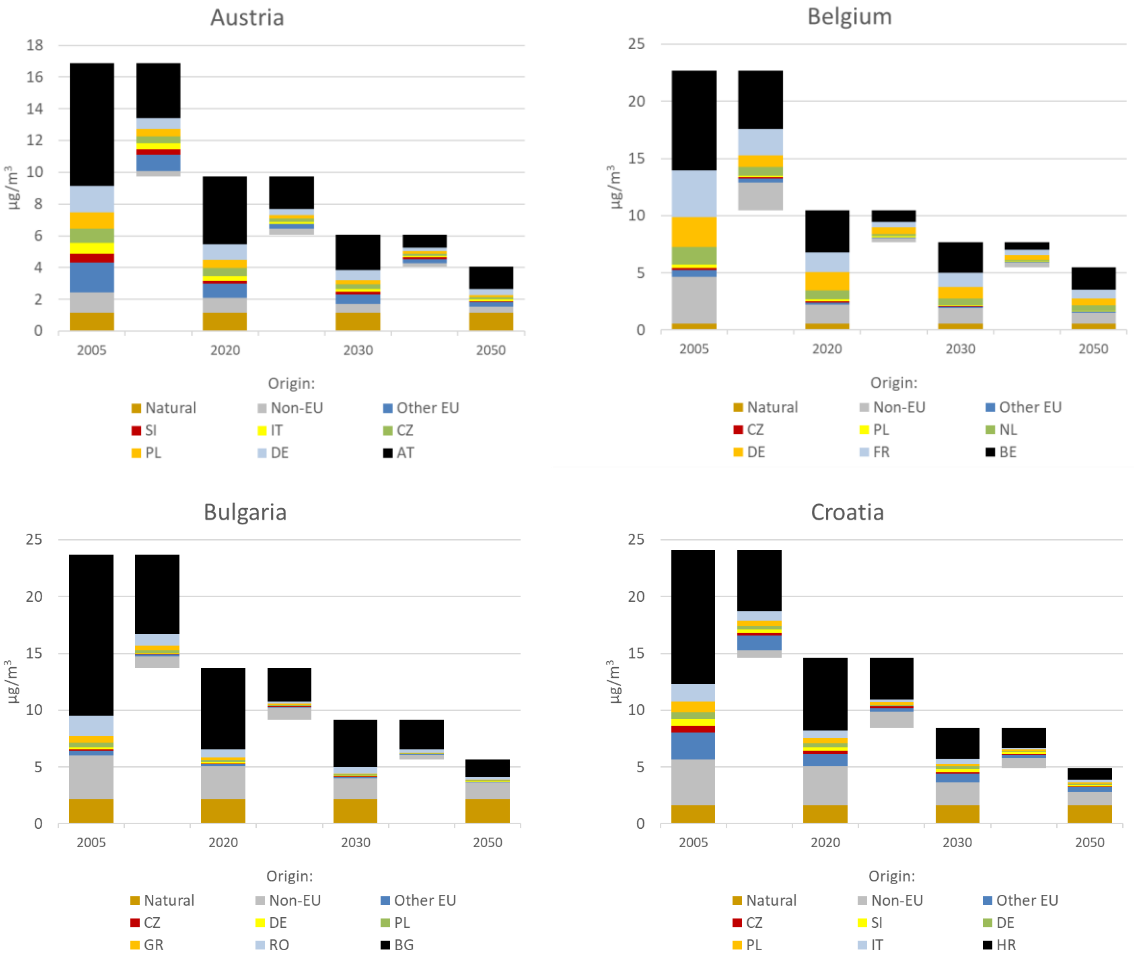
Another way of revealing the importance of the joint action and international collaboration in air quality management, including benefits of the coordinated EU policy stimulating emission reductions, is to show the origin of contribution to background $PM_{2.5}$ in each Member State and over time.

The charts in Figure 4-31 show for each Member State the contributions to population-weighted $PM_{2.5}$ and their change over time (for four selected years: 2005, 2020 and 2030 and 2050 *Baseline* scenario). They show for each Member State own contribution (always in black), six largest contributors from the EU, and always (and in the same colours) contribution from natural, non-EU, and other-EU sources.

For many Member States, their own domestic reductions represent often about 50% or more of the reduction of $PM_{2.5}$ concentrations. An important contribution driven by measures introduced across the EU highlights the importance of coordinated action and for some Member States these reductions dominate the estimated reduction of $PM_{2.5}$ concentrations. Similarly to the observation made in the previous section, and unsurprisingly, the role of sources outside the EU increases over time and their importance varies from country to country. However, compared to CAO3, the non-EU contribution in absolute terms is lower owing to consideration (in CAO4 *Baseline*) of the results of the EU4Green study for West Balkan, which include decarbonization policy and effective implementation of air pollution legislation in power, industry, and transport sectors.

This analysis also shows that over time, some countries or regions contribute to an increase of concentrations in a given time period, however, this is always more than compensated by remaining reductions and so a declining trend in concentrations is observed throughout the whole time horizon. In such cases, the bars illustrating differences between scenario years are broken into increases and decreases. These examples include Finland, Malta, Italy, Portugal, Spain, Sweden where typically the non-EU contribution leads to a slight increase in the period 2020-30 or 2030-2050. Finally, some countries have very different structure of contributing sources and natural sources and shipping dominate[39].

Figure 4-31: Origins of ambient background concentrations of $PM_{2.5}$ (population-weighted) in each Member State in the period 2005 to 2050 and the contribution to the changes during respective periods (bars 2, 4, 6). The category 'Non-EU' includes West Balkan, Belarus, Norway, the European part of Russia, Switzerland, Turkey, the UK, the Ukraine, and international shipping.



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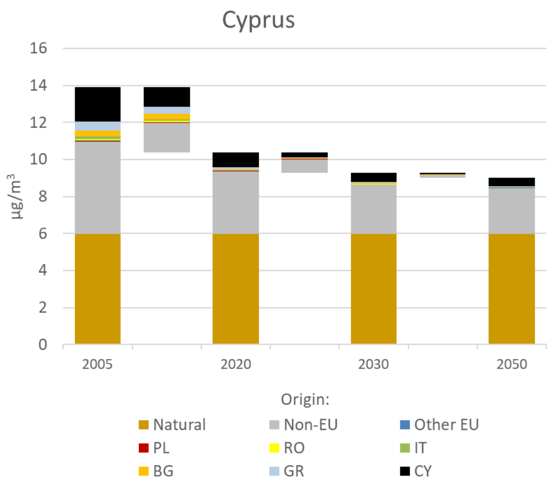
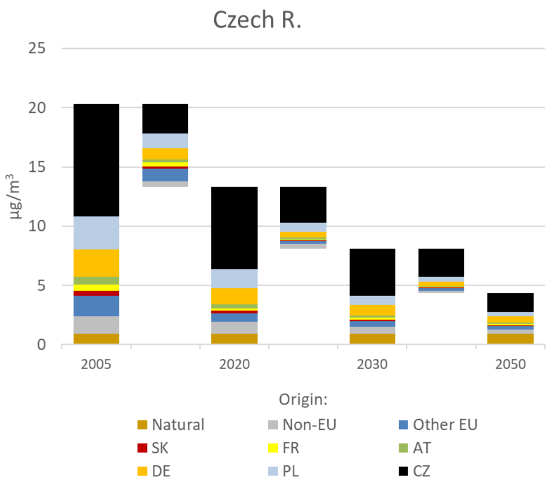
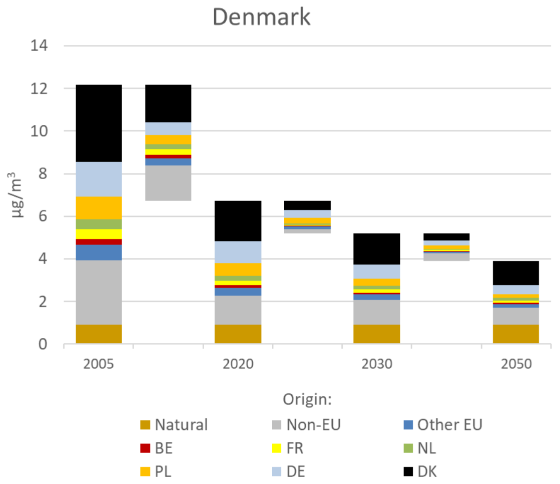
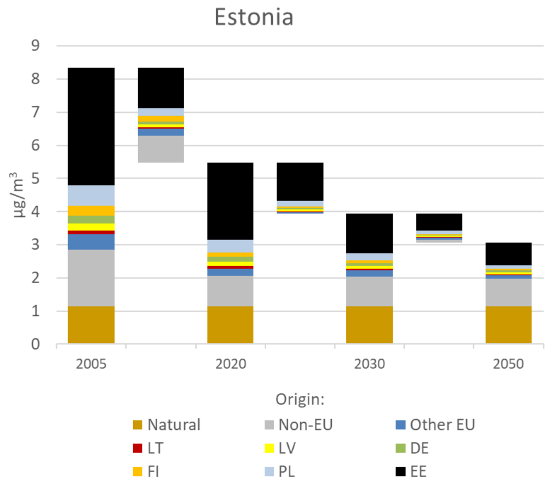
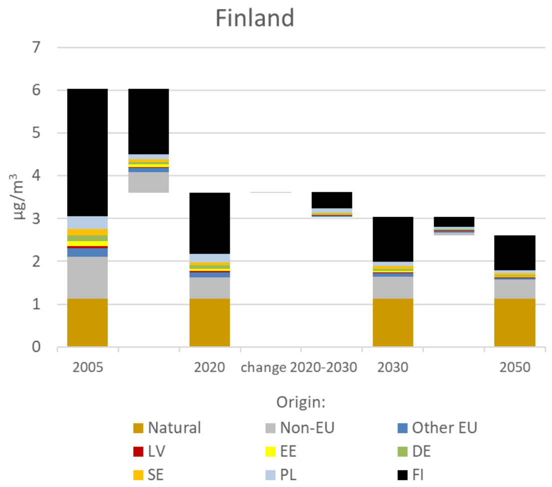
[39] Note that in this figure, shipping is included in the category 'non-EU', but the explicit contribution of shipping can be read from the tables in the previous section.

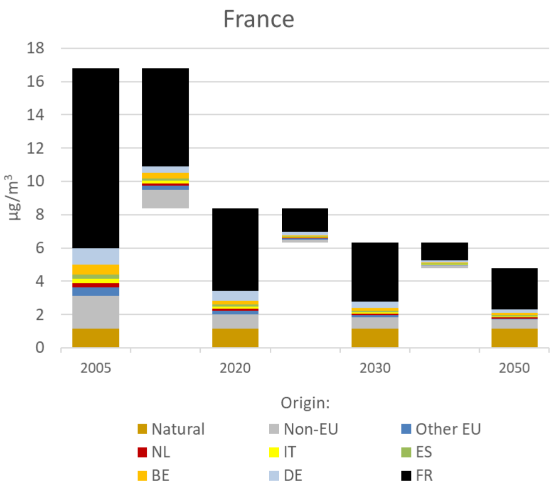

Cyprus
µg/m³
0
2
4
6
8
10
12
14
16
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
PL
RO
IT
BG
GR
CY

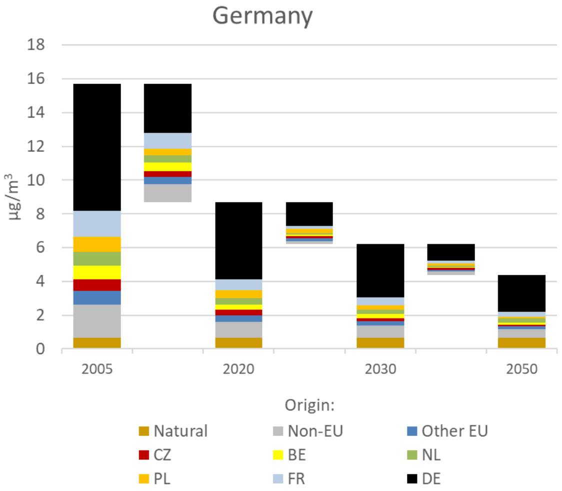

Czech R.
µg/m³
0
5
10
15
20
25
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
SK
FR
AT
DE
PL
CZ

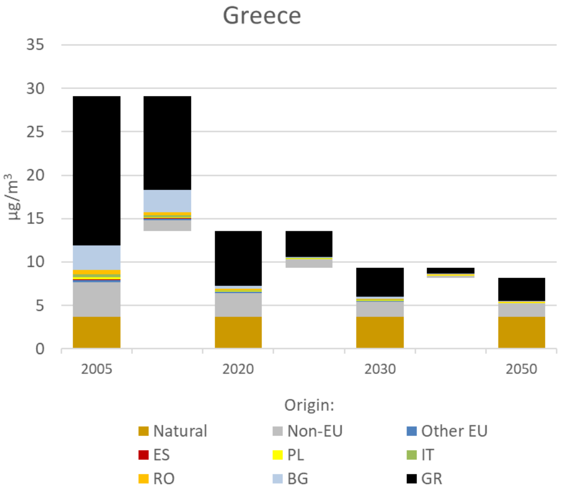

Denmark
µg/m³
0
2
4
6
8
10
12
14
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
BE
FR
NL
PL
DE
DK

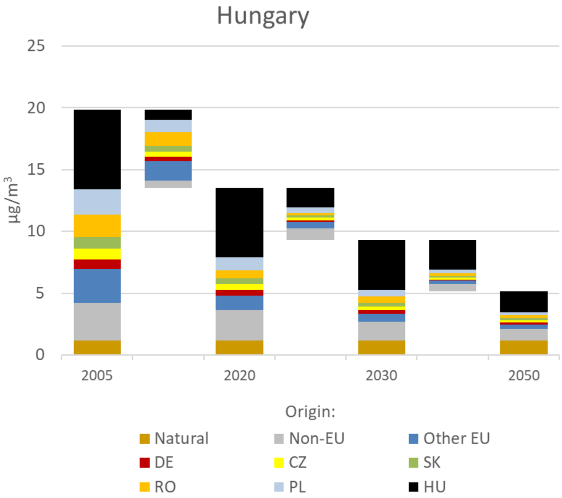

Estonia
µg/m³
0
1
2
3
4
5
6
7
8
9
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
LT
LV
DE
FI
PL
EE

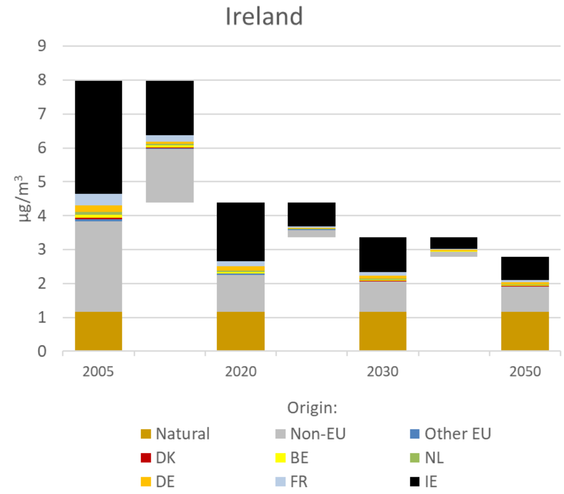

Finland
µg/m³
0
1
2
3
4
5
6
7
2005
2020
change 2020-2030
2030
2050
Origin:
Natural
Non-EU
Other EU
LV
EE
DE
SE
PL
FI

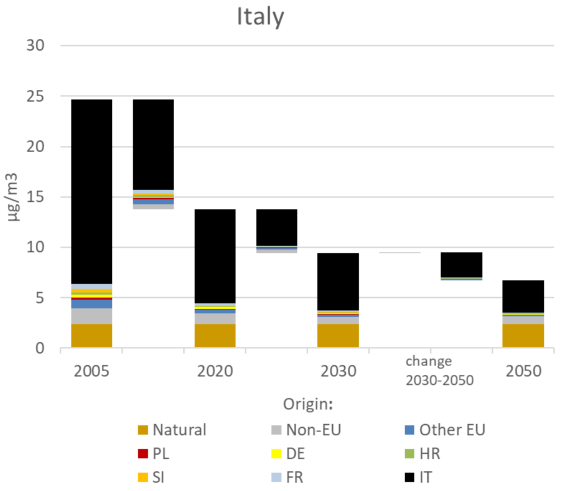

France
µg/m³
0
2
4
6
8
10
12
14
16
18
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
NL
IT
ES
BE
DE
FR

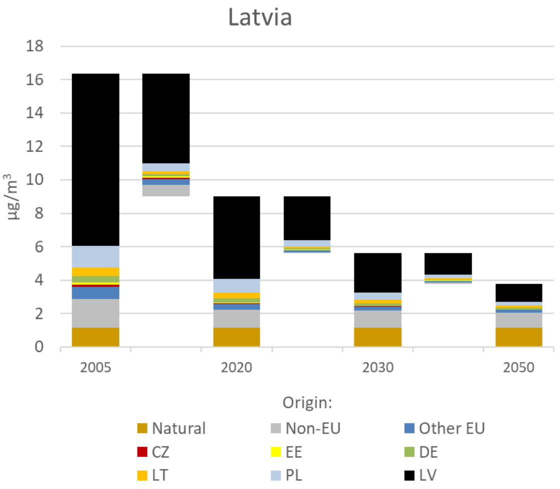

Germany
µg/m3
0
2
4
6
8
10
12
14
16
18
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
CZ
BE
NL
PL
FR
DE

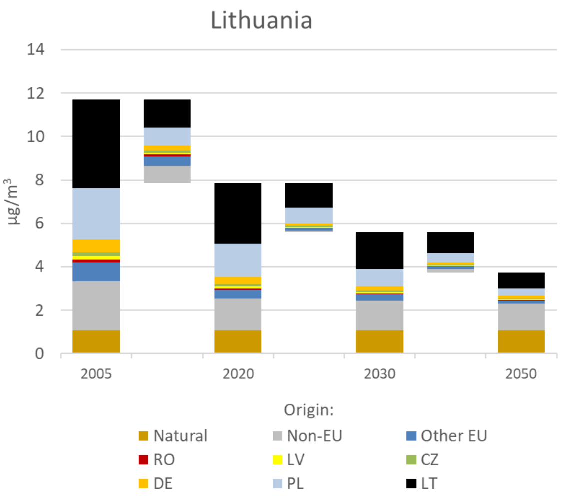

Greece
µg/m3
0
5
10
15
20
25
30
35
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
ES
PL
IT
RO
BG
GR

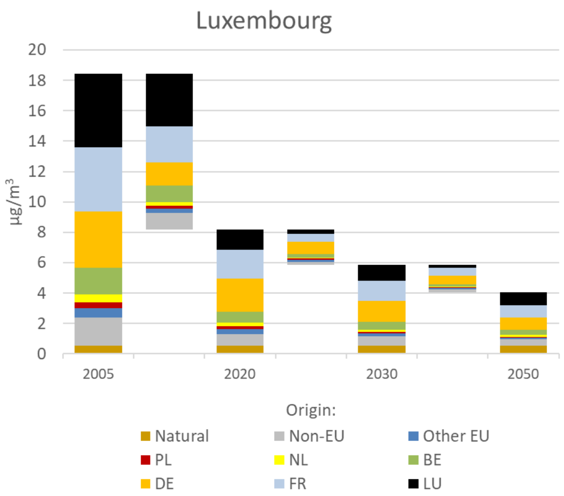

Hungary
µg/m3
0
5
10
15
20
25
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
DE
CZ
SK
RO
PL
HU

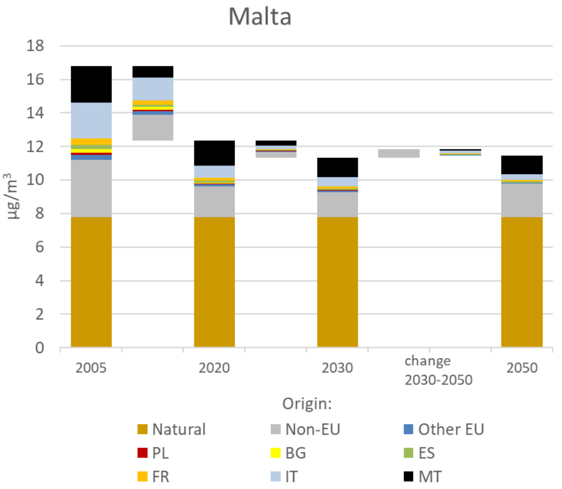

Ireland
µg/m3
0
1
2
3
4
5
6
7
8
9
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
DK
BE
NL
DE
FR
IE

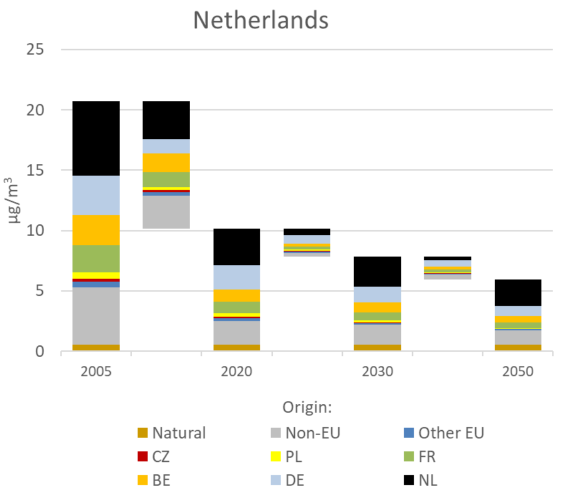

Italy
µg/m3
0
5
10
15
20
25
30
2005
2020
2030
change 2030-2050
2050
Origin:
Natural
Non-EU
Other EU
PL
DE
HR
SI
FR
IT

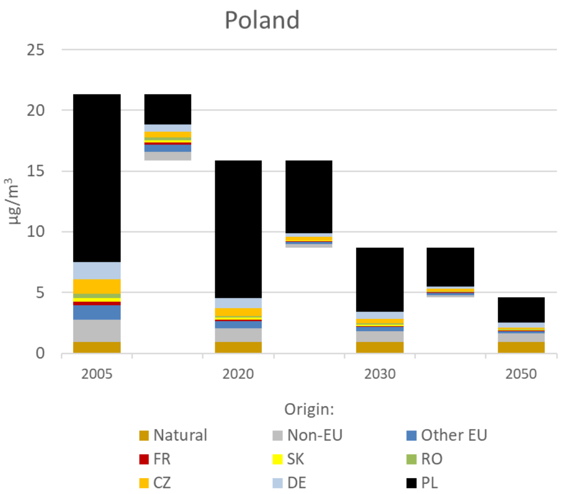

Latvia
µg/m3
0
2
4
6
8
10
12
14
16
18
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
CZ
EE
DE
LT
PL
LV

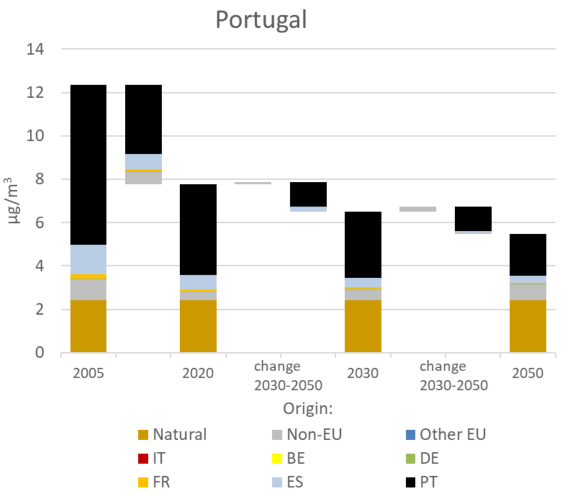

Lithuania
14
12
10
8
6
4
2
0
µg/m3
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
RO
LV
CZ
DE
PL
LT

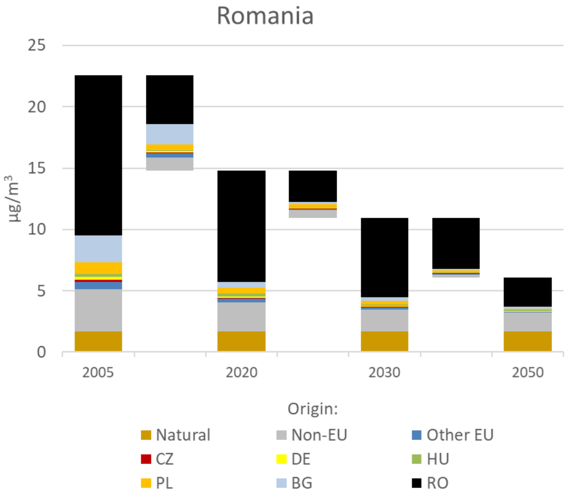

Luxembourg
20
18
16
14
12
10
8
6
4
2
0
µg/m3
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
PL
NL
BE
DE
FR
LU

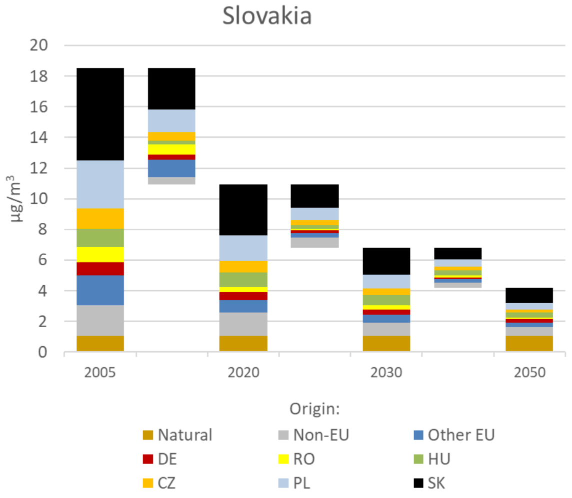

Malta
18
16
14
12
10
8
6
4
2
0
µg/m3
2005
2020
2030
change 2030-2050
2050
Origin:
Natural
Non-EU
Other EU
PL
BG
ES
FR
IT
MT

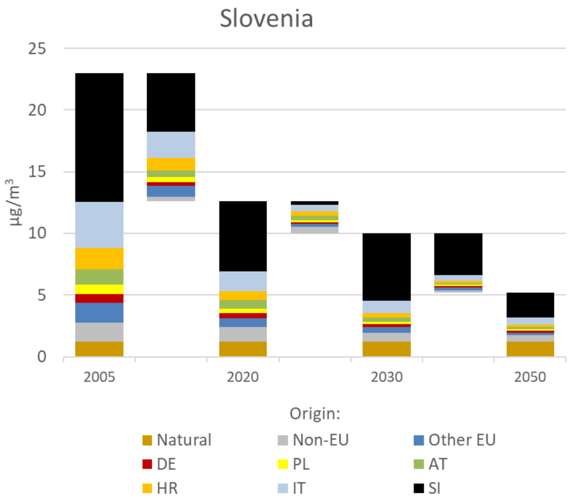

Netherlands
25
20
15
10
5
0
µg/m3
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
CZ
PL
FR
BE
DE
NL

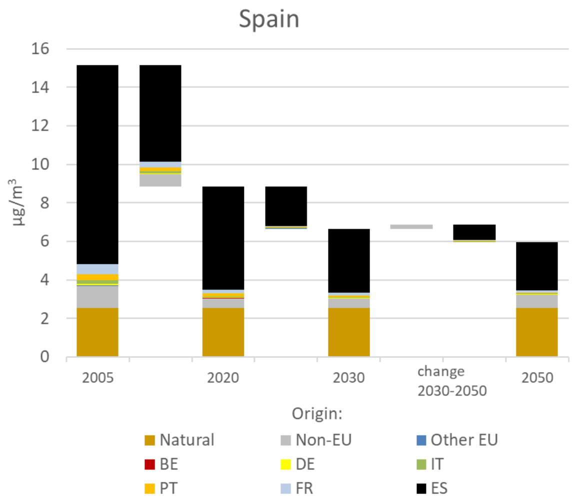

Poland
25
20
15
10
5
0
µg/m3
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
FR
SK
RO
CZ
DE
PL

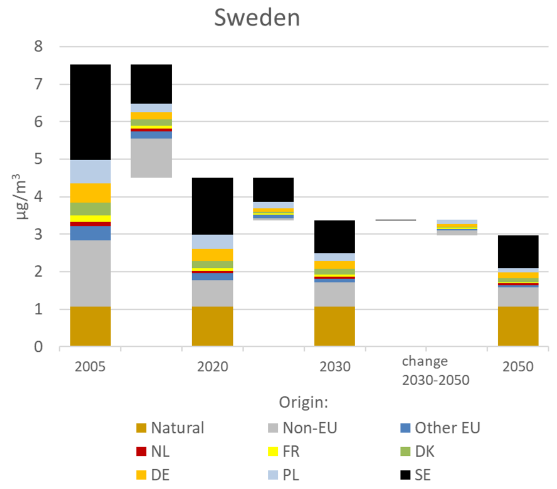

Portugal
14
12
10
8
6
4
2
0
µg/m3
2005
2020
change 2030-2050
2030
change 2030-2050
2050
Origin:
Natural
Non-EU
Other EU
IT
BE
DE
FR
ES
PT


Romania
µg/m³
25
20
15
10
5
0
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
CZ
DE
HU
PL
BG
RO


Slovakia
µg/m³
20
18
16
14
12
10
8
6
4
2
0
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
DE
RO
HU
CZ
PL
SK


Slovenia
µg/m³
25
20
15
10
5
0
2005
2020
2030
2050
Origin:
Natural
Non-EU
Other EU
DE
PL
AT
HR
IT
SI


Spain
µg/m³
16
14
12
10
8
6
4
2
0
2005
2020
2030
change 2030-2050
2050
Origin:
Natural
Non-EU
Other EU
BE
DE
IT
PT
FR
ES


Sweden
µg/m³
8
7
6
5
4
3
2
1
0
2005
2020
2030
change 2030-2050
2050
Origin:
Natural
Non-EU
Other EU
NL
FR
DK
DE
PL
SE

5 Costs of air pollution and the benefits of air pollution reduction

5.1 Introduction

This chapter analyses mitigation costs, impact costs of air pollution, and quantifies benefits of air pollution reduction, for the scenarios developed in in this project (see Section 4.3), except the condensable and methane sensitivity scenarios.

5.2 Approach

Costs of air pollution control measures are calculated with the GAINS model for each scenario and presented in Section 5.3.

Impact costs are estimated in Section 5.4. The valuation methods used in the assessment (GAINS and ALPHA-RiskPoll models) are consistent with the ones used in the third Clean Air Outlook. However, the methods have been updated (see Section 2.3).

The following aspects are monetised for the core scenarios described in Section 4.3.1:

- Cost of air pollution in 2020, 2025, 2030, 2040, 2050, comprising market costs (i.e. healthcare costs, lost workdays costs, lost crops costs) and non-market costs of mortality and morbidity and, to the extent possible, costs of lost ecosystem services;
- The market and non-market costs of pollution are put in perspective with the cost of the measures to reduce pollution that would be put in place under the various scenarios, for 2020, 2025, 2030, 2040, 2050.

Subsequent analysis of the macro-economic impact of air pollution and the costs of control measures has been performed by the Commission's Joint Research Centre with the Computable General Equilibrium (CGE) Model JRC-GEM-E3[40] using outputs from this analysis, in particular costs and benefits of the analysed scenarios (Section 5.5). The analysis addresses, for each scenario, the impact on the EU GDP, employment, and trade flows, broken down by sector.

Results presented in this Section account for the full change in pollutant concentrations as a consequence of the ERC, ZPAP, ERC+ZPAP and MTFR scenarios (see Section 4.3). Section 5 of the Annex provides further results including cost-benefit analysis where cut-off points at the level of WHO Global Air Quality Guidelines are applied to quantification of effects of $PM_{2.5}$ and NO_2.

5.3 Costs of the measures at the EU level

The cost of air pollution control measures calculated by the GAINS model for the key analysed scenarios are shown in Table 5-1 and Table 5-2. According to the GAINS calculation, the Baseline costs decline after 2025 and by 2050 could represent less than half of the current cost. Also, the distribution across sectors will change, with reductions expected in power plants and transport sector owing to decarbonization (GAINS does not consider costs of structural changes but only costs for air pollution control measures) and therefore lower demand for controlled capacity, including fossil fuel power plants or vehicles.

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[40] https://joint-research-centre.ec.europa.eu/scientific-tools-and-databases/jrc-gem-e3-model/overview-jrc-gem-e3-model_en

The additional costs for the mitigation (Table 5-2) necessary to achieve the ERCs in 2020 and 2025 are very low compared to the costs of current legislation, i.e., only in order of 0.03-0.19 % of the *Baseline* costs in these years, but they increase to about 0.75 % of *Baseline* (or over 550 million €/year) for the attainment of the ERC in 2030. The initial lower costs are linked to typically smaller reductions needed and also potential for rather cheap measures, including strict enforcement of open burning bans, elimination of high-emitting vehicles, improved efficiency of applying mineral fertilizers. Costs grow in the future to achieve the ERCs in 2030 and are comparable to the costs estimated to achieve the ZPAP objectives for ecosystems, i.e., about 400 million €/year, which represent about 0.55 % of the *Baseline* costs.

Applying all technical measures defined in the GAINS model (the *MTFR* scenarios) leads to a large increase in abatement costs. For 2030, the additional costs of the *MTFR* over the *Baseline* scenario (Table 5-2) are in the order of 23 billion €/year and represent over 30% of the *Baseline* costs, while for 2050 this difference is lower in absolute terms, estimated at about 20 billion €/year, representing nearly 70 % of the respective total *Baseline* costs in 2050.

Table 5-1: Total air pollution control costs for the EU for analysed scenarios. Units: million €/year.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	44338	55154	67772	67928	79853	73249	60405	44263	34361	28992
ERC				68054	79931	73806		44418		29118
ERC 2020					79897					
ZPAP						73648				
ERC+ZPAP						74047				
MTFR						96262		64875		48886

Table 5-2: Additional air pollution control costs over the Baseline for the EU for analysed scenarios. Units: million €/year.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ERC				0.126	78	556		155		126
ERC 2020					26					
ZPAP						399				
ERC+ZPAP						798				
MTFR						23013		20611		19894

5.4 Benefits analysis with the ALPHA-RiskPoll model

5.4.1 Economic value of health impacts

Figure 5-1 shows annual health damage in €billion/year for the CAO4 *Baseline* scenario from 2005 to 2050. Impacts are split into three 'tiers', as described in Section 2.3.1. Tier 1 is based on mortality response functions from the WHO Air Quality Guidelines (WHO 2021) and morbidity effects from long-term exposure from the EMAPEC study also coordinated by WHO (Forastiere et al. 2024). Tier 2 includes additional functions, largely for effects of short-term exposure, that were included in CAO3 (the remit of EMAPEC did not extend to assessment of effects of short-term exposure). Tier 3 includes two further long-term exposure effects from EMAPEC, concerning type 2 diabetes and dementia, both of which were given a lower confidence rating by Forastiere et al. Given higher uncertainty the Tier 3 effects are not included in the analysis that follows Figure 5-1.

Figure 5-1 accounts for sensitivity to two factors, the first concerns the approach to mortality valuation, whether using the value of a life year (VOLY) or the value of a statistical life (VSL), noting that for ozone mortality only the VOLY is applied given uncertainties in the modelling of the impact. The second sensitivity concerns the extent to which NO_2 effects are included. A simple approach is taken here, showing results with and without NO_2 impacts where there is potential for effects to be double counted against the quantification of $PM_{2.5}$ effects. The left-hand side of the figure includes all modelled NO_2 effects (mortality from long term exposure, asthma in children and adults, acute lower respiratory infections (ALRI), bronchitis in children and respiratory hospital admissions), and the right-hand side of the figure only includes asthma in adults and ALRI (the other impacts being covered also for $PM_{2.5}$). This approach provides a range within which the true estimate of the combined effect of $PM_{2.5}$ and NO_2 impacts should lie. Note that this approach is slightly different from CAO3 where all effects of NO_2 were either taken on board, or completely ignored (sensitivity case). In CAO4 we attempt to decrease the uncertainty range by excluding only those outcomes where there is a risk for double counting.

Figure 5-1: Economic value of health impacts of air pollutants for the EU under the Baseline scenario, showing the split between impacts quantified according to the three tiers of analysis (see text). Mortality is valued using the VOLY (top) and VSL (bottom). Figures on the left-hand side include all NO_2 impacts, whilst those on the right-hand side exclude NO_2 effects where there is a risk of double counting impacts quantified against $PM_{2.5}$ exposure. Units: €billion/year. Note the difference in scales for the upper and lower figures.

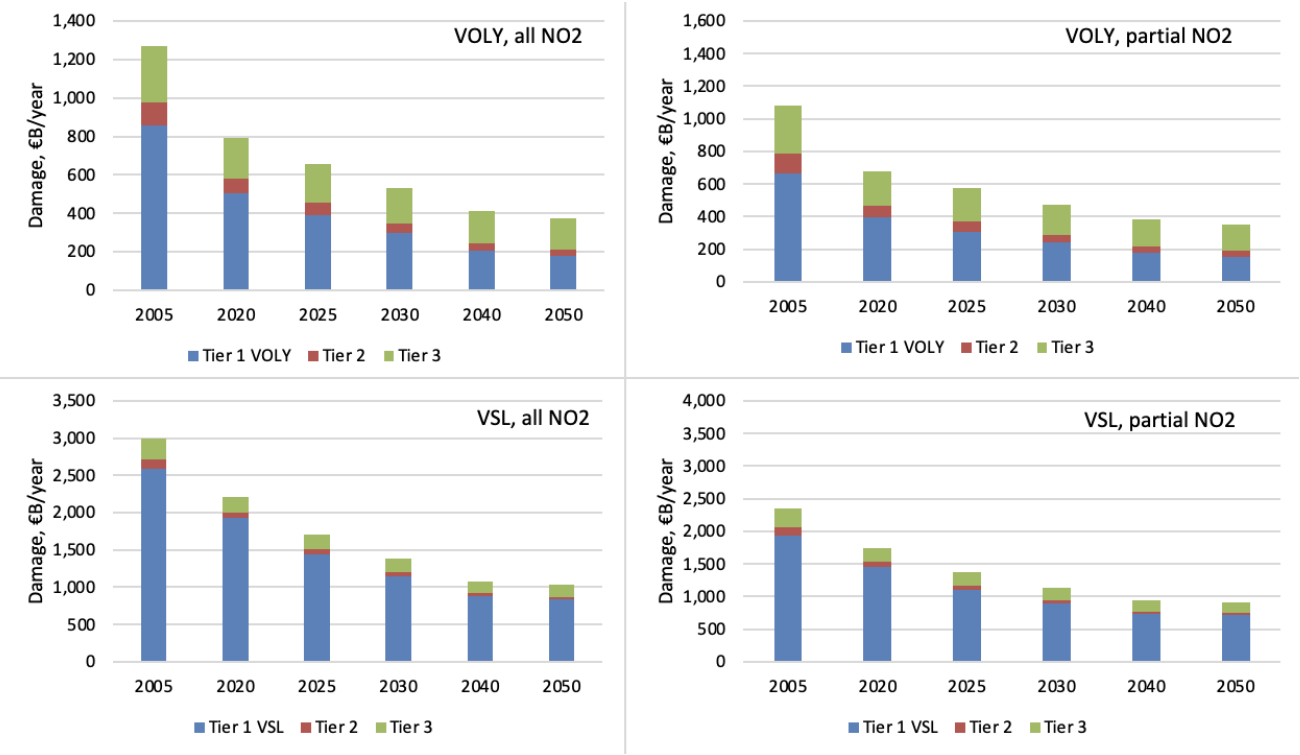

Figure 5-2 provides total estimates of impact (mortality and morbidity) for $PM_{2.5}$, NO_2 and O_3, corresponding to the upper left panel of Figure 5-1 but excluding Tier 3 effects (a similar graph including Tier 3 is included in the Annex). For each pollutant total damage is shown, ignoring potential for double counting when impacts are aggregated across the pollutants. Health costs are dominated throughout by the impacts quantified against $PM_{2.5}$ exposure, followed by NO_2 and then O_3. The results for ozone are very sensitive to the quantification and valuation of mortality impacts given that only acute exposure on hospital admissions is included for morbidity. Over the period 2005-2050 there is a 77% decline in damage linked to $PM_{2.5}$, an 88%

decline for NO_2 but only a 2% decline for ozone. The result for ozone is strongly influenced by demographic changes: results above (Table 4-11, based on a static population) indicate a larger change, reflecting reduction in individual risk as ozone levels fall. A conservative position (tending to lower bound estimates) is adopted here for consistency with earlier analysis and recognising uncertainties in recent meta-analyses of ozone and mortality where conclusions have varied with respect to both cause and exposure metrics (WHO, 2021; Kasdagli et al, 2024).

Figure 5-2: Value of damage due to $PM_{2.5}$, O_3 and NO_2 exposure for the EU under the Baseline scenario. Mortality is valued using the VOLY. Units: €Billion per year. Tier 3 effects (dementia and diabetes) not included.

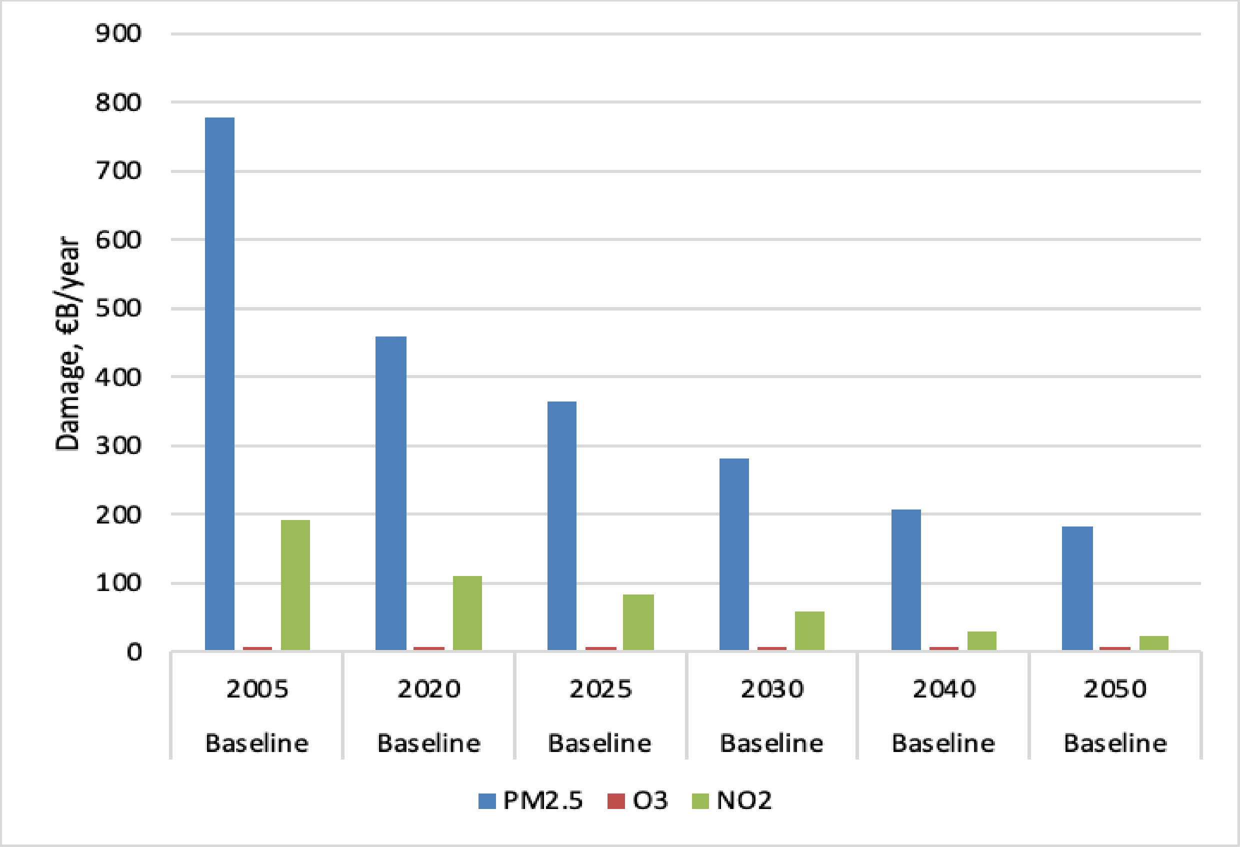

Table 5-3 shows the total economic value of health impacts by scenario over time, excluding Tier 3 effects. The table again shows sensitivity to the approach used for mortality valuation (VOLY – value of a life year, or VSL – value of statistical life) and to potential double counting of impacts when using functions for both $PM_{2.5}$ and NO_2. Results for each Member State and Baseline year are included in the Annex Section 5.1.

Table 5-3: Economic value of health impacts linked to $PM_{2.5}$, NO_2 and O_3 by scenario accounting for sensitivity to the approach used for mortality valuation (VOLY, VSL) and testing sensitivity to the inclusion of NO_2 impacts. Units €million/year, 2015 prices. Excludes Tier 3 impacts.

	2020	2025	2030	2040	2050
Including all NO_2 functions					
Mortality valued using VOLY					
Baseline	579,322	454,652	348,284	245,746	213,476
ERC			339,043		
ZPAP			334,216		
ERC+ZPAP			328,872		
MTFR			295,384	207,890	185,782
Mortality valued using VSL					
Baseline	2,001,029	1,508,157	1,202,636	917,127	870,226
ERC			1,171,200		
ZPAP			1,152,837		
ERC+ZPAP			1,133,403		
MTFR			1,022,348	775,464	757,123
Including NO_2 functions only for adult asthma and child ALRI morbidity					
Mortality valued using VOLY					
Baseline	468,774	371,981	290,323	215,939	190,751
ERC			282,601		
ZPAP			280,426		
ERC+ZPAP			277,172		
MTFR			246,933	183,697	167,088
Mortality valued using VSL					
Baseline	1,529,474	1,165,193	949,764	771,278	745,366
ERC			924,948		
ZPAP			918,124		
ERC+ZPAP			907,518		
MTFR			810,913	657,145	654,418

5.4.2 Non-health effects

Damage to building materials was extensively researched in the 1980s and 1990s. Although research in the area continues, it is less active now than previously. Damage values per unit emission for SO_2 and NOx have been taken from an earlier EC research project, CASES.

Damage to crops is assessed using the methods developed in the ECLAIRE study (Holland et al. 2015). This includes impacts of ozone on all crops grown in Europe. It does not, however, include impacts on the production of meat and animal products (milk, cheese, wool, honey, etc.) via impacts on grass production. Impacts to forests are also quantified using methods from ECLAIRE, accounting for reduced production of wood and reduced carbon sequestration linked to ozone exposure.

Economic analysis of ecosystem damage is also based on the ECLAIRE study. It assesses impacts related to terrestrial ecosystems only. ECLAIRE used three methods to estimate damage costs for ecosystems, a willingness to pay (WTP) approach based on the results of research by Christie et al. (2006, 2011; 2012), a repair cost approach described by Ott et al. (2006) and a 'regulatory revealed preference' approach (developed in the ECLAIRE study). The focus of analysis is on exceedance of the critical load for nitrogen in Natura 2000 sites, with valuation applied to the area subject to critical loads exceedance. No account was taken of exceedance of the critical load for acidification, because the area concerned is far less than that affected by eutrophication and there is potential for double counting if results for both effects are combined. The WTP based approach, representing WTP of the public for ecosystem protection, is adopted here as the preferred option because it is most consistent with the method used for other impacts assessed in this report. Uncertainties in the methods used in ECLAIRE led to the use of a factor 3 variation between low and high estimates of damage. The economic cost of impacts to materials, crops, forests and ecosystems is shown in Table 5-4, Table 5-5, Table 5-6, and Table 5-7, respectively.

Table 5-4: Economic valuation of air pollution impacts to materials for selected scenarios for the EU. Units: €million/year (2015 prices).

	2020	2025	2030	2040	2050
Baseline	1,231	1,011	742	445	384
ERC			730		
ZPAP			714		
ERC+ZPAP			714		
MTFR			523	289	246

Table 5-5: Economic valuation of air pollution impacts to crops for selected scenarios for the EU. Units: €million/year (2015 prices).

	2020	2025	2030	2040	2050
Baseline	13,840	13,481	12,948	12,220	12,087
ERC			12,867		
ZPAP			12,818		
ERC+ZPAP			12,815		
MTFR			12,545	11,848	11,750

Table 5-6: Economic valuation of air pollution impacts to forests for selected scenarios for the EU. Units: €million/year (2015 prices).

	2020	2025	2030	2040	2050
Baseline	18,768	18,435	17,927	41,504	41,156
ERC			17,852		
ZPAP			17,799		
ERC+ZPAP			17,798		
MTFR			17,566	40,686	40,405

Table 5-7: Economic valuation of air pollution impacts to ecosystems for selected scenarios for the EU. Units: €million/year (2015 prices).

	2020	2025	2030	2040	2050
Ecosystem damage - Low					
Baseline	4,072	3,914	3,675	3,396	3,293
ERC			3,506		
ZPAP			3,359		
ERC+ZPAP			3,353		
MTFR			3,023	2,642	2,560
Ecosystem damage - High					
Baseline	12,217	11,741	11,024	10,188	9,880
ERC			10,518		
ZPAP			10,077		
ERC+ZPAP			10,058		
MTFR			9,070	7,926	7,679

The large increase in the value of impacts to forests between 2030 and 2040 is attributable to the change in carbon values for future years recommended in the DG MOVE Handbook on External Costs of Transport (CE Delft et al. 2020). This recommends values of €100/t CO_2 up to 2030 and €267/t CO_2 from 2040 to 2060. This change has limited effect on the cost-benefit analysis below, given that there are only small changes in forest exposure to ozone across the scenarios in any year.

5.4.3 Cost-benefit analysis

This section provides cost-benefit analysis (CBA) for total change in the benefits of the non-Baseline scenarios. Incremental cost data for scenarios above Baseline, calculated with the GAINS model, are shown in Table 5-8. Summary of the total EU costs for the Baseline and analysed scenarios were shown in Table 5-1 and Table 5-2.

Table 5-8: Additional costs above the Baseline. Units €million/year.

	2030				2040	2050
Country	**ERC**	**ZPAP**	**ERC+ZPAP**	**MTFR**	**MTFR**	**MTFR**
Austria	-	0.2	0.2	423	441	420
Belgium	0.5	9.1	6.8	363	407	429
Bulgaria	1.0	15.1	14.9	336	288	221
Croatia	5.2	10.2	9.3	318	260	234
Cyprus	-	0.5	0.5	49	40	42
Czech Rep.	17.4	2.3	17.5	721	625	590
Denmark	0.8	8.3	4.7	329	304	298
Estonia	0.0	2.1	2.0	144	139	130
Finland	0.0	3.4	3.4	572	516	378
France	7.7	102.4	97.1	3,308	3,104	2,913
Germany	225.6	52.9	226.7	4,672	3,704	3,688
Greece	0.0	1.5	1.5	780	621	625
Hungary	82.1	8.4	82.2	426	451	458
Ireland	17.2	8.8	17.5	318	342	338
Italy	0.1	5.1	5.1	2,003	1,836	1,830
Latvia	1.7	1.5	2.0	171	174	166
Lithuania	-	0.4	0.1	212	162	153
Luxembourg	1.7	0.5	1.7	36	39	41
Malta	1.8	0.0	1.8	13	12	9
Netherlands	1.5	2.6	2.8	558	563	571
Poland	19.3	72.6	69.2	2,664	2,333	2,268
Portugal	6.5	11.8	11.7	465	435	416
Romania	117.2	19.6	127.5	988	916	782
Slovakia	0.8	8.2	4.7	311	304	306
Slovenia	34.8	0.7	35.3	117	140	119
Spain	13.4	45.0	46.1	2,323	2,104	2,107
Sweden	0.3	5.5	5.5	391	351	362
EU	**556.4**	**398.7**	**797.9**	**23,013**	**20,611**	**19,894**

Benefits are assessed by combining the results on impacts from the previous section (health, crops, forest, materials and ecosystems) for each scenario relative to the CAO4 Baseline in the appropriate year (2030 or 2050). Results are shown in Table 5-9, which includes the sensitivity cases considered above. VOLY- and VSL-based estimates for health benefit are combined with the Low and High estimates for ecosystems, respectively, to show the range of overall estimated benefits.

Results show that benefits by scenario increase in order from ERC to ZPAP, to ERC+ZPAP to MTFR. Going forward in time, the annual benefits of the MTFR scenario are reduced, largely reflecting action accounted for in the Baseline.

Table 5-9: Benefits from reduced health and non-health damage relative to the CAO4 Baseline for the EU. Units: €M/year, 2015 prices. Tier 3 health effects excluded.

Including all NO_2 functions	**2030**	**2040**	**2050**
Mortality valued using VOLY			
ERC	9,578		
ZPAP	14,670		
ERC+ZPAP	20,024		
MTFR	54,535	39,956	29,653
Mortality valued using VSL			
ERC	32,110		
ZPAP	51,032		
ERC+ZPAP	70,489		
MTFR	183,225	145,271	116,530
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	8,059		
ZPAP	10,499		
ERC+ZPAP	13,763		
MTFR	45,025	34,342	25,622
Mortality valued using VSL			
ERC	25,490		
ZPAP	32,873		
ERC+ZPAP	43,502		
MTFR	141,788	117,741	94,375

Net benefits (benefits – costs) are shown in Table 5-10 and benefit-cost ratios (net benefits divided by net costs, taken from Table 5-2) in Table 5-11. In all cases results demonstrate a strong excess of benefit over further control costs. Analysis accounting for the use of cut-off points for $PM_{2.5}$ and NO_2 set at the WHO Global Air Quality Guidelines is presented in Section 5.3 of the Annex. Results there show broadly similar trends. The effect of the cut-off points in reducing estimated damage is modest for 2030, but grows over time as increasing areas are forecast to meet the WHO Guidelines. In all cases except MTFR in 2040 and 2050 with mortality valued with the VOLY, results demonstrate a strong excess of benefit over further control costs. Proportionally, impacts on the benefit-cost ratios through the application of the cut-off points increase over time, as the area subject to their exceedance shrinks and estimated benefits fall.

Care is needed in interpretation of the results for the MTFR scenarios as they could be interpreted as demonstrating a net benefit for all measures included for MTFR. In reality, some of the measures included in the cost curve will be cost-efficient whilst some others are extremely expensive per unit emission abated, and on their own may not generate a net benefit either across the EU or in all Member States. This is suggested by the decline in benefit-cost ratios when moving down through scenarios to the MTFR. More detailed analysis, involving a series of additional scenarios would be needed to test the costs and benefits of the increasingly less cost-effective measures towards the upper end of the cost curve.

Table 5-10: Net benefits from reduced health and non-health damage relative to the CAO4 Baseline for the EU. Units: €M/year, 2015 prices. Tier 3 health effects excluded.

Including all NO_2 functions	2030	2040	2050
Mortality valued using VOLY			
ERC	9,022		
ZPAP	14,271		
ERC+ZPAP	19,226		
MTFR	31,522	19,344	9,758
Mortality valued using VSL			
ERC	31,554		
ZPAP	50,633		
ERC+ZPAP	69,691		
MTFR	160,212	124,660	96,636
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	7,503		
ZPAP	10,100		
ERC+ZPAP	12,965		
MTFR	22,012	13,731	5,727
Mortality valued using VSL			
ERC	24,933		
ZPAP	32,474		
ERC+ZPAP	42,704		
MTFR	118,775	97,129	74,481

Table 5-11: Benefit-cost ratios by scenario for the EU. Tier 3 health effects excluded.

Including all NO_2 functions	2030	2040	2050
Mortality valued using VOLY			
ERC	17		
ZPAP	37		
ERC+ZPAP	25		
MTFR	2.4	1.9	1.5
Mortality valued using VSL			
ERC	58		
ZPAP	128		
ERC+ZPAP	88		
MTFR	8.0	7.0	5.9
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	14		
ZPAP	26		
ERC+ZPAP	17		
MTFR	2.0	1.7	1.3
Mortality valued using VSL			
ERC	46		
ZPAP	82		
ERC+ZPAP	55		
MTFR	6.2	5.7	4.7

5.5 Macro-economic impact analysis

This section integrates the air pollution control costs (Section 5.3) and the corresponding benefits of clean air (Section 5.4) into the broader, economy-wide framework as captured by the JRC-GEM-E3 model at member state level. A suitable data interface between the GAINS and JRC-GEM-E3 models has been developed and successfully applied in the previous Clean Air Outlook studies. Results of the GAINS model, including cost data at the agreed sectoral level suitable for the JRC-GEM-E3 analysis as well as population weighted concentrations of $PM_{2.5}$ for the analysed scenarios were provided to the JRC team. In addition, results of the cost benefit analysis with the ALPHA-RiskPoll model has been completed and Work Lost Days and crop yields data provided to JRC.

For the analysis, the JRC-GEM-E3 model represents abatement costs as additional intermediate inputs required in the production process. With respect to the benefits, two different methods are used. i) macro-economic gains from improved productivity by 0.80% per 1 μgm^{-3} decrease in the concentration of fine particulate matter (Dechezleprêtre et al. 2019), ii) macro-economic gains from changes in labour supply based on lost work days estimates from Alpha-RiskPoll Framework (Ostro, 1987). In addition, it includes to the two above mentioned market benefits, gains from changes in total factor productivity of the crop sector based on changes in crop yield, available from the Alpha-RiskPoll model.

The time periods estimated varies across the scenarios. The macro-economic effects of the MTFR scenario have been estimated for 2030, 2040 and 2050. For the ERC scenario, work lost days and crop yield estimates were not available in 2040 and 2050 due to no ozone data. Therefore, the macro-economic effects of the ERC, ZPAP and ERC+ZPAP scenarios are only available in 2030.

The time periods estimated varies across the scenarios. The macro-economic effects of the MTFR scenario have been estimated for 2030, 2040 and 2050. For the ERC scenario, work lost days and crop yield estimates were not available in 2040 and 2050 due to no ozone data. Therefore, the macro-economic effects of the ERC, ZPAP and ZPAP+ERC scenarios are only available in 2030.

Table 5-12 summarises the macro-economic GDP impacts and Table 5-13, Table 5-14, Table 5-15, and Table 5-16 the output effects for specific sectors when considering additional abatement costs (compared to the baseline) and two different measures of 'market' benefits. These two measures of benefits consider the following; i) avoided lost work days and increased crop yields (Table 5-12, Table 5-13, Table 5-14) and ii) labour productivity and increased crop yields (Table 5-12, Table 5-15, Table 5-16) as discussed above.

Air pollution control costs differ across scenarios and sectors, reflecting the mitigation strategy. The MTFR scenario has an ambitious pollution control that requires additional investment in agriculture, industry and the residential sector in particular, while the scenarios targeting the ERC and ZPAP mainly increase cost for agriculture due to additional reductions of NH_3 emissions in these scenarios. Higher pollution control costs in MTFR scenario also imply larger benefits compared to the other scenarios. Nevertheless, the net effect (costs and benefits) in the MTFR can be negative (Ostro 1987) or positive (Dechezleprêtre et al. 2019) depending on the method used to estimate benefits. On the other hand, in 2030, the ZPAP scenario indicates positive net effects irrespective of the methodology used to estimate benefits.

Figure 5-3 provides the summary of macro-economic impacts on the economy showing that when the benefits through the labour productivity and crop yield gains (drawing on the recent empirical evidence) are considered, the benefits offset the costs. In the MTFR scenario, the EU aggregate GDP would increase, by up to 0.243% in 2030, to 0.187% in 2040 and 0.146% in 2050 compared to the baseline.

Table 5-12. Macro-economic impacts in 2030, 2040 and 2050, considering the full concentration range (no cut-off); % GDP change compared to the respective baseline; except 'Benefit/cost ratio' that shows the ratio of benefits to costs. Source: JRC-GEM-E3 model

	2030				2040				2050			
Scenario	Costs	Benefits	Net effect	Benefit / cost ratio	Costs	Benefits	Net effect	Benefit / cost ratio	Costs	Benefits	Net effect	Benefit / cost ratio
Considering benefits through work days lost (WLD) based on Ostro (1987)												
MTFR	-0.154	0.012	-0.142	0.080	-0.119	0.010	-0.109	0.080	-0.098	0.008	-0.091	0.078
ERC	-0.003	0.002	-0.002	0.531	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ZPAP	-0.002	0.003	0.001	1.433	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ERC+ZPAP	-0.004	0.003	-0.001	0.748	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Considering benefits through work days lost (WLD) based on Ostro (1987) and crop yield gains												
MTFR	-0.154	0.015	-0.139	0.099	-0.119	0.012	-0.107	0.101	-0.098	0.010	-0.089	0.099
ERC	-0.003	0.002	-0.001	0.691	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ZPAP	-0.002	0.004	0.002	1.908	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ERC+ZPAP	-0.004	0.004	0.000	0.964	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Considering benefits through labour productivity using Dechezleprêtre et al (2019)												
MTFR	-0.154	0.394	0.240	2.6	-0.119	0.303	0.185	2.553	-0.098	0.242	0.144	2.5
ERC	-0.003	0.056	0.052	17.0	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ZPAP	-0.002	0.092	0.090	46.2	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ERC+ZPAP	-0.004	0.109	0.104	24.4	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
Considering benefits through labour productivity using Dechezleprêtre et al (2019) and crop yield gains												
MTFR	-0.154	0.397	0.243	2.6	-0.119	0.306	0.187	2.571	-0.098	0.244	0.146	2.5
ERC	-0.003	0.056	0.053	17.2	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ZPAP	-0.002	0.093	0.091	46.6	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
ERC+ZPAP	-0.004	0.110	0.105	24.6	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a

The impacts on sectoral output are available in Table 5-13 to Table 5-16. The scenarios ZPAP, ERC and ERC+ZPAP are only considered in 2030. The power sector, industries and services are in all scenarios equal or better off compared to the change in economic activity at the aggregate level (Table 5-13, Table 5-14, Table 5-15, Table 5-16). The power sector benefits in all scenarios, and is the sector that benefits most in the MFTR scenario when only introducing abatement costs into the model. This is an effect that arises within the CGE model, as the fossil fuel sectors bear some of the abatement costs, there is a substitution from fossil fuels to cleaner electricity. The crops sector increases output compared to the Baseline in the ZPAP, ERC and ERC+ZPAP scenarios when including crop yield gains (Table 5-13, Table 5-16). The livestock sector faces the largest output reduction due to the abatement costs (except in the ZPAP scenario, where the output drop is higher for crops). The livestock and fossil fuel sectors increase outputs compared to the Baseline in the ZPAP scenario when benefits are estimated according to Dechezleprêtre et al (Table 5-15, Table 5-16).

Figure 5-3. Macro-economic market effects of clean air scenarios in the EU considering the full concentration range (no cut-off). Benefits include labour productivity losses following Dechezleprêtre et al (2019) and crop yield gains. % GDP change relative to baseline. Source: JRC-GEM-E3 model.

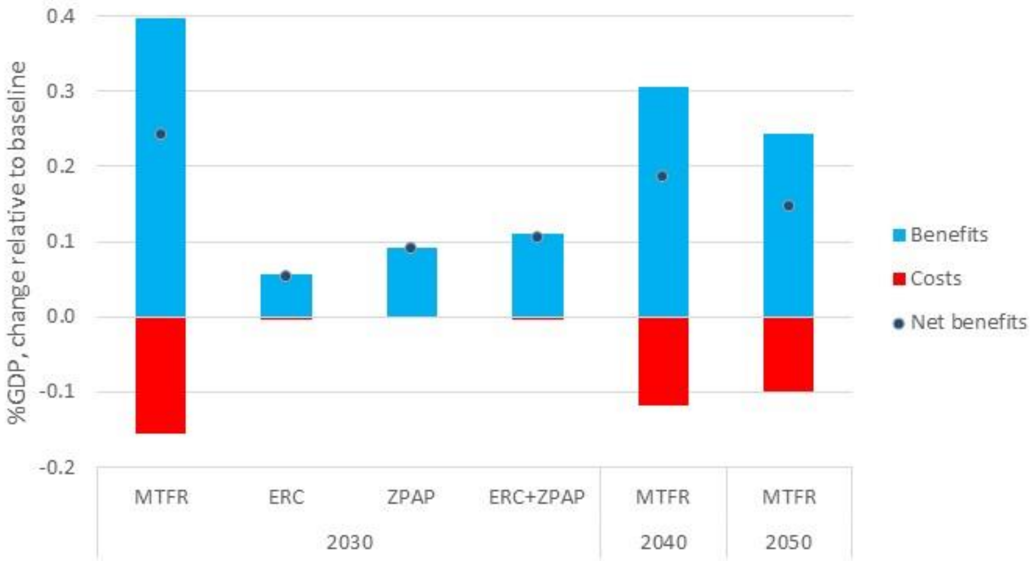

Table 5-13. Sector-specific market impacts compared to respective baseline (% change in output)[41], in 2030, 2040 and 2050, considering the full concentration range (no cut-off) and work loss days (WLD) based on Ostro (1987); Source: JRC-GEM-E3 model.

	WLD based on Ostro (1987)							
	2030							
	MTFR		**ERC**		**ZPAP**		**ERC+ZPAP**	
	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.718	-0.697	-0.037	-0.034	-0.127	-0.122	-0.137	-0.131
Livestock	-2.143	-2.127	-0.154	-0.152	-0.100	-0.097	-0.192	-0.187
Fossil fuels	-0.337	-0.325	-0.004	-0.002	0.001	0.003	-0.003	0.000
Power sector	0.124	0.135	0.001	0.002	0.002	0.005	0.002	0.005
Industry	-0.013	0.003	0.005	0.008	0.006	0.010	0.009	0.014
Services	0.004	0.016	0.000	0.002	0.001	0.004	0.001	0.004
Memo: GDP	-0.154	-0.142	-0.003	-0.002	-0.002	0.001	-0.004	-0.001

	2040		**2050**	
	MTFR		**MTFR**	
	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.725	-0.708	-0.638	-0.625
Livestock	-2.320	-2.307	-2.245	-2.235
Fossil fuels	-0.213	-0.205	-0.146	-0.140
Power sector	0.125	0.134	0.134	0.141
Industry	-0.004	0.008	-0.008	0.002
Services	0.012	0.021	0.014	0.021
Memo: GDP	-0.119	-0.109	-0.098	-0.091

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[41] Note: All results are expressed in percent difference relative to the respective baseline. In each column, the "Costs" column indicate the impacts of the cost of the pollution abatement measures, when benefits from clean air are not considered. The "Cost & benefits" column includes market benefits from clean air measures, in terms of enhanced worker productivity and costs, therefore this column represents a net effect. Non-market benefits of clean air and costs of climate policy are not included.

Table 5-14. Sector-specific market impacts compared to respective baseline (% change in output)[41], in 2030, 2040 and 2050, considering the full concentration range (no cut-off) and work loss days (WLD) based on Ostro (1987) with crop yield gains; Source: JRC-GEM-E3 model.

	WLD based on Ostro (1987) and crop yield gains							
	2030							
	MTFR		ERC		ZPAP		ERC+ZPAP	
	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.718	-0.175	-0.037	0.050	-0.127	0.043	-0.137	0.036
Livestock	-2.143	-2.096	-0.154	-0.146	-0.100	-0.088	-0.192	-0.178
Fossil fuels	-0.337	-0.333	-0.004	-0.003	0.001	0.002	-0.003	-0.002
Power sector	0.124	0.129	0.001	0.001	0.002	0.002	0.002	0.003
Industry	-0.013	-0.010	0.005	0.006	0.006	0.006	0.009	0.010
Services	0.004	0.013	0.000	0.001	0.001	0.003	0.001	0.003
Memo: GDP	-0.154	-0.139	-0.003	-0.001	-0.002	0.002	-0.004	0.000

	2040		2050	
	MTFR		MTFR	
	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.725	-0.195	-0.638	-0.156
Livestock	-2.320	-2.279	-2.245	-2.209
Fossil fuels	-0.213	-0.211	-0.146	-0.146
Power sector	0.125	0.129	0.134	0.136
Industry	-0.004	-0.006	-0.008	-0.010
Services	0.012	0.018	0.014	0.017
Memo: GDP	-0.119	-0.107	-0.098	-0.089

Table 5-15. Sector-specific market impacts compared to respective baseline (% change in output)[41], in 2030 and 2050, considering the full concentration range (no cut-off) and recent empirical evidence on impact on labour productivity following Dechezleprêtre et al (2019); Source: JRC-GEM-E3 model.

	Labour productivity based on Dechezleprêtre et al. (2019)							
	2030							
	MTFR		ERC		ZPAP		ERC+ZPAP	
	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.718	-0.007	-0.037	0.081	-0.127	0.037	-0.137	0.074
Livestock	-2.143	-1.593	-0.154	-0.072	-0.100	0.028	-0.192	-0.035
Fossil fuels	-0.337	0.025	-0.004	0.058	0.001	0.082	-0.003	0.103
Power sector	0.124	0.516	0.001	0.059	0.002	0.094	0.002	0.115
Industry	-0.013	0.481	0.005	0.078	0.006	0.119	0.009	0.146
Services	0.004	0.364	0.000	0.049	0.001	0.085	0.001	0.099
Memo: GDP	-0.154	0.240	-0.003	0.052	-0.002	0.090	-0.004	0.104

	2040		2050	
	MTFR		MTFR	
	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.725	-0.174	-0.638	-0.202
Livestock	-2.320	-1.892	-2.245	-1.904
Fossil fuels	-0.213	0.059	-0.146	0.055
Power sector	0.125	0.429	0.134	0.369
Industry	-0.004	0.381	-0.008	0.297
Services	0.012	0.288	0.014	0.235
Memo: GDP	-0.119	0.185	-0.098	0.144

Table 5-16. Sector-specific market impacts compared to respective baseline (% change in output)[41], in 2030, 2040 and 2050, considering the full concentration range (no cut-off) and benefits through labour productivity following Dechezleprêtre et al (2019) and crop yield gains; Source: JRC-GEM-E3 model.

	Labour productivity based on Dechezleprêtre et al. (2019) and crop yields gains							
	2030							
	MTFR		ERC		ZPAP		ERC+ZPAP	
	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.718	0.523	-0.037	0.160	-0.127	0.204	-0.137	0.239
Livestock	-2.143	-1.569	-0.154	-0.068	-0.100	0.035	-0.192	-0.029
Fossil fuels	-0.337	0.017	-0.004	0.057	0.001	0.081	-0.003	0.102
Power sector	0.124	0.510	0.001	0.058	0.002	0.092	0.002	0.113
Industry	-0.013	0.468	0.005	0.076	0.006	0.115	0.009	0.142
Services	0.004	0.361	0.000	0.049	0.001	0.084	0.001	0.099
Memo: GDP	-0.154	0.243	-0.003	0.053	-0.002	0.091	-0.004	0.105

	2040		2050	
	MTFR		MTFR	
	Costs	Costs & benefits	Costs	Costs & benefits
Crops	-0.725	0.342	-0.638	0.275
Livestock	-2.320	-1.869	-2.245	-1.882
Fossil fuels	-0.213	0.053	-0.146	0.049
Power sector	0.125	0.424	0.134	0.365
Industry	-0.004	0.367	-0.008	0.285
Services	0.012	0.284	0.014	0.232
Memo: GDP	-0.119	0.187	-0.098	0.146

6 Key findings

This report presents a set of model calculations which explore the likely future development of air pollutant emissions and air quality in the European Union and assesses health and environmental impacts, as well as costs and benefits associated with further pollution mitigation. To inform and support the development of the Fourth Clean Air Outlook report of the European Commission, the analysis incorporates recently proposed EU policies as well as the latest information on air pollutant emission inventories and projections and pollution control policies that have been reported by the Member States in their official inventory submissions and discussed in bilateral consultations between IIASA and Member States.

The modelling framework and approach used in the analysis is consistent with the work on the Third Clean Air Outlook. However, it considers updates to methodologies applied for health impact assessment and valuation of benefits as well as a refined modelling of ozone concentrations enabling analysis of ozone sensitivity to changes in global emissions of ozone precursors, including methane.

Analysis of the baseline scenario, which assumes full compliance with the current and proposed EU and national legislation, shows that only four Member States (down from five in CAO3) would fulfil all NEC Directive reduction commitments (i.e. sufficient reduction for each of the 5 pollutants) in 2030. Reduced ambition of the revised IED for agriculture (compared to the assumptions from the revision proposal included in the CAO3) results in higher ammonia emissions in CAO4, compared to CAO3, in 2030, leading to lower compliance with ERCs for ammonia. In the CAO4 Baseline scenario only 6 Member States are estimated to comply with ammonia ERCs by 2030. While for SO_2, full compliance is expected and only few Member States could exceed ERCs for NOx, and NMVOC, there are 8 Member States where ERCs for $PM_{2.5}$ would not be achieved under the Baseline – this is twice as many as in CAO3. While for two of the countries likely non-compliance is within 1% of the ERCs, for the other two Member States, revision of the national and GAINS estimates for residential combustion and agricultural waste burning results in changes of 2005 and 2030 emissions leading to increased likelihood of missing the ERC. The analysis has also shown that while the air pollution-related ZPAP target on reducing premature deaths would be achieved in the baseline scenario, the ZPAP target for reducing eutrophication would require further measures, primarily in agriculture.

The status of inclusion of condensable PM in the inventories and further evaluation of various emission factors has been addressed in sensitivity scenarios concluding that the currently recommended (EEA/EMEP Guidebook) and already extensively used emission factors by Member States, appear to provide a satisfactory assessment of emissions assuring a fair representation of observations.

Increasing over time the clean air and climate ambition, by implementing and enforcing proposed and agreed policies, would continue to drive significant reductions of air pollutant emissions and hence reduce exposure to $PM_{2.5}$ and NO_2 in the Baseline. However, in 2030, nearly 87% of the EU population are projected to still be exposed to $PM_{2.5}$ levels above the WHO guidelines (and about 28 % for NO_2) in the Baseline case. The CAO4 outlook is slightly less optimistic than the results of the analysis for the Baseline scenario in CAO3, where each of the health indicators shown above was better by a few percentage points. For $PM_{2.5}$, the major reasons include higher emissions from residential combustion sector in CAO4 (driven by slightly higher consumption of solid fuels, i.e., coal and biomass, until 2030, revised data and assumptions on structure of installations, and a more consistent inclusion of condensable) and less optimistic outlook for ammonia emissions (precursor of PM). While the ZPAP target for reduction of premature deaths (reduction by 55% by 2030, compared to 2005) is achieved in the baseline, this still leaves in 2030 over 220 000 premature deaths due to exposure to all $PM_{2.5}$ in the EU (including below WHO guideline levels). The exposure is expected to decline towards 2050, but at the same time there are proven measures to reduce emissions further and earlier, and those should be implemented. For NO_2, the revised estimate of soil NOx and lesser impact of Euro 7 by 2030 are key reasons, but the difference is not large and in the long term (by 2050) the indicators for NO_2 are better than in CAO3.

Compliance with ZPAP targets and ERCs would bring important benefits following emissions decline, reducing premature mortality from $PM_{2.5}$, NO_2 and ozone by 2-8% and impact on ecosystems from 7% for eutrophication to over 20% for acidification (relative to Baseline in 2030), at a moderate additional (to Baseline) costs of less than 0.5 billion €/year (or up to about 0.75% of the estimated Baseline cost for air pollution controls in 2030). Further potential exists bringing obvious larger benefits, but the cost increase rapidly and MTFR costs are in order of 23 billion €/year in 2030, declining in the longer term due to decarbonization and lesser need for flue gas cleaning investments. If all technically available measures are put in place, the analysis conducted for this report clearly indicates net benefits from additional actions towards cleaner air, with positive macro-economic implications in the near- and long-term for all clean air scenarios, when labour productivity effects are evaluated following Dechezleprêtre et al (2019) .

The changes to morbidity assessment alter their contribution to total damage (with mortality valued using the VOLY) from a range of 25% to 31% in CAO3 to 18% to 27% in CAO4 baseline leading to a slight reduction in the estimated economic benefits of pollution control measures. However, CAO4 analysis also shows that including updated long-term morbidity functions for dementia and diabetes would increase the contribution from morbidity to between 37% and 58%. The ranges reflect population ageing with the lower bound being for 2005 and the upper bound for 2050.

Owing to the atmospheric lifetime of $PM_{2.5}$ from hours to several days, the $PM_{2.5}$ concentration at any given location originates from a large area, including outside of national borders. For each Member State, the study quantifies the contributions of other countries to national $PM_{2.5}$ exposure, as well as the destinations of a given Member State's 'exported' pollution. It is found that while domestic sources are the main sources of pollution in most Member States, a significant contribution to $PM_{2.5}$ background concentration is generated in other Member States. Consistent with what was shown in CAO3, full implementation of the NEC Directive will lead to improvements in European air quality within and beyond national borders. Over time, the share of pollution from within the EU is projected to fall, increasing the relative importance of non-EU sources. However, compared to CAO3, the non-EU contribution is lower owing to recent commitments of, for example, West Balkan countries to decarbonization policies and improved effectiveness of implementation of policies in power and industry sectors. This highlights once more the case for internationally coordinated policy action for clean air in view of meeting more stringent air quality standards going forward.

The influence of transboundary sources on air quality in the EU is even larger for ozone. One sensitivity case analysed the role of reductions in global emissions of methane and non-methane ozone precursors for ambient ozone concentrations in Europe. It shows that global emission trends of CH_4, NOx and NMVOCs will influence ground-level ozone in Europe significantly; ambitious action outside of the EU would help to achieve compliance with recently adopted legislation on ambient air quality targets in the EU. Methane emission reductions in the EU only, on the other hand, have a very limited potential to influence ground level ozone in Europe.

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8 Annex

A1. Introduction

This is the Annex to the main report of the Specific Contract No 090202/2023/906366/SER/ENV.C.3 – "Support to the development of the fourth Clean Air Outlook". It provides additional information for various tasks that were developed during the course of work. The material provided here shows several extended outputs for both scenarios and years assuring full transparency of the work done during this service contract.

A1.1 Structure of the Annex

Major elements include full documentation of the comparison of historical emissions estimated in GAINS and reported by Member States (Section 2), more details on the model updates (Section 2), detailed sectoral and national data and GAINS estimates for past and future emissions, including comparison to the national projections which have been performed during the consultations with the Member States and development of the Baseline emission scenario (Section 3). Furthermore, additional details for the analysed policy and sensitivity scenarios are provided in Section 4 and 5.

A2. Updating modelling framework and a *Baseline* scenario

This section provides additional documentation of the updates to the GAINS database, applied methods, and development of the *Baseline* scenario. Some parts of the text below are the same as in the main report where only summary of key updates is provided.

A2.1 Approach

While maintaining the consistency of the modelling approach applied in the CAO3[42] and IA AAQD[43], the modelling framework has been updated considering latest improvements and recalculations of reported historic emissions by Member States (MS), in particular NEC base year 2005 as well as 2020, and is consistent with the recently updated EMEP/EEA air pollutant emission inventory guidebook[44]. Special attention has been paid to condensable and non-condensable part of particulate matter emissions, identifying which Member States and sectors the condensable part is included in the national inventories.

IIASA employs its Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model. GAINS is a fully-fledged integrated assessment model which traces the entire causal chain from the drivers of air pollution emissions to their impacts (Amann et al. 2011). The GAINS model is calculating emissions of key air pollutants (SO_2, NOx, NMVOC, NH_3, $PM_{2.5}$ (including black and organic carbon)) as well as GHGs, including methane (CH_4). Atmospheric calculations in GAINS are based on a linearized version of the EMEP atmospheric chemistry transport model. Together with the uEMEP extension, the EMEP model is capable of linking air pollution on urban to regional to global scales and quantify ambient pollution levels at very high resolution (Denby et al.

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[42] https://environment.ec.europa.eu/topics/air/clean-air-outlook_en

[43] https://environment.ec.europa.eu/topics/air/air-quality/revision-ambient-air-quality-directives_en

[44] https://www.eea.europa.eu/publications/emep-eea-guidebook-2023

2020). During the CAO3 project as well as work on the review of the Gothenburg Protocol to the UNECE LRTAP Convention (2021-2022) the GAINS atmospheric calculations have been updated and harmonized with the EMEP/uEMEP models and no substantial updates are envisaged within this work. As before, five-year average meteorological conditions (2016-2020) are used for the atmospheric calculations.

Health and environmental impacts are assessed with the GAINS model, although for ozone, the results of the EMEP model are used. GAINS provides health impact from exposure to $PM_{2.5}$ and exceedance of critical loads for acidification and eutrophication due to deposition of sulphur and nitrogen. For the latter, the latest database of critical loads (CLs) applied within the Air Convention is used. This 2021 dataset has been reviewed by the Coordination Centre for Effects (CCE) of the Working Group on Effects and approved by the Executive Body of the Convention and has been implemented in the GAINS model during the CAO3 study. For ozone, health impacts are calculated by IIASA making use of the results of the EMEP chemical transport model runs for the baseline and respective policy scenarios. Monetary evaluation of health and other benefits is performed with the ALPHA-RiskPoll model, based on the GAINS outputs. Overall, the impact assessment methodology is consistent with the one used in the CAO3 but includes updates taking into account most recent advancements, including the EMAPEC study results; HRAPIE-2 results have not become available on time and therefore cannot be included.

The baseline scenario for this work is an update of the CAO3 baseline incorporating all relevant EU legislation proposed by the Commission or adopted by the co-legislators since the CAO3 analysis was undertaken. This relates in particular to:

- Climate and energy legislation, reflecting latest political agreements on the legislative initiatives part of the Fit for 55 package as well as of the REPowerEU initiatives, incorporating in particular details related to projected solid fuel use development and other climate or energy measures that would have an important impact (positive or negative) on air pollution;
- The most recent developments in other relevant source legislation, reflecting latest political agreements on relevant legislative initiatives, notably on:
  - updated emission standards for vehicles (Euro 7),
  - CO_2 standards for light- and heavy-duty vehicles,
  - the revised Industrial Emissions Directive

  Since revision of the Ecodesign rules is still ongoing, no changes have been introduced for residential solid fuel stoves and boilers and the CAO4 Baseline remains consistent with the CAO3 assumptions. Consideration of Commission initiatives on urban mobility[45] in the modelling framework was discussed during inception phase but owing to lack of respective data and modelling inputs form the PRIMES model an agreement was reached not to pursue development of such sensitivity scenarios within this assignment;
- The information provided by MSs in their latest submitted air pollutant emission projections, NAPCPs and PaMs updates since the analysis done for the third Clean Air Outlook;
- The information provided by MSs on agricultural measures put in place, not only from their NAPCPs but also, where available, from their latest rural development plans and CAP strategic plans;
- Any other relevant developments, including for instance maritime emissions regulations.

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[45] EU Urban Mobility Framework (COM(2021)811

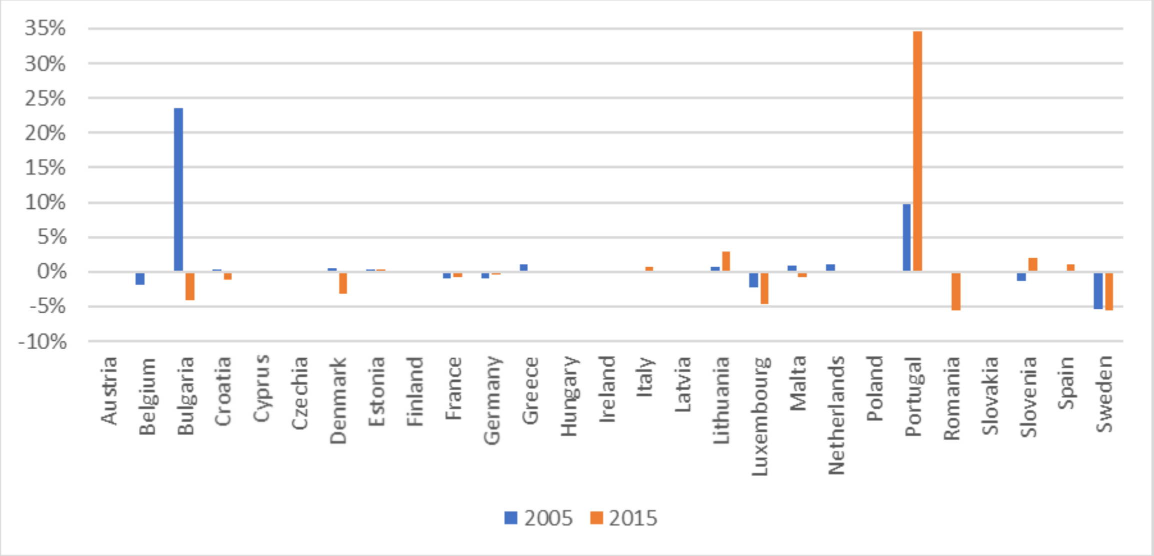
A2.2 Update of the GAINS model databases

New methods for emission estimation and newly assessed or developed emission factors are reflected in the regularly updated EMEP/EEA Guidebook (latest release in October 2023)[46] which is supporting the Member States to estimate their national emissions. As shown and discussed in previous Clean Air Outlooks, several Member States recalculate their historic emission inventories (including those for 2005) leading sometimes to substantial changes when compared to data reported earlier which in turn had implications on the achievement of the NECD emission reduction requirements in 2030. Beyond updated methods, revised estimates reflect corrections of calculation errors, revision of activity data and/or emissions factors, implementation of recommendations from reviews of respective submissions. The Member States have continued to update the emission estimates since 2021 submission and IIASA has reviewed the major recalculations included in the 2023 submission, as well as their impact on the GAINS model estimates for historical years and the baseline scenario.

Compared to the GAINS model version used in the CAO3 study, updates were made to PM emission factors for wood and coal use in residential sector in order to improve consistency of accounting for condensable PM. This is specifically the case for Austria, Estonia, Germany where updated emission factors in GAINS are consistent with the latest EMEP/EEA Guidebook and therefore much larger that emission factors used by Member States in their submissions since these three countries do not account for condensable PM when reporting PM.

The following figures provide a comparison of changes in the national emission reporting in 2021 (used in CAO3) and 2023 (used in CAO4) for the year 2005 and 2015; in further sections a comparison is provided for 2020 but this has not been possible for the 2021 submissions, which did not include, or only very preliminary, estimates for that year. The percentage change shows the change in 2023 reporting compared the 2021 submission for respective year. While most of the updates and revision result in changes smaller than 10%, there are several cases for each pollutant where differences are very significant also illustrating a challenge modelling teams face in addressing such updates. These updates were subject of exchange between IIASA and national experts during Member States consultations.

Figure 8-1: Change in 2023 Member States submission of SO_2 emissions for 2005 and 2015, compared to 2021 submission.



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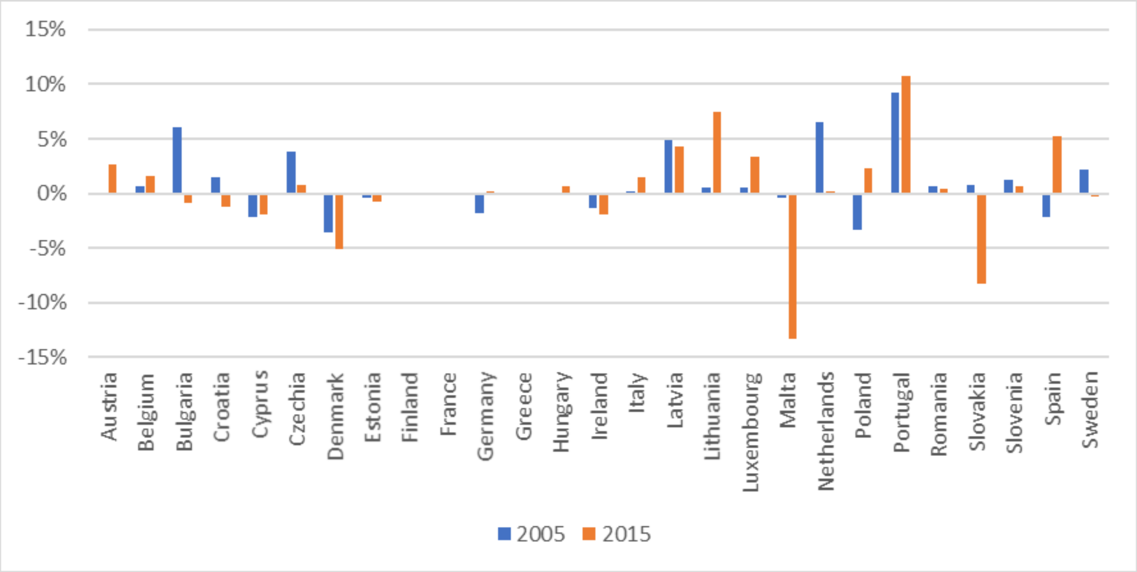
[46] https://www.eea.europa.eu/publications/emep-eea-guidebook-2023

Figure 8-2: Change in 2023 Member States submission of NOx emissions for 2005 and 2015, compared to 2021 submission.



Revisions for emissions of $PM_{2.5}$ are most significant, at least for some countries (Figure 8-3). An about factor two increase in reported emissions by Czechia and Poland and a very large increase for France are linked primarily to inclusion of condensable PM in their 2023 submissions.

Figure 8-3: Change in 2023 Member States submission of $PM_{2.5}$ emissions for 2005 and 2015, compared to 2021 submission.

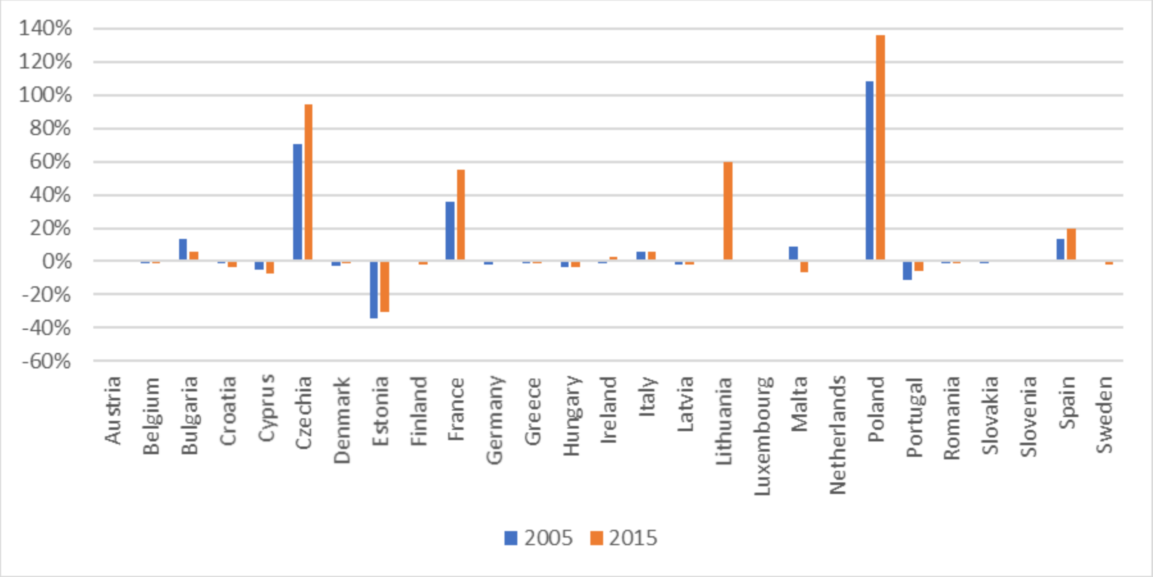


Figure 8-4: Change in 2023 Member States submission of NH3 emissions for 2005 and 2015, compared to 2021 submission.

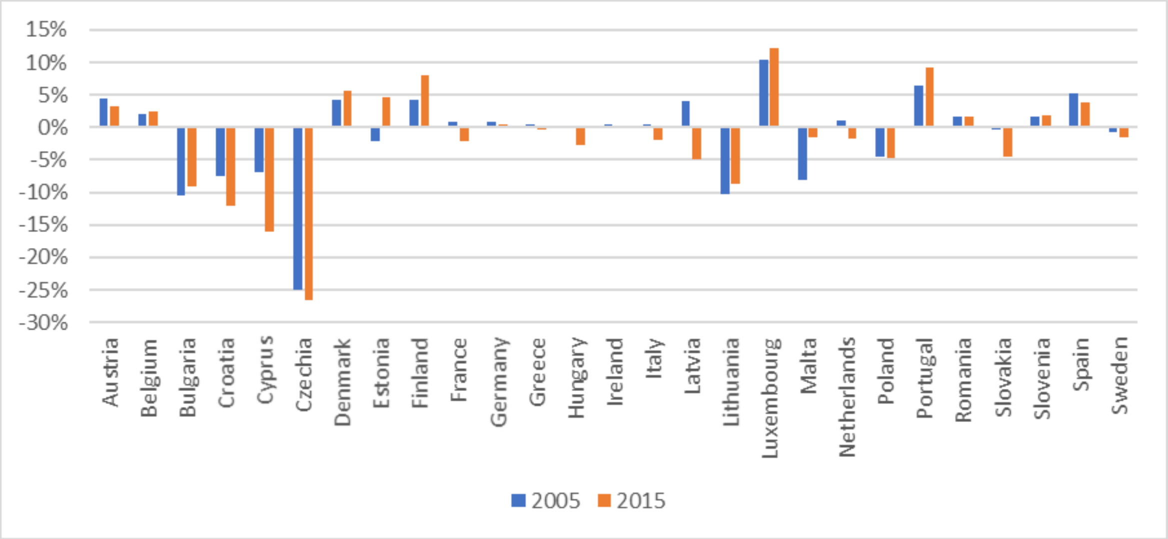
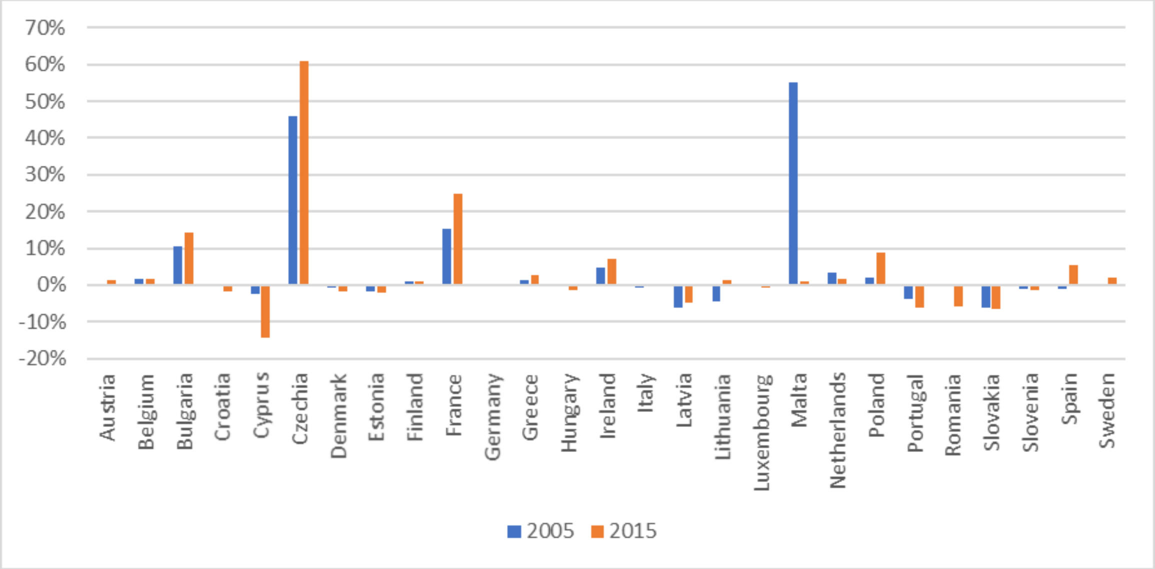


Figure 8-5: Change in 2023 Member States submission of NMVOC emissions for 2005 and 2015, compared to 2021 submission.



IIASA has compiled an updated dataset of SO_2, NO_x, VOC, NH_3 and $PM_{2.5}$ emissions for all 27 EU Member States. The analysis has been relying on the NECD inventory (and projections) submission in 2023 available at: ReportekEngine (europa.eu), focusing on the most relevant recalculations for the years 2005 through 2020 to assure the trends in the GAINS model are aligned with those in the inventories. The analysis and comparison of the national data submissions under the NEC Directive has been complemented by methodological information provided in the Informative Inventory Reports (IIRs) submitted along the national emission data as well as resubmissions of 2023 datasets in the second half of 2023, following the inventory review process.

Special attention has been paid to the condensable part of particulate matter emissions, identifying for which Member States and sectors the condensable part is included in the national inventories and which measuring method is used, pointing out any changes compared to the situation at the time the CAO3 was prepared. This is based on an analysis of most recent Member States emission inventory submissions that was available at the start of the project (2023 submission and respective IIR) and expert knowledge from development of an independent estimate consistently including condensable PM (the "Ref2" emission inventory) by TNO in 2022. The results of the CLRTAP Stage 3 review carried out in 2022 were also considered in this assessment. That review analysed submission of all Parties in the CLRTAP region in detail for the small combustion sector, looking at various aspects including if and to what extent condensables are included in their PM emissions. The results of this assessment are synthesized and reported in a table by country, highlighting if and to what extent condensables are included.

During the CAO3 study, several updates to road transport emission factors and fleet characteristics were made, drawing on the results of remote sensing measurements across Europe[47], data from SIBYL model, discussions with national experts during CAO3 consultations as well as the proposal for the Euro 7 standard; the latter was based on preliminary data. In December 2023, the European Parliament and the Council reached an agreement on the Euro 7 Regulation[48]. The upcoming Euro 7 emission standard for road vehicles has been underpinned by an impact assessment study that the European Commission assigned to the CLOVE consortium[49] led by EMISIA (and Aristotle University of Thessaloniki) examining different policy options and scenarios. In the framework of that study, road transport activity data and emission factors were reviewed and updated. The results have been adjusted based on the recent final Euro 7 agreement and used to review and update the GAINS model emission and cost characteristics for road transport sector.

Latest developments and updates on emission factors for shipping activities are also available through the H2020 EMERGE[50] project (nearing finalization) and the recently completed SCIPPER[51] project. Within SCIPPER, a new set of emission factors was developed based on both literature and measurements. The emission factors had been distinguished according to engine and fuel type and concern the main gaseous pollutants and greenhouse gases as well as energy consumption.

A2.3 Comparison of GAINS and Member States reported emissions

This section documents the comparison of air pollutant emission calculation in the GAINS model with the Member States submission in 2023. The objective has been to arrive at the differences at the national level not larger than about 5% for $SO_{2,}$ NOx, NH_3, and 10-20% for NMVOC and $PM_{2.5}$ that are burdened with larger uncertainties with respect to activity data beyond emission factor. Differences larger than 5% are marked in orange in the tables shown in Section 3.4 where detailed national total and sectoral data is shown and discussed.

The following figures summarize the status of how current GAINS calculation of emissions for 2005 and 2020 compare to the national submissions in 2023; note that in previous section national submissions of 2021 and 2023 are compared for 2005 and 2015, rather than 2020 since the 2021 submission have not included, or only very preliminary, estimate for 2020. On each of the figures, the 5% (larger for NMVOC and $PM_{2.5}$) difference range is marked in green showing larger discrepancies or differences. Note, that here we compare totals including NEC Directive sectors and so agricultural emissions of NOx and NMVOC are not considered, even though reported by Member States and calculated in GAINS as is demonstrated in the country-specific comparisons in Section 3.4.

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[47] CARES Project; H2020 Grant Agreement No. 814966. www.cares-project.eu

[48] Final text of the Euro 7 agreement https://data.consilium.europa.eu/doc/document/ST-16960-2023-REV-1/en/pdf

[49] DG GROW, Framework Contract 688/PP/2018/FC

[50] EMERGE - Evaluation, control and mitigation of the Environmental impacts of shipping emissions. H2020 Grant Agreement No. 874990. emerge-h2020.eu

[51] SCIPPER -: Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations. H2020 Project under Grant Agreement Nr.814893. www.scipper-project.eu

One common feature for all pollutants is that for 2020 differences are much larger than for 2005. This is not surprising since there is a longer history of reporting data for 2005 and since this was the 'COVID year' some of the statistical information and especially sectors for which typically no hard data is available and extrapolation of trends is used, will carry larger uncertainty. GAINS energy, industry, agriculture data is based on import of statistics but has similar issues and uncertainties are larger for 2020. The analysis of the informative reports (IIRs) provided along the national submissions has been very helpful to identify reasons for differences allowing for better alignment.

Figure 8-6: Difference between GAINS SO_2 emissions for 2005 and 2020 and the 2023 Member States submissions

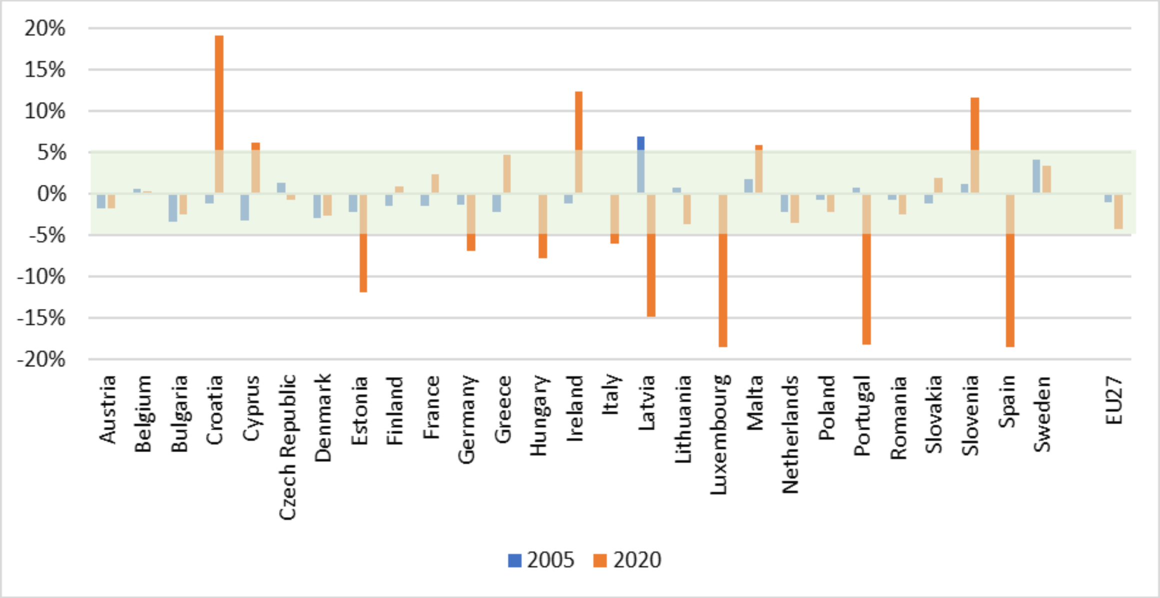
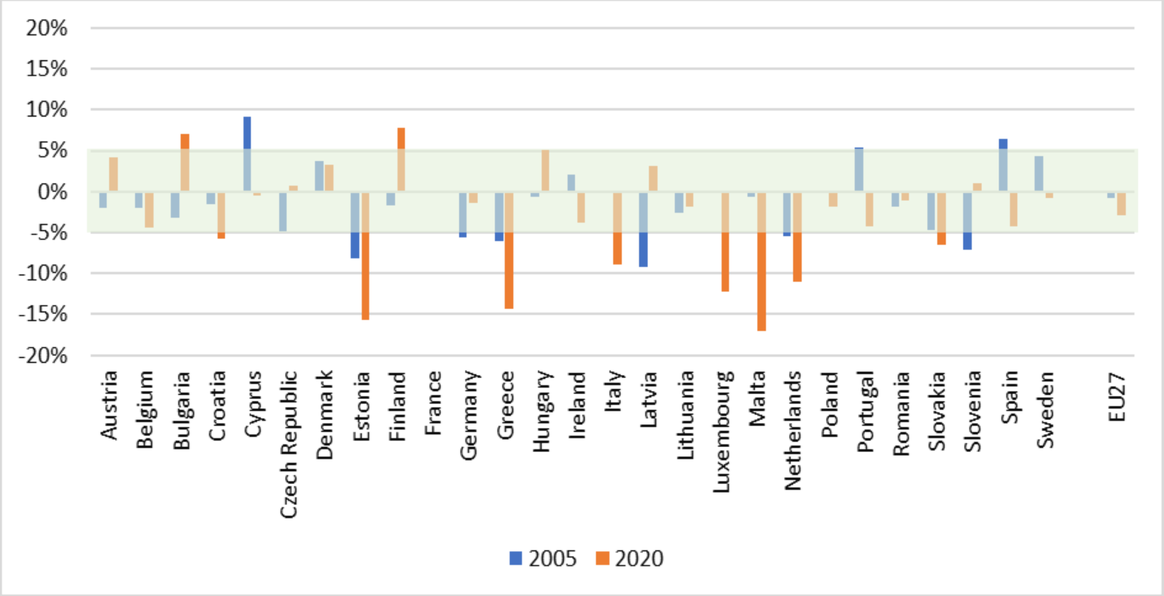
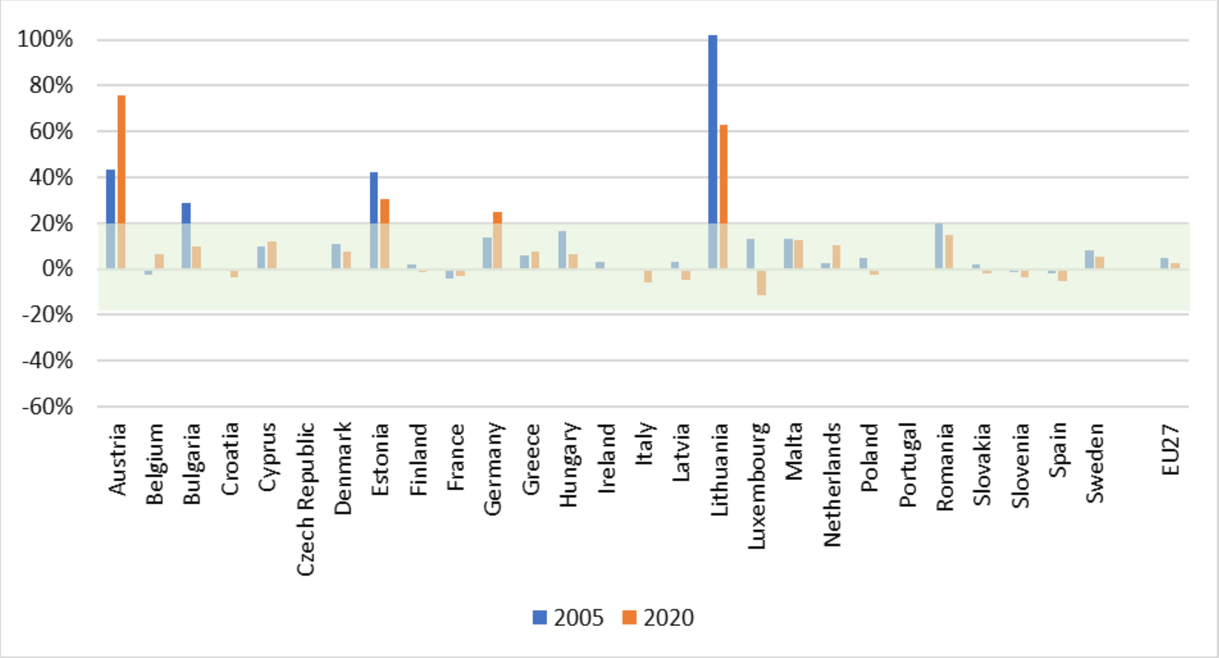


Figure 8-7: Difference between GAINS NO_x emissions for 2005 and 2020 and the 2023 Member States submissions



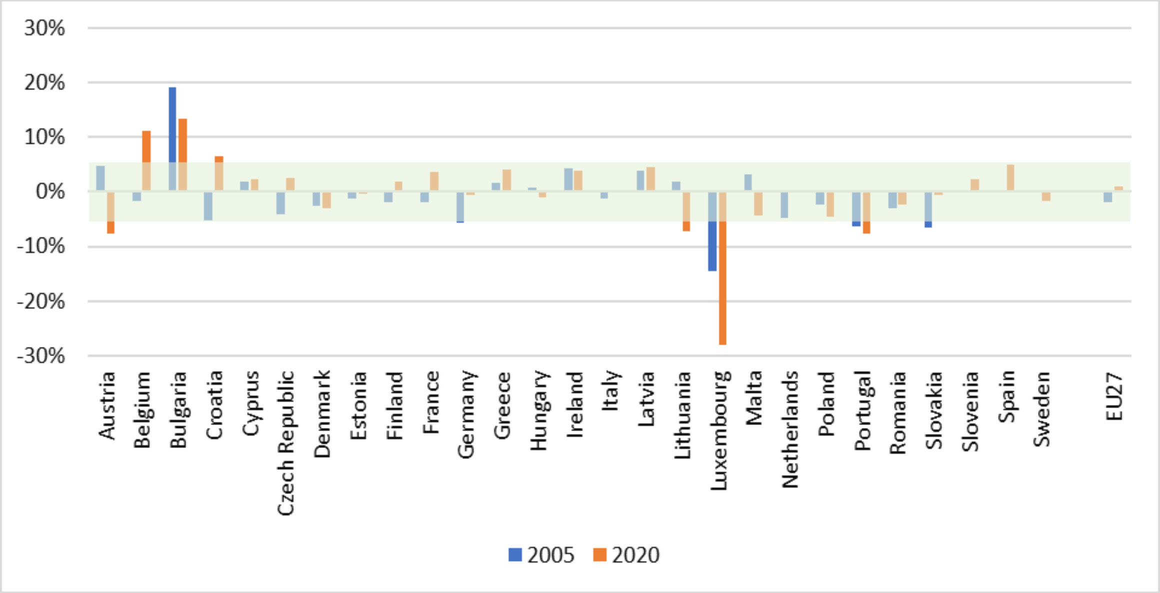
While for most pollutants the larger differences occur for few countries and more likely for 2020, the picture for $PM_{2.5}$ is different as here estimates vary much more and for both 2005 as well as for 2020. The key sources of these differences include residential combustion sector, open burning of agricultural residues, and in some cases also fugitive emissions from construction, quarrying, and road paving. Considering often lack of robust data for consumption of fuelwood and on structure of combustion installations as well as uncertainties in emission factors, differences in order of ±10% or more have to be considered acceptable. However, there are countries where the discrepancy is much larger and here key reason is often consideration of condensable PM in GAINS but not in the national inventory (Austria, Estonia, Germany, Lithuania). In few other cases (e.g., Bulgaria, Romania), different methods or lack of estimates for open burning of agricultural residues is the leading cause of discrepancy.

Figure 8-8: Difference between GAINS $PM_{2.5}$ emissions for 2005 and 2020 and the 2023 Member States submissions



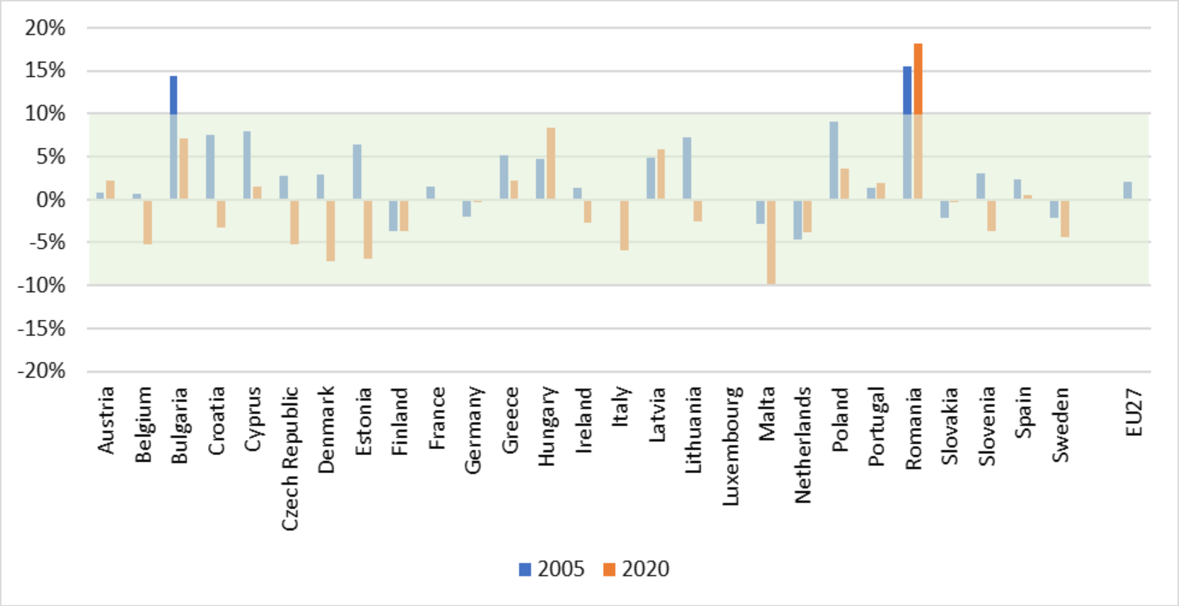
Least differences are seen for ammonia, which is also a result of extensive documentation and typically use of higher tier methods in national inventories allowing for good calibration of GAINS. There are few exceptions where available information did not allow to arrive at a better match.

Figure 8-9: Difference between GAINS NH_3 emissions for 2005 and 2020 and the 2023 Member States submissions



For NMVOC, one of the key areas of analysis included increase in use of sanitizers during COVID period, leading to rather large increases in NMVOC which then decline by 2025. In some countries, there was an emission spike only in 2020, after which emissions returned to normal historical levels. However, a few countries, which had not previously accounted for the 'use of sanitizers' as a source in their national inventories, re-evaluated and added this source-sector across all years while updating their 2020 data. All this information has been continuously exchanged during and after the consultation meetings and has been implemented into the GAINS model.

Figure 8-10: Difference between GAINS NMVOC emissions for 2005 and 2020 and the 2023 Member States submissions



Comparison of country level totals and sectoral emissions at the GNFR level is reported in Section A3.4.

A3. Consultation of the *Baseline* with Member States

A3.1 Objectives

The purpose of this task is to present, discuss, and validate the assumptions and key results of the Baseline scenario developed (see Section 3 in the main report) with the Member States. Where necessary, the discussion includes also review of the data and assumptions used in the development of the historical emissions. As a result of consultations with the Member States, the assumptions used in the Baseline have been complemented or modified accordingly, where necessary.

The GAINS model update during development of the Baseline and Member States consultations is also of relevance for the recently started project on the EU GHG modelling. This project is led by the Pollution Management research group at IIASA that also leads the CAO4 work and focuses on emissions of non-CO_2 GHG in the Commission service request (Contract number — 090203/2023/SER/ 905239/CLIMA.A.2) on the "EU GHG modelling for beyond 2030"; internally referred to as EUCLIMIT-7. IIASA will be using the data/assumptions/information updated prior and during the Member States consultations for estimation of air pollutant emissions in the GAINS model since most of the same data/assumptions are of relevance for the non-CO_2 GHG calculation. This concerns specifically activity data (energy use, livestock numbers, etc.) for historical years as well as included air pollution policies and key structural assumptions (e.g., Member State and livestock category-specific farm size structure) for the baseline scenario. Consequently, calculation and reporting of air pollutant emissions in the EUCLIMIT-7 project for the past years will be entirely consistent with CAO4. While the EUCLIMIT-7 project extends into 2025 and will use a newly developed baseline scenario, consistency of key assumptions will enable robust comparisons and allow for disentangling of the impact of the new baseline on air pollutant emissions, if such analysis will be desired in the future.

A3.2 Approach

The consultations were organized as half day online meetings with experts representing each Member State to share the GAINS model Baseline scenario developed for this assignment and to discuss specific national features included in the Baseline and the modelling framework. The following elements are of particular interest in the context of this service request:

- Policies and measures with an air pollution impact (positive or negative) already in place or for which a decision about implementation in the near future has already been taken, at different levels of governance (national, regional, local), having an impact on national emission levels and which can be represented in the modelling framework,
- Methodological features having an impact on emission inventories, in particular, how the condensable part of particulate matter is reflected in national inventories for various emitting sectors and in the modelling framework,
- Additionally, any unresolved emission inventory issues that remain after completion of work on the development of the Baseline were also discussed and solutions identified during and shortly after the Member States consultations,

The results of the discussion during individual Member States consultations were summarized in minutes shared with the teams, including specification of next steps. Where necessary, the GAINS model databases and assumptions were revised and reflected in the updated Baseline. The summary of introduced changes, in responses to inputs from Member States and discussions at the consultation meetings, as well as the final revised Baseline were presented at the online meeting with all Member States and the Commission on the 17th of June, 2024.

A3.3 Preparation and organization of the consultation meetings

On the basis of a list of issues for discussion at the consultations that IIASA prepared, DG-ENV has sent an invitation letter early February to the members of the Ambient Air Quality Expert Group working on NECD implementation. National Contact Points nominated Member States experts that would take part in the consultation meetings within the fourth Clean Air Outlook and IIASA has followed up searching for suitable dates for the meetings. Consultations meetings with all Member States have been scheduled and IIASA has carried out 27 meetings that started early March and concluded on the June 4th.

The individual Member States consultations were organized as half day virtual meetings and were preceded with analysis of the national NEC Directive inventory and projection submission in 2023 available at the ReportekEngine (europa.eu) and analysis of the NAPCPs and PaMs. Remaining discrepancies between GAINS and the national emission inventories that could not be satisfactory resolved were summarized in the presentation opening the consultation meetings along with the assumptions behind the Baseline scenario and its emission trajectory (all presentations and minutes of the meetings are available at request). Several countries asked for a list of questions or even datasets prior to the consultation meeting enabling the most efficient resolution of identified issues.

At the beginning of every consultation meeting, the IIASA team gave an overview of the CAO4 objectives and purpose/goals of the consultation meeting. Additionally, information about the team involved in the CAO4 project and an overview of the timeline was given. This information was followed by a presentation of the work on the development of the GAINS model baseline scenario and the discussion of differences between national emission estimates (NFR2023) and GAINS for historical years as well as future outlook comparing the WM/WaM national projection with GAINS Baseline and reviewing compliance with ERCs. This presentation included a comparison and discussion of key activity assumptions and emissions of all NEC Directive pollutants as reported by the Member States and calculated in GAINS. While national data/information has been taken from the inventories submitted in 2023, if substantive improvements were made (or errors identified) in the 2024 submission, these were discussed and considered to the possible extent.

The presentation and minutes of the meeting were shared within days after the meeting. The minutes included actions following the meeting and each Member States was asked to provide comments to the minutes as soon as possible.

The Baseline was updated for use in the policy analysis and assessment in this work based on the results of these Member States consultations. In case the national elements in the GAINS Baseline cannot be confirmed by the Member States and an agreement between the Member States experts and the modelling team cannot be reached (due for instance to insufficient provision of information from the Member States), the discrepancies of views were documented, and the modelling team justified its approach.

Following the individual consultations and bilateral exchanges, leading to the establishment of an updated Baseline, a meeting was convened with all Member States and the Commission on the 17th of June 2024 where the summary of the changes made in response to input from Member States were presented.

A3.4 Documentation and reporting

The results of the discussion during individual Member States consultations have been summarized in minutes, including specification of the next steps, shared with the national teams and can be provided to the Commission upon request along with the presentations given at the meetings. Comparison of Member States reporting of national totals and GAINS was shown Section 2 while the next section (3.4.1) provides further details including sectoral comparisons and brief discussions of remaining differences. Section 3.4.2 provides further material comparing the GAINS Baseline with the WM and WaM projections for each country and illustrates compliance with the ERCs calculated against both the GAINS and the national estimates of 2005 emissions. The results presented here have been updated based on the discussions during the consultations and new comments or data provided through the meetings, and these have been implemented into the GAINS model.

The summary includes Member States specific comparisons of historical emissions for the period from 2005 as well as remaining issues, i.e., cases where the national elements in the consultant baseline cannot be confirmed by a Member State and an agreement between the Member State and the contractor cannot be reached (due for instance to insufficient provision of information from the Member State).

A3.4.1 Comparison of GAINS estimates with Member States submissions

The following sections provide comparison of country level total and sectoral (GNFR sectors) emissions reported by Member States in 2023 with current GAINS calculations. Brief discussion or highlight of some key remaining differences is given, while more details are available in the presentations and minutes of the discussions with the Member States during consultations. The tables presenting comparison of national totals refer to the NEC Directive totals, while the figures include all sources and so also emissions of NOx and NMVOC from agriculture are shown explicitly for both national and GAINS estimates. The orange-coloured cells in the tables below highlight differences larger than 5%.

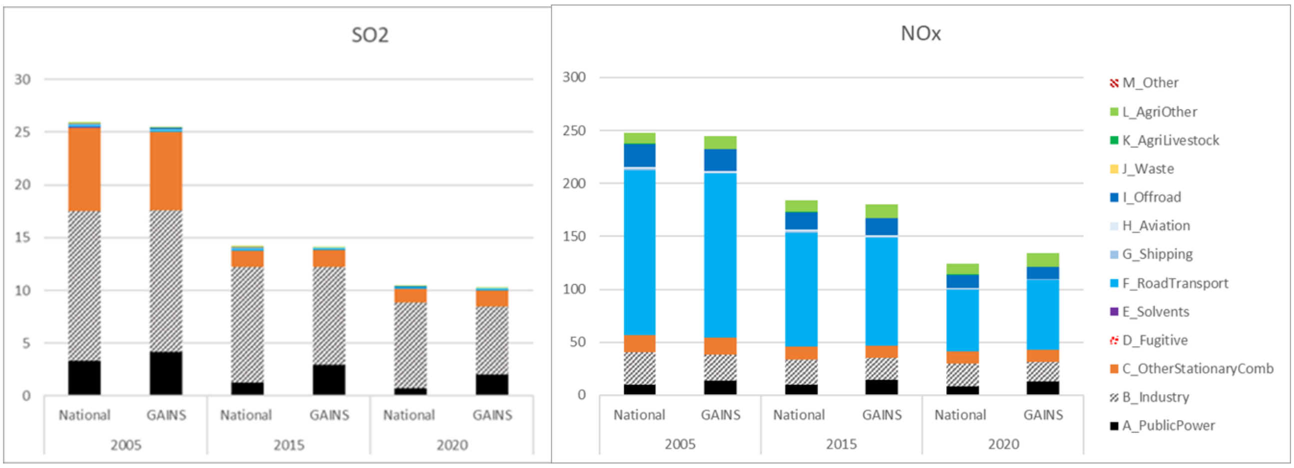
AUSTRIA

Table 8-1: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	26	25	-1.8%	14	14	-0.1%	10	10	-1.8%
NOx	237	232	-2.0%	172	167	-3.0%	114	118	4.2%
PM2.5	23	33	43.6%	16	28	73.4%	13	23	75.9%
NH3	63	66	4.8%	66	65	-2.5%	66	61	-7.5%
VOC	119	120	0.7%	77	79	3.2%	75	77	2.2%

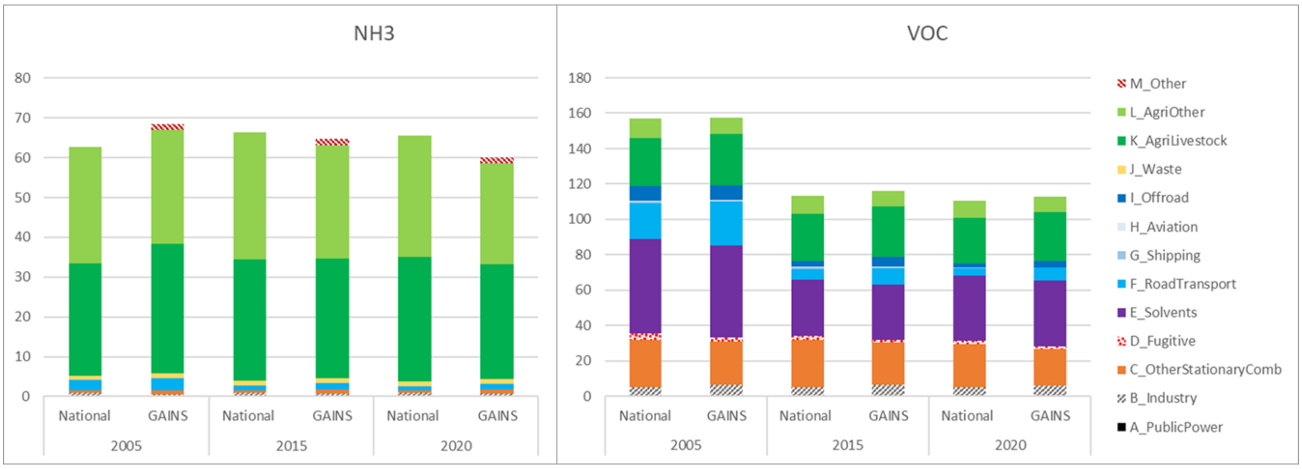
Overall, good agreement at the national and sectoral level for **SO_2, NOx, NH_3, and NMVOC**. The large difference for **$PM_{2.5}$** is due the fact that GAINS includes condensable PM fraction and the national inventory reports only filterable PM. This has been discussed during consultations and acknowledged by the national experts. This has of course an impact on the projection comparison as well.

Figure 8-11: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



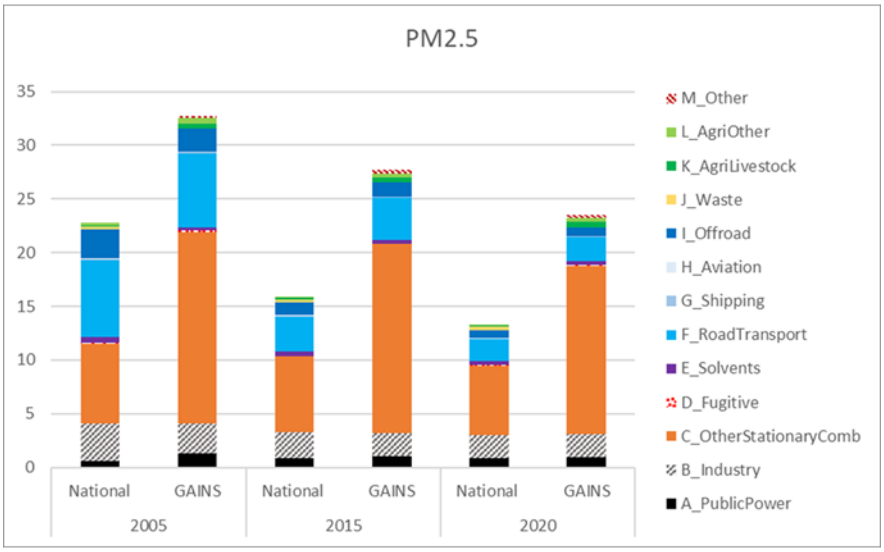
For **ammonia (NH_3),** overall, acceptable agreement at the national level. There are small differences in 2005 and 2020 due to the transition from tied to lose dairy cattle housing systems. Emissions from other sub-categories such as mineral fertilizers and other livestock match well.

Figure 8-12: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



For **$PM_{2.5}$,** the reason for discrepancy is inclusion of condensable PM in GAINS, while national reporting includes filterable PM. This has been discussed further during the consultations. Other sectors align well.

Figure 8-13: Comparison of the 2023 MS inventory submission $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



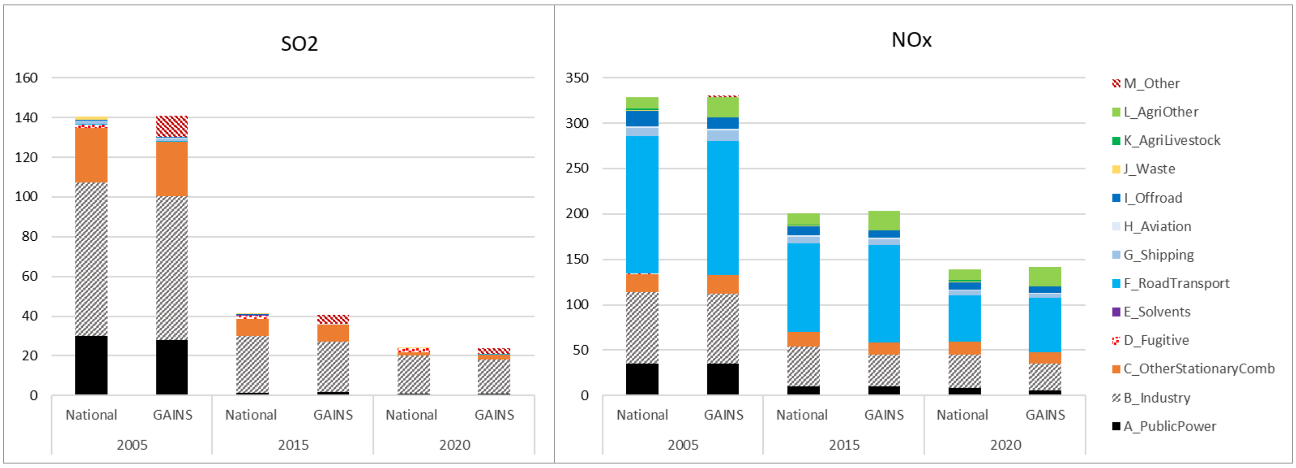
BELGIUM

Table 8-2: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	140	141	0.5%	41	41	-0.6%	24	24	0.2%
NOx	314	308	-1.9%	187	182	-2.7%	126	120	-4.4%
PM2.5	34	33	-2.6%	22	22	-2.3%	17	18	6.6%
NH3	80	79	-1.6%	72	76	5.4%	68	76	11.3%
VOC	155	156	0.6%	89	90	1.4%	87	82	-5.3%

Very good agreement for **SO_2.** The issues related to sulphur content for fuel oil discussed resulting in improved alignment of estimate after updates. Acceptable agreement at the national and sectoral level for **NOx** and **$PM_{2.5}$**.

Figure 8-14: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



For **ammonia (NH_3),** differences for 2015/20 above 5% mostly due to higher emissions from dairy cattle in national reporting.

For **NMVOC,** overall, very good agreement at the national and sectoral level in 2005 and 2015. Small differences are remaining in 2020 due to using different emission factor for livestock and crops in the agriculture sector. The comparison is also good for **$PM_{2.5}$** with some differences for livestock but not having impact on the overall agreement.

Figure 8-15: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

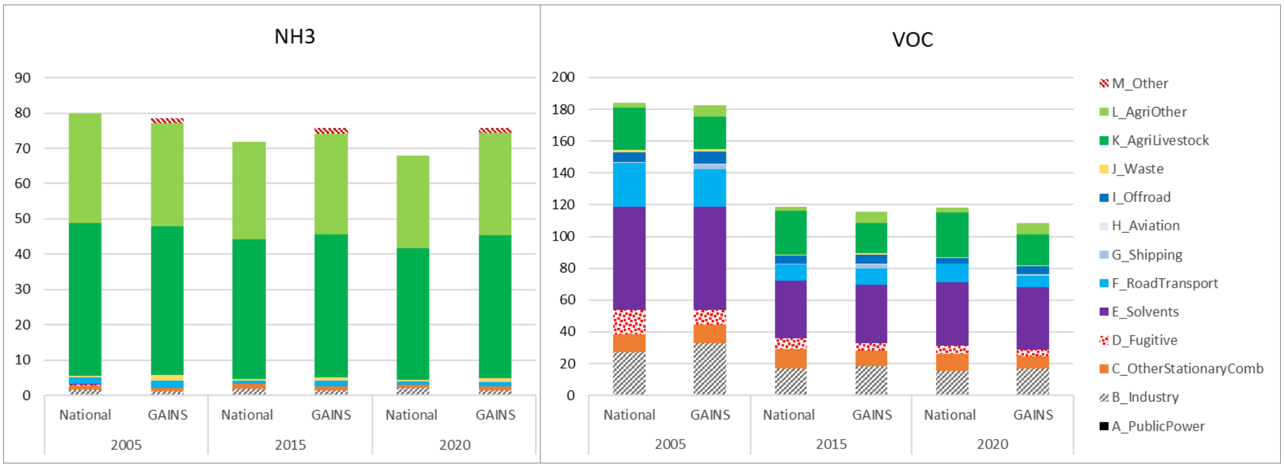
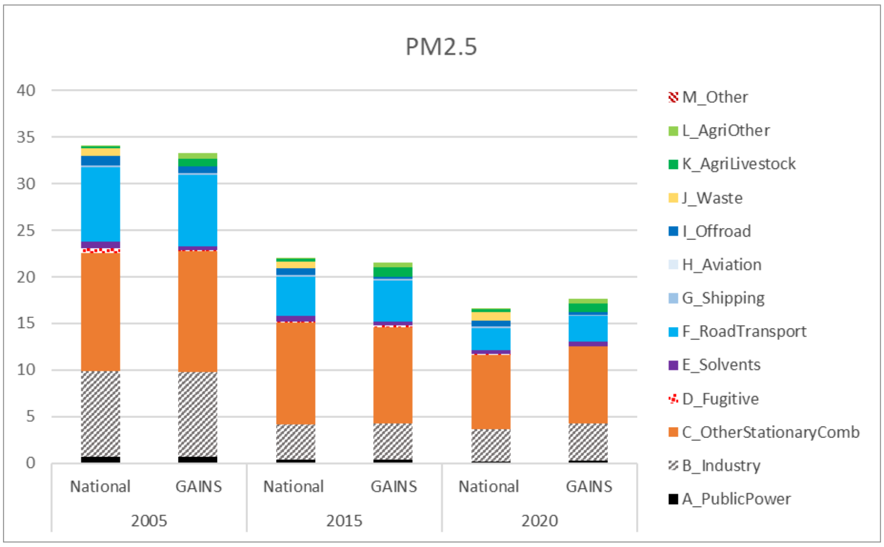


Figure 8-16: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



BULGARIA

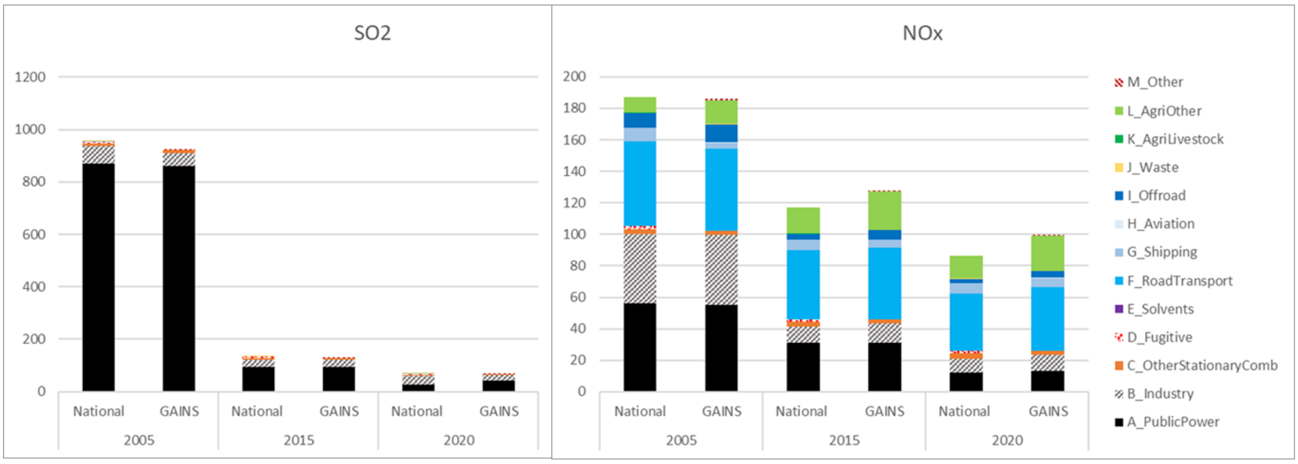
Table 8-3: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	955	923	-3.4%	135	128	-5.6%	69	67	-2.5%
NOx	177	171	-3.2%	100	103	2.8%	72	77	7.0%
PM2.5	39	51	28.6%	34	35	2.9%	31	34	9.6%
NH3	43	52	19.2%	41	48	16.2%	42	48	13.3%
VOC	92	105	14.4%	78	81	3.4%	71	76	7.1%

Larger differences remain for **NH_3, $PM_{2.5}$, and NMVOC**. Power and industry sector compares well for all pollutants. Large discrepancies for **$PM_{2.5}$,** and **NMVOC** in 2005 are due to agricultural residue burning (3F); see further text for more details.

For **SO_2,** overall acceptable agreement. Issues related to sulphur content for fuel oil in 2005 were resolved. Remaining discrepancies in **NOx** are due to transport where large share of fleet is old and its characteristics and emissions more uncertain.

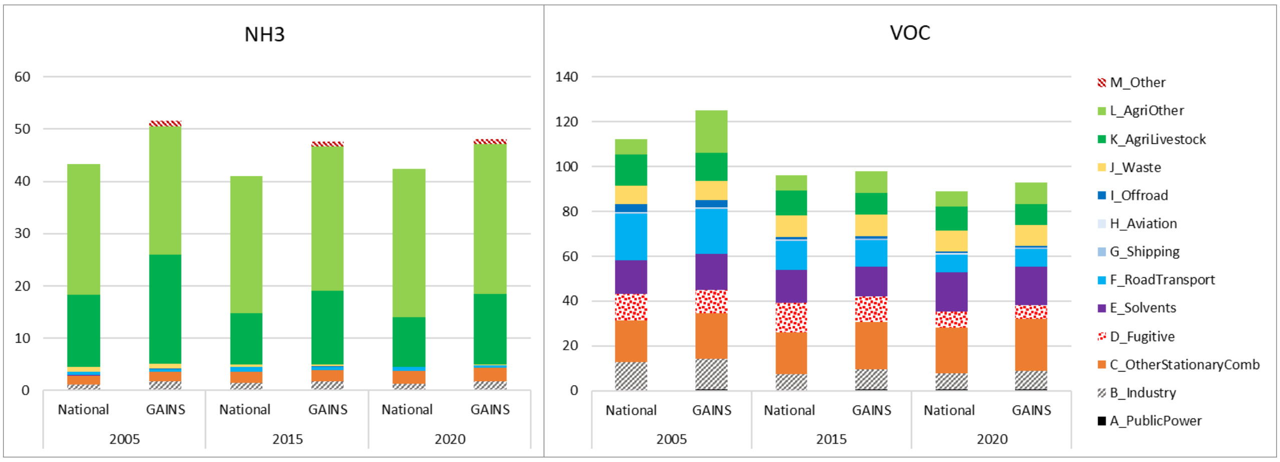
Figure 8-17: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



For **ammonia (NH_3),** larger differences due to discrepancies in cattle emissions and emissions from synthetic fertilizer application. Major revisions were done for the Member State submission in 2024 that lead to better alignment with GAINS.

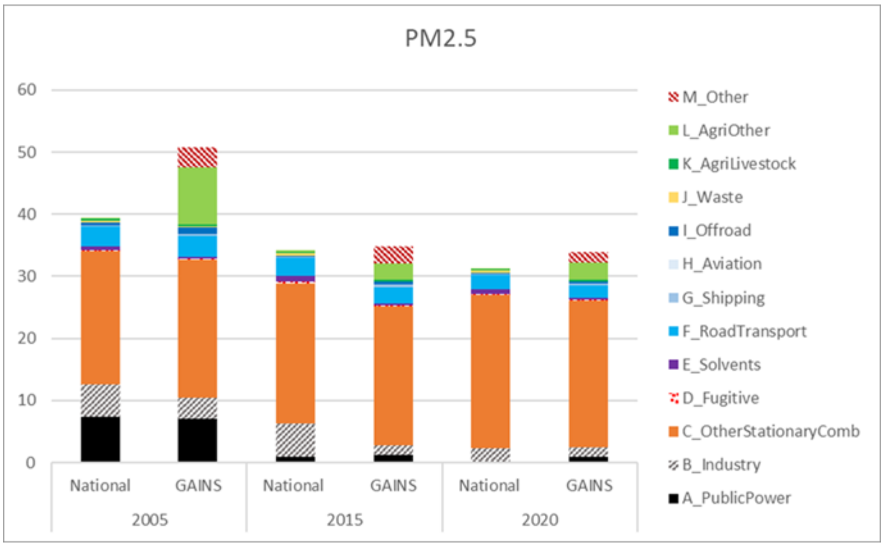
For **NMVOC,** differences at the sectoral level other than agricultural sectors are very small. Differences in 2020 and larger differences in 2005 are from agricultural waste burning. The **$PM_{2.5}$** description below addresses more details of agriculture burning-related issues.

Figure 8-18: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



For **$PM_{2.5}$,** the reason for discrepancy is open burning of agricultural residues (included in the sector L_AgriOther), which is consistently higher in GAINS than in the national estimates. GAINS builds on a systematic approach using remote sensing data making use of the FINN estimates (https://www2.acom.ucar.edu/modeling/finn-fire-inventory-ncar), a product developed at NCAR. This is also consistent with the use of FINN by the EMEP model for quantification of forest fires. Bulgaria shared their assumptions, which are drawing on bottom-up data and do not assume any trend or changes over time. GAINS (FINN) shows a decline and emission become less important in the future. Other sectors align well; the difference for industry is due to different allocation of some sources in GAINS – these are included in the M_Other category, therefore industry and M_Other have to be compared together and then match well.

Figure 8-19: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



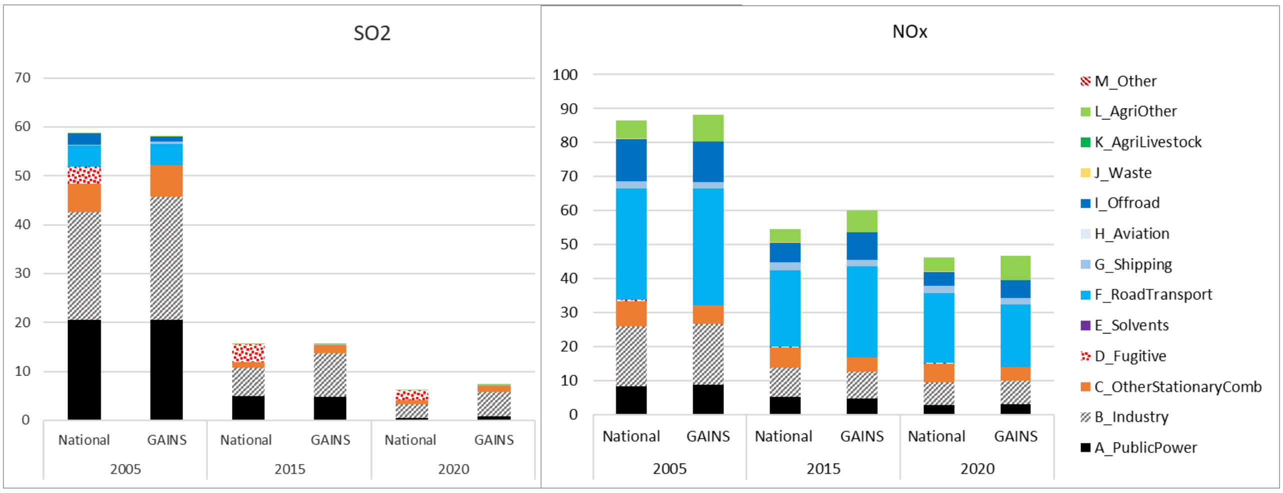
CROATIA

Table 8-4: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	59	58	-1.2%	16	16	0.0%	6	7	19.1%
NOx	82	80	-1.5%	51	54	5.8%	42	40	-5.8%
PM2.5	44	43	-0.3%	32	34	6.3%	28	27	-3.7%
NH3	43	41	-5.1%	33	34	1.7%	34	36	6.6%
VOC	104	112	7.5%	61	61	0.4%	61	59	-3.3%

Overall, acceptable agreement, although in relative terms the difference for **SO_2** in 2020 is quite large and is due to emissions from residential combustion in GAINS, specifically fuelwood for which EFs in GAINS are larger; however, the difference is small in absolute terms and will become less important over time. Some sectoral structure differences are related to different classification of sources in industry and power sector but the total agrees. Some differences remain for **NO_x** where transport sector, specifically non-road, i.e. coastal shipping, is key. Data on assumptions for penetration of Euro stages and age distribution of vehicles have been discussed and aligned to the possible extent. Acceptable agreement for **$PM_{2.5}$**.

Figure 8-20: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



For **ammonia (NH_3)**, some remaining discrepancies in 2020 emissions are driven by differences in emissions from dairy cattle. All other sectors match well.

For **NMVOC**, discrepancies in 2005 emissions are driven by differences in estimates from passenger cars in the transport sector. All other sectors match well, including strongly declining emissions from transport.

Figure 8-21: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the preliminary GAINS estimates for 2005, 2015, and 2020.

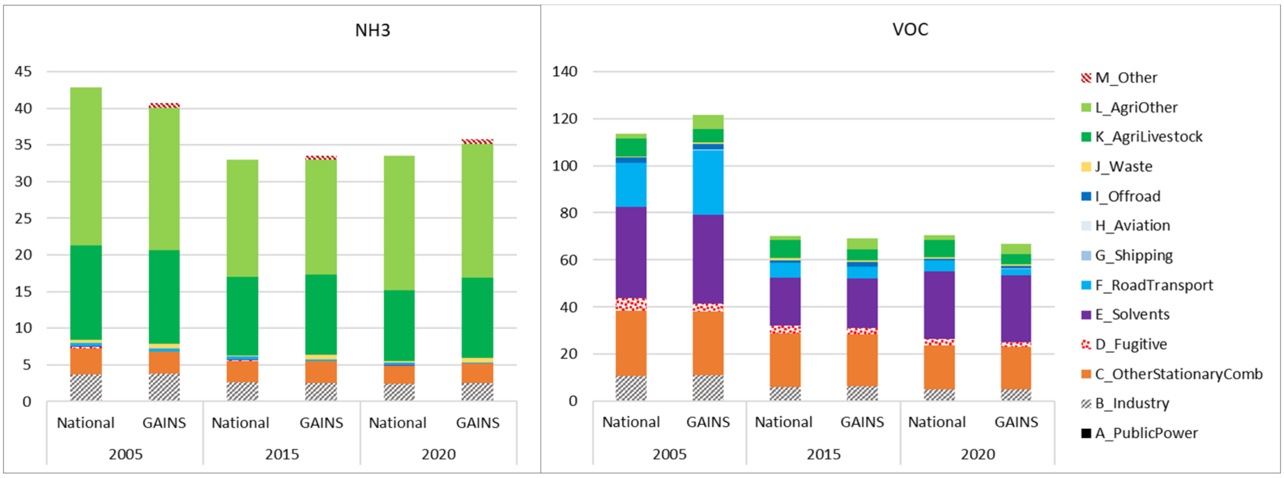
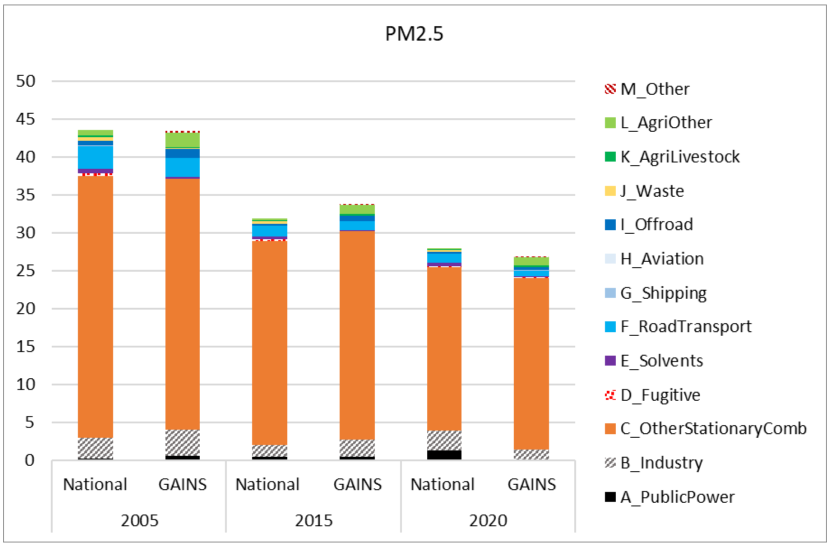


Figure 8-22: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



CYPRUS

Table 8-5: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	38	37	-3.2%	13	13	-1.2%	12	12	6.2%
NOx	21	23	9.2%	13	14	12.8%	10	10	-0.5%
PM2.5	2	2	9.9%	1	1	22.0%	1	1	11.9%
NH3	9	9	1.8%	7	7	3.7%	8	8	2.4%
VOC	14	15	7.9%	7	7	12.5%	7	7	1.5%

Emissions from power and industry sectors align well for all pollutants. Very good match for NH_3. Key remaining differences for **$PM_{2.5}$**, **NO_x** and **NMVOC** are due to transport sector estimates. Data on assumptions for penetration of Euro stages and age distribution of vehicles have been exchanged and aligned to the possible extent.

For **$PM_{2.5}$**, differences for residential combustion, where GAINS/PRIMES data for 2015 and 2020 seemed rather high compared to the national statistics, were resolved following the exchange of information with the national experts.

Figure 8-23: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

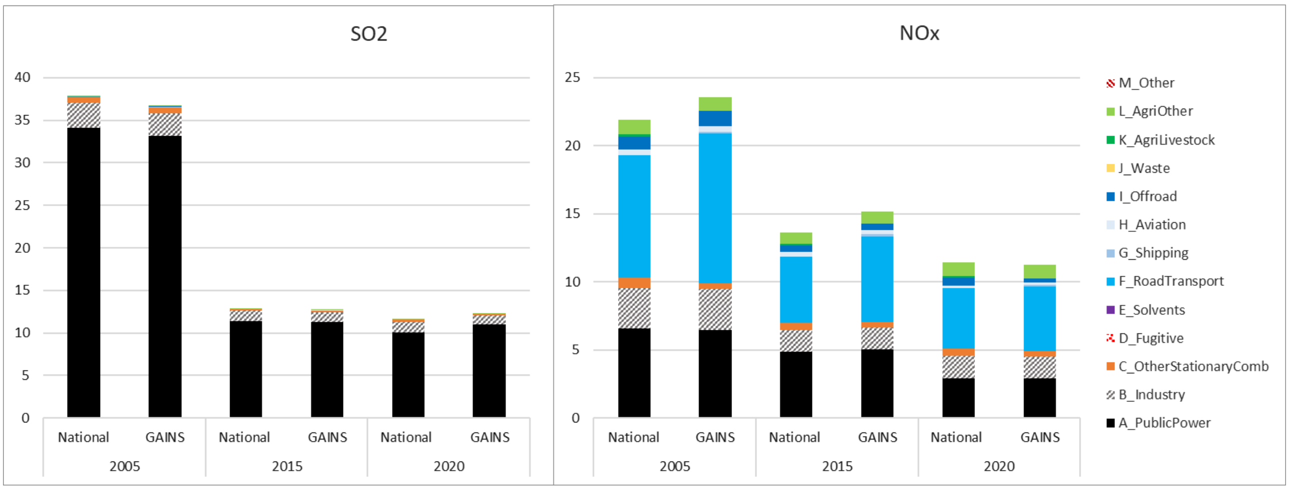


Figure 8-24: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

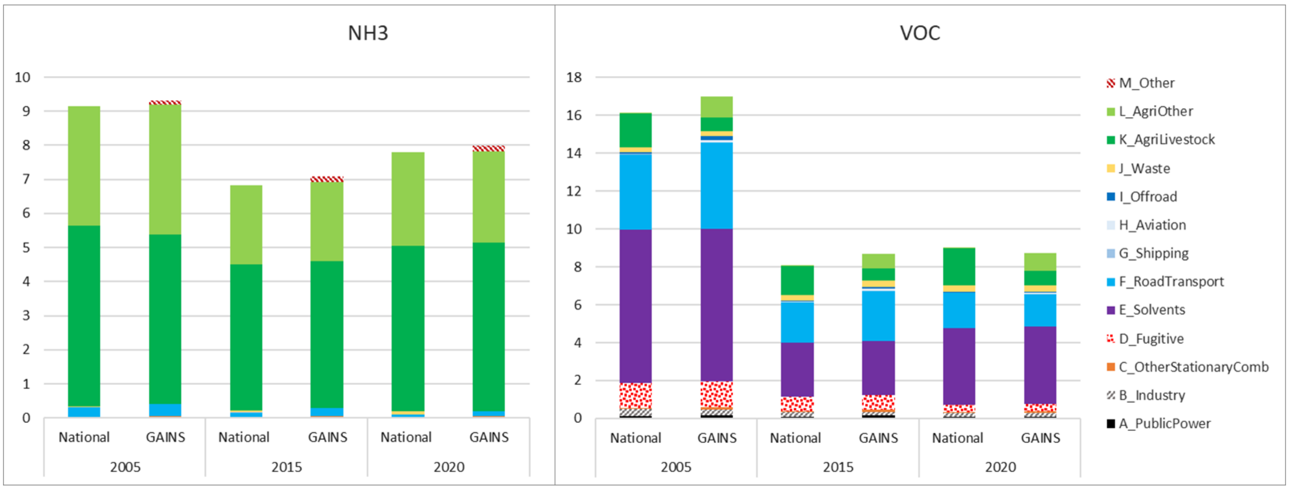
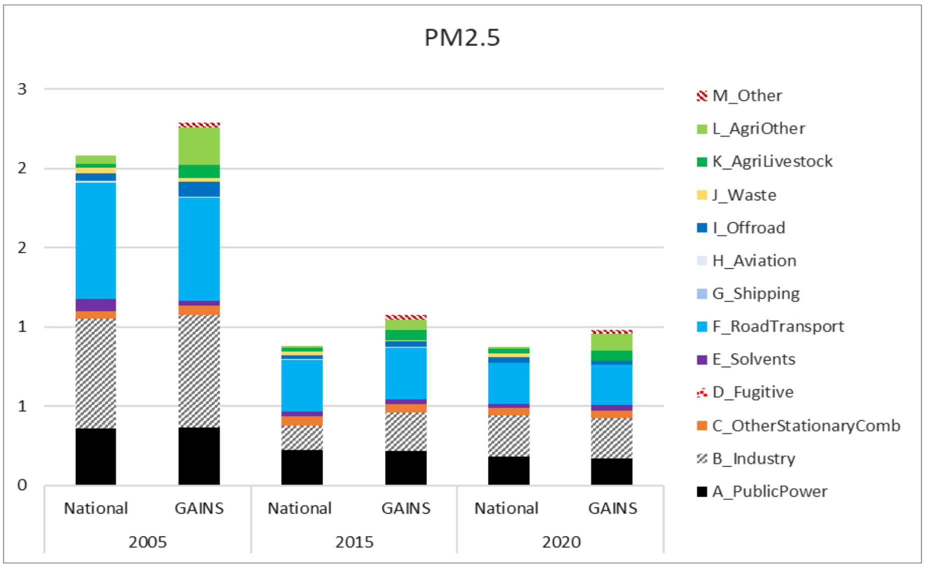


Figure 8-25: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



CZECH REPUBLIC

Table 8-6: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	208	211	1.3%	129	129	-0.3%	67	66	-0.7%
NOx	283	269	-4.9%	182	192	5.4%	135	136	0.7%
PM2.5	74	73	-0.7%	80	60	-24.1%	60	59	-0.6%
NH3	74	71	-4.2%	79	79	0.0%	67	69	2.6%
VOC	343	352	2.7%	316	292	-7.7%	263	249	-5.2%

Very good match for **SO_2** and **NH_3** as well as for power and industry sector for all pollutants.

Some differences remain in estimates of **$PM_{2.5}$, NMVOC** and **NOx** from transport sector. Data on assumptions for penetration of Euro stages and age distribution of vehicles have been exchanged and used to harmonize estimates to the possible extent. Additionally, for **$PM_{2.5}$** additional detailed data were exchanged for residential sector leading to good overall agreement apart from the year 2015 where larger differences remain (also for NMVOC) due to differences in handling structure and assumptions about old inefficient boilers – however, this causes temporary problems for consistency of intermediate past estimates while the current and future assumptions and emission estimates (including condensables) are consistent.

Most of the differences for **NMVOC** are similar like PM and link to residential sector. For **NH₃:** Slight discrepancies due to differences in emissions from other poultry and rabbits but overall, very good agreement. Rabbits are included in GAINS but not in the national inventory anymore.

Figure 8-26: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

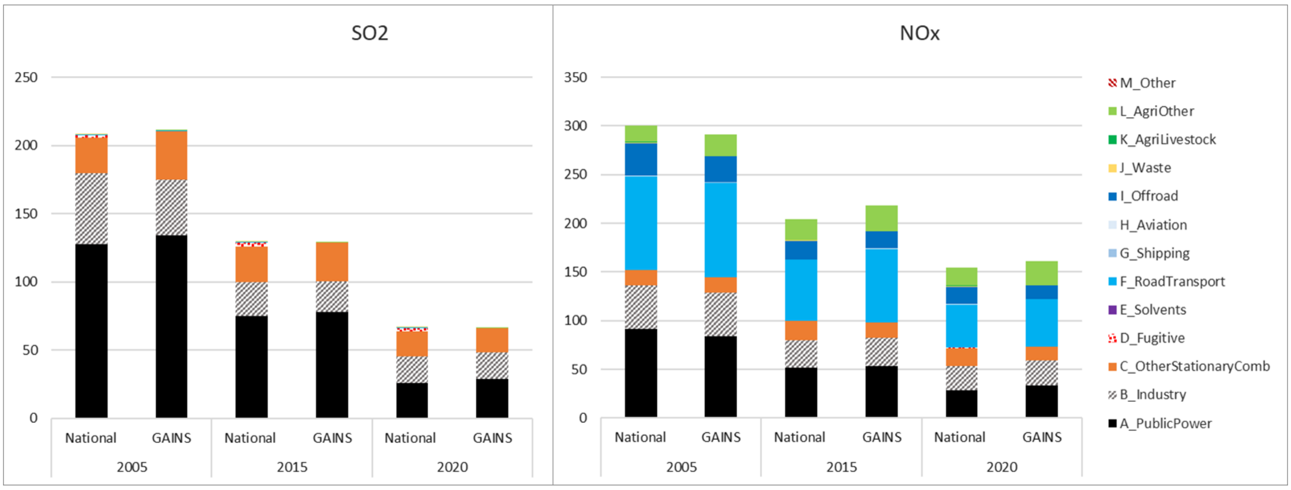


Figure 8-27: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

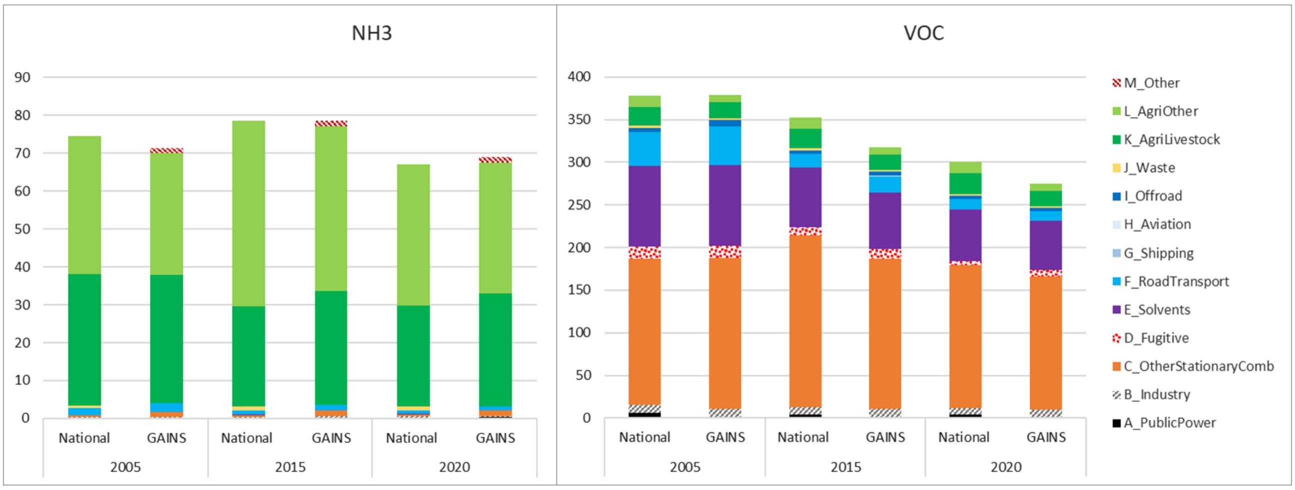
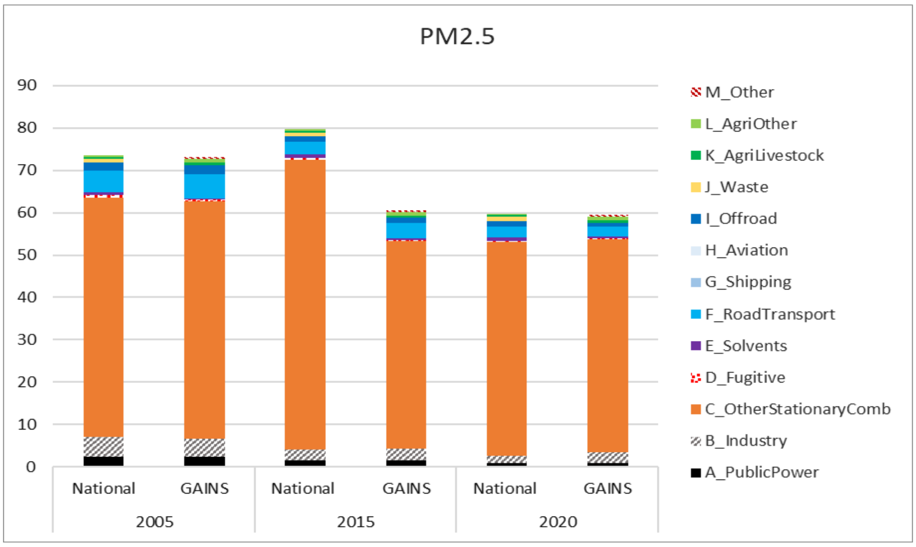


Figure 8-28: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



DENMARK

Table 8-7: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	26	26	-2.9%	10	10	3.0%	9	9	-2.6%
NOx	181	187	3.7%	91	106	16.3%	70	72	3.3%
PM2.5	21	23	10.7%	17	18	4.8%	12	13	7.5%
NH3	87	91	3.7%	73	79	7.6%	72	77	5.6%
VOC	111	114	2.8%	70	65	-7.3%	60	56	-7.2%

A good agreement at national and also sectoral level for **SO_2,** and some differences slightly over 5% for other pollutants.

A larger difference for **NO_x** for 2015 linked to road transport in GAINS, even though the data on assumptions for penetration of Euro stages has been used from the IIR. Discussion with national experts indicated that assumptions on emission factors for vehicles affected by ‘diesel gate’ differ but this disappears over time as their share declines. For **$PM_{2.5}$** some differences remain for off-road transport sources, especially for 2005, and emissions from livestock and harvesting. For **NH_3,** the estimates for emissions from crops vary slightly and for **NMVOC**, GAINS has slightly more optimistic assumptions about emission factors for fuelwood stoves; these become less and less relevant over time with newer installations increasing their share.

Note that some categories are differently allocated and so some elements of the ‘J_Waste’ in the national inventory are allocated in the ‘M_Other’ in GAINS.

Figure 8-29: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

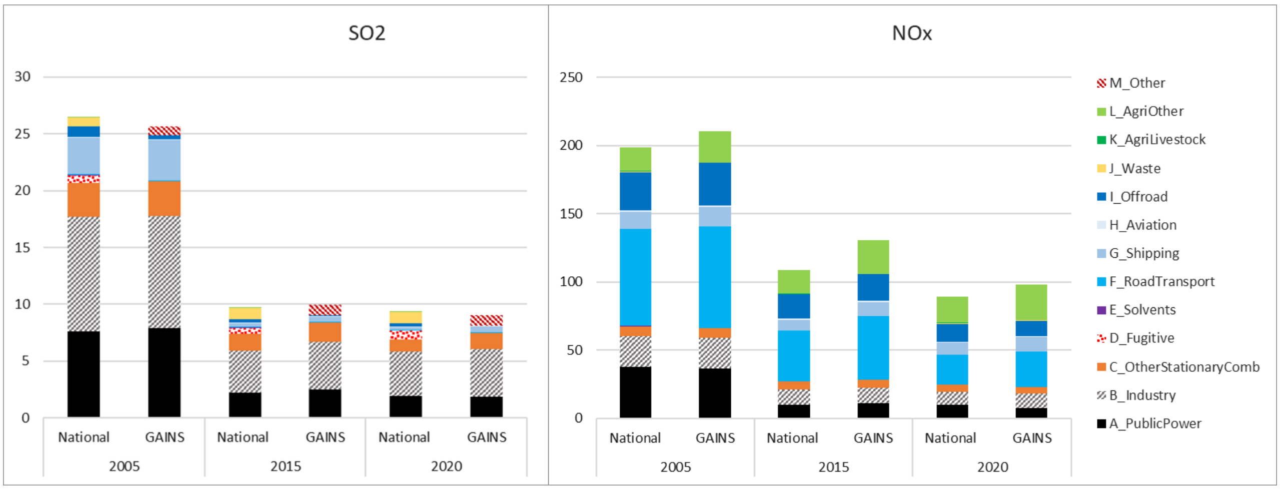


Figure 8-30: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

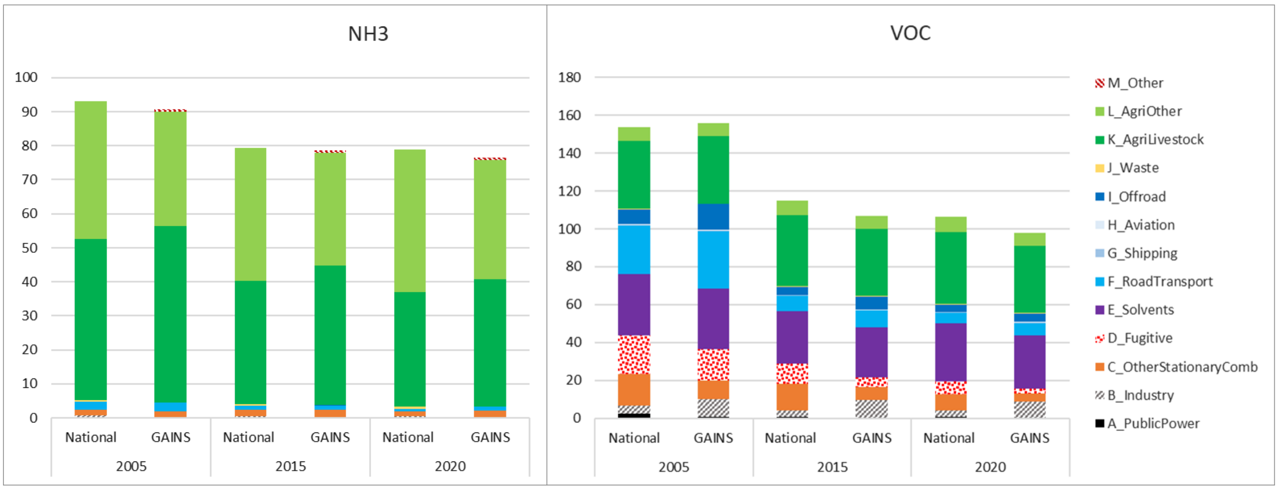
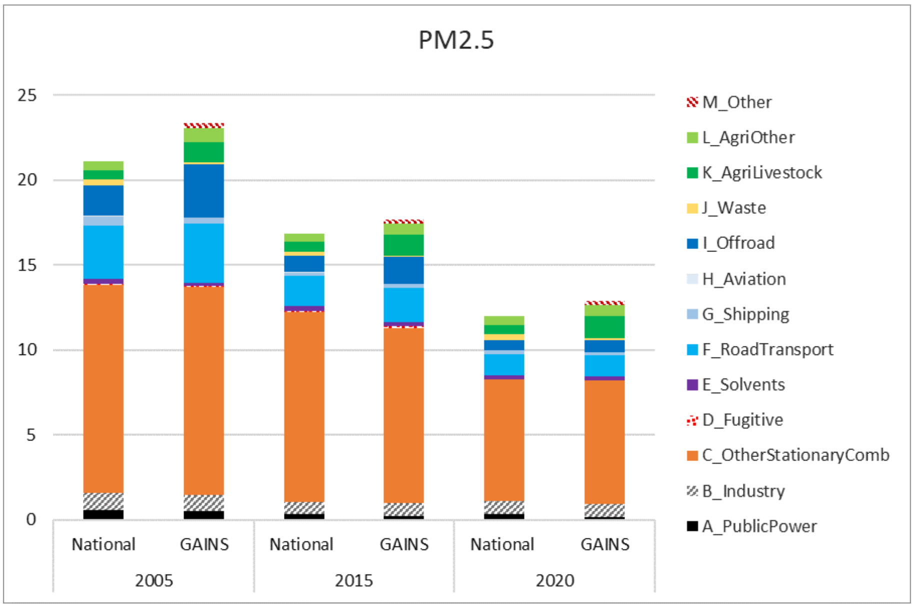


Figure 8-31: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



ESTONIA

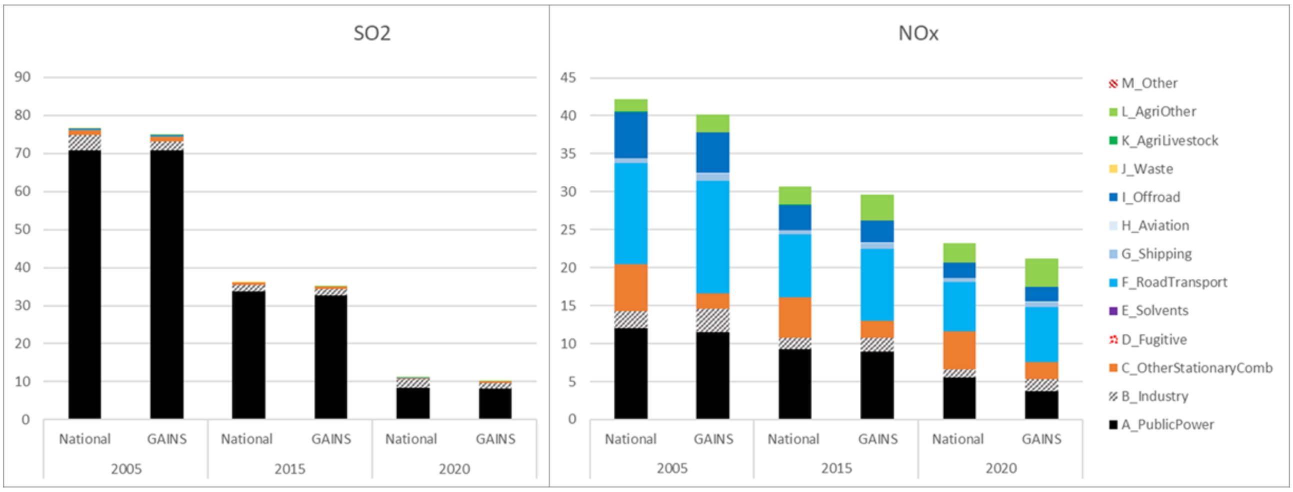
Table 8-8: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	77	75	-2.3%	36	35	-4.0%	11	10	-11.9%
NOx	41	37	-8.2%	28	26	-7.3%	21	17	-15.7%
PM2.5	8	12	42.0%	7	9	31.0%	5	7	30.6%
NH3	10	10	-1.2%	11	10	-10.2%	10	10	-0.3%
VOC	27	29	6.4%	17	17	1.0%	19	18	-6.9%

Good agreement for **SO_2**, apart from 2020 where cement emission factors differ slightly; Estonia is not producing clinker, all imported from Sweden, which is also reflected in low EFs in GAINS. Consistently lower GAINS for **NO_x** and this is linked mostly to residential sector emission factors. The national emission factors for wood boilers are very high, in fact comparable to emission factors for internal combustion engines. Since we have not found comparably high emission factors used in other countries or reported in peer-reviewed literature, GAINS factors continue to be applied. Additionally, GAINS process emissions appear higher owing to glass production estimates; after discussion with national experts the conclusion was reached that national estimate is too low and will be reviewed in the 2024 submission.

For **PM$_{2.5}$** key differences are for residential sector where GAINS applies emission factors with condensable PM. GAINS uses national information about the structure of the installations.

Figure 8-32: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



Overall, acceptable match for **NMVOC,** some small differences remain for transport sector but these decline over time and matter less. For **NH$_3$**, difference slightly higher in 2015 due to higher discrepancies in dairy cattle emissions in spite of harmonization, to the possible extent, of the data on N excretion and measures. But overall, ammonia compares well.

Figure 8-33: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

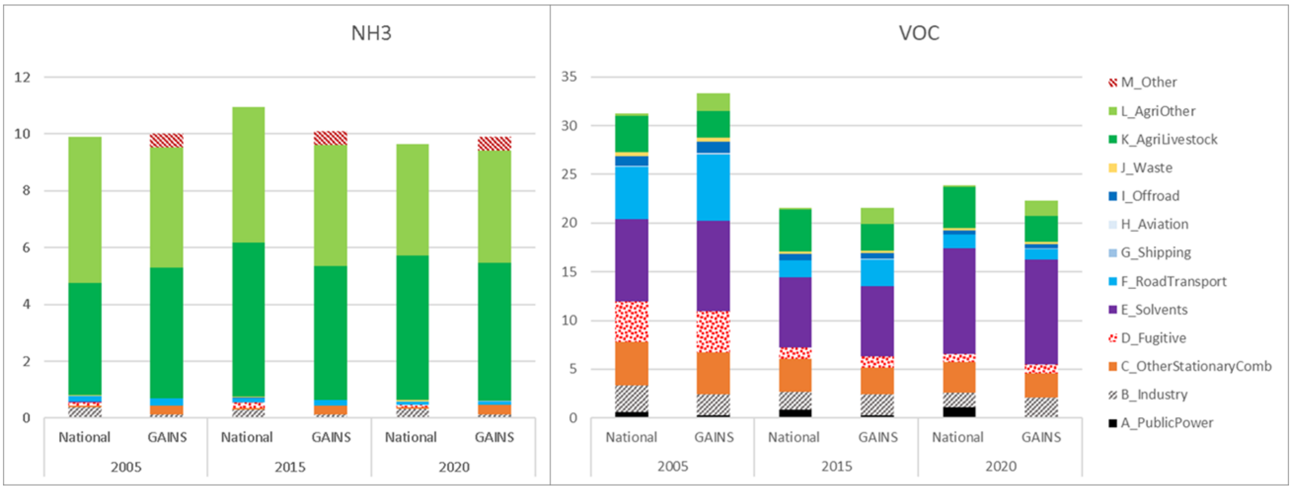
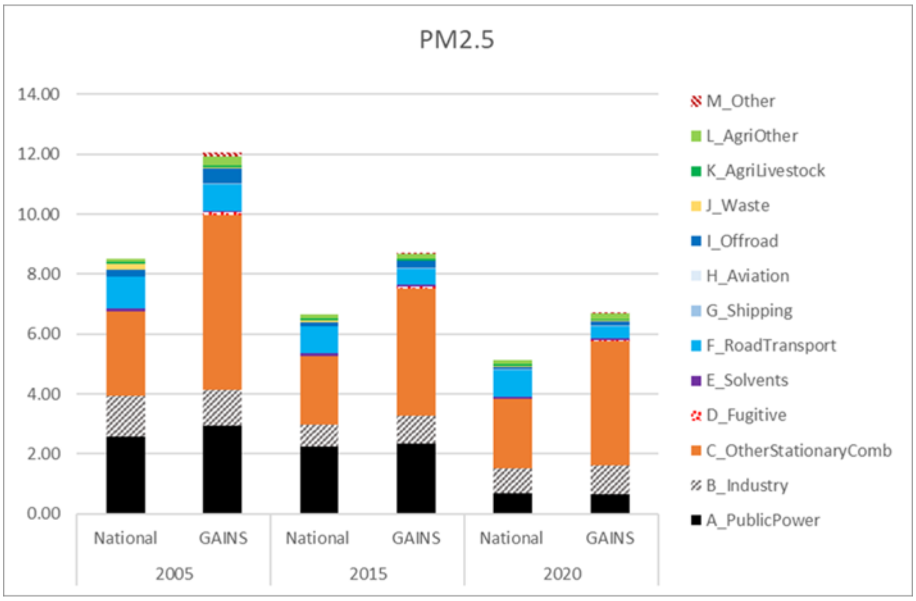


Figure 8-34: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



FINLAND

Table 8-9: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	70	68	-1.5%	41	41	-0.1%	23	23	0.9%
NOx	198	195	-1.7%	129	132	2.4%	96	103	7.8%
PM2.5	26	26	1.7%	17	17	-3.4%	14	14	-1.4%
NH3	40	39	-1.9%	36	35	-4.2%	32	32	1.8%
VOC	130	126	-3.6%	73	74	1.1%	69	66	-3.7%

Overall, very good consistency with the national submission for all pollutants. Slightly larger differences in 2020 for **NO_x** mostly in road transport but it is declining and small in absolute terms.

Figure 8-35: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

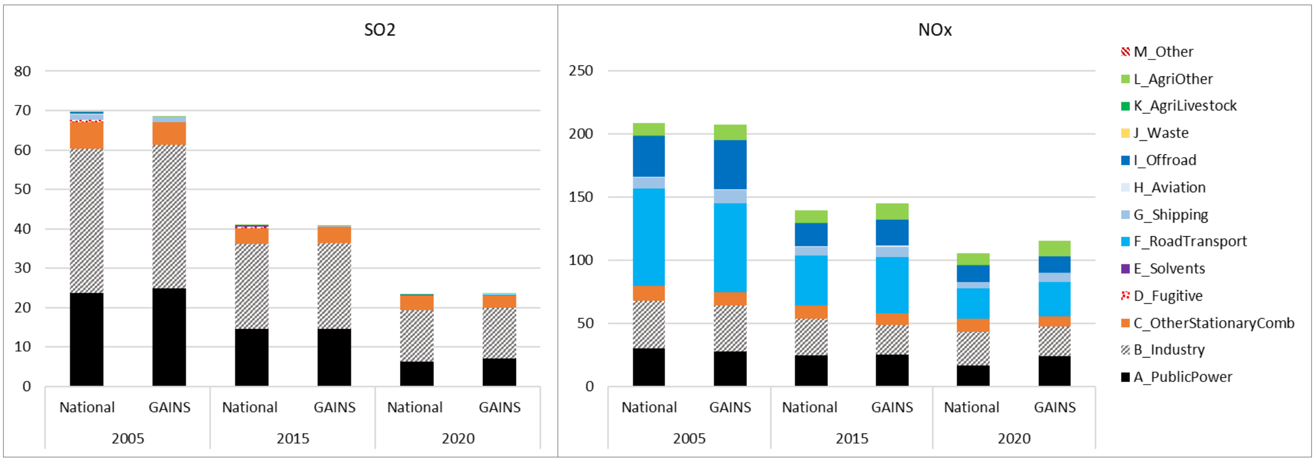


Figure 8-36: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

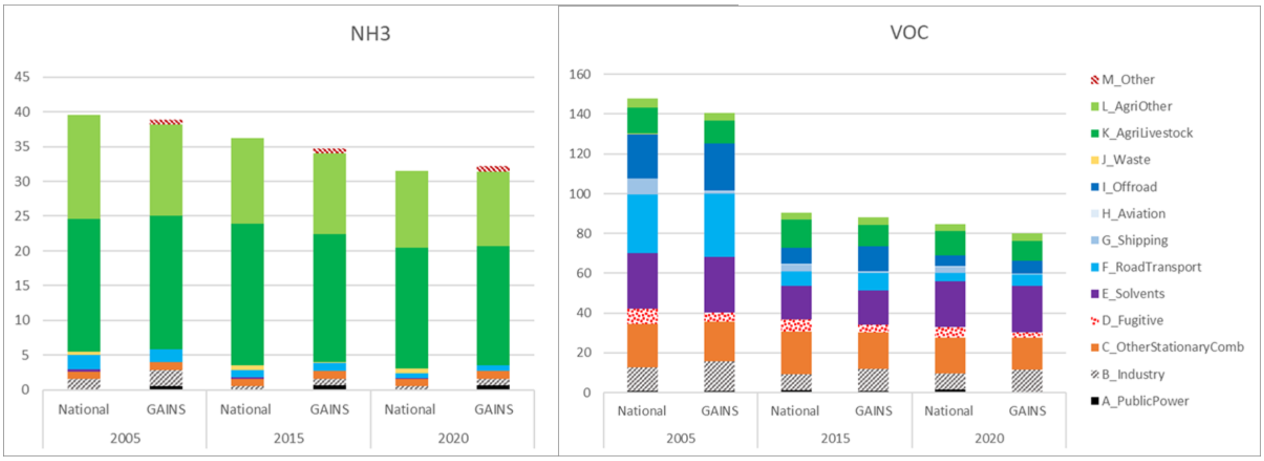
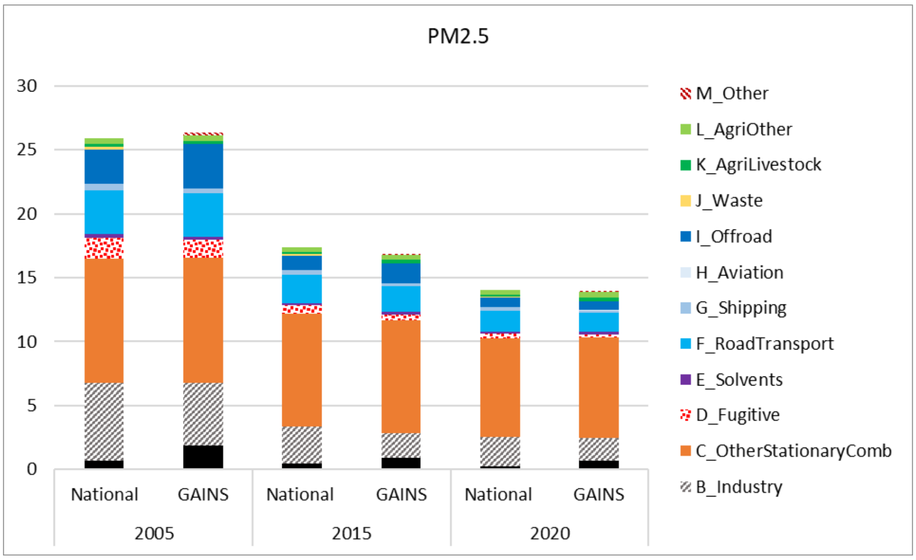


Figure 8-37: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



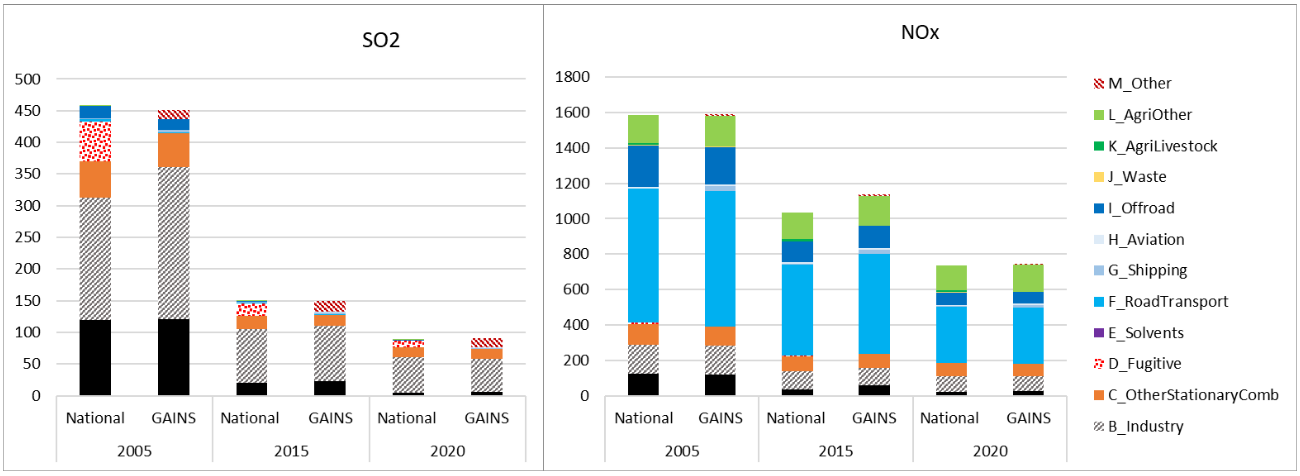
FRANCE

Table 8-10: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	458	451	-1.4%	150	150	-0.1%	89	91	2.3%
NOx	1420	1417	-0.3%	875	968	10.6%	588	589	0.2%
PM2.5	335	320	-4.4%	220	210	-4.5%	172	167	-2.9%
NH3	627	615	-1.8%	603	626	3.8%	560	580	3.6%
VOC	1372	1393	1.5%	788	783	-0.6%	708	708	0.0%

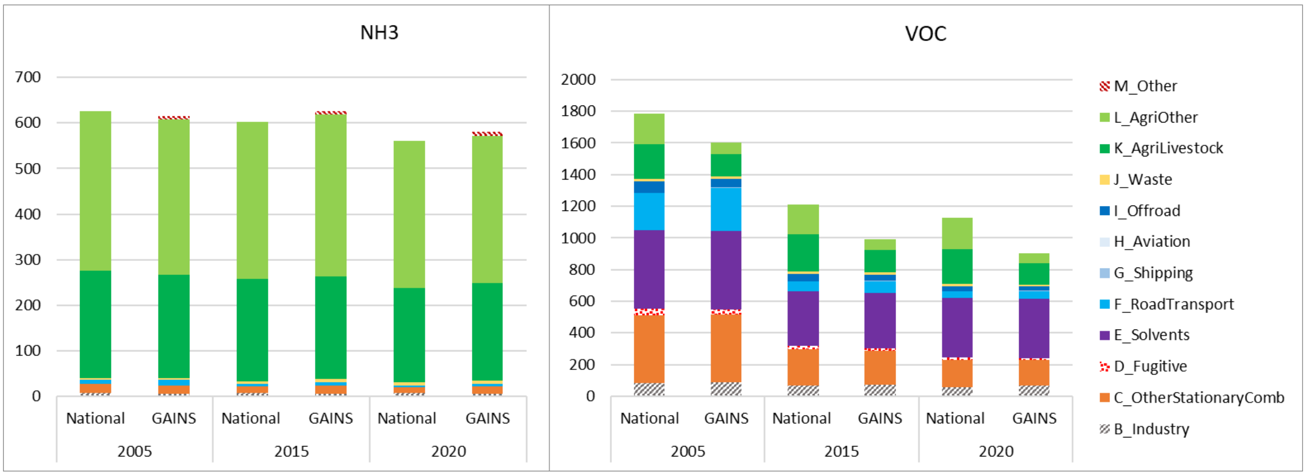
Overall, very good consistency with the national submission. For **NOx**, small differences in emissions from road transport for 2015 remain.

Figure 8-38: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



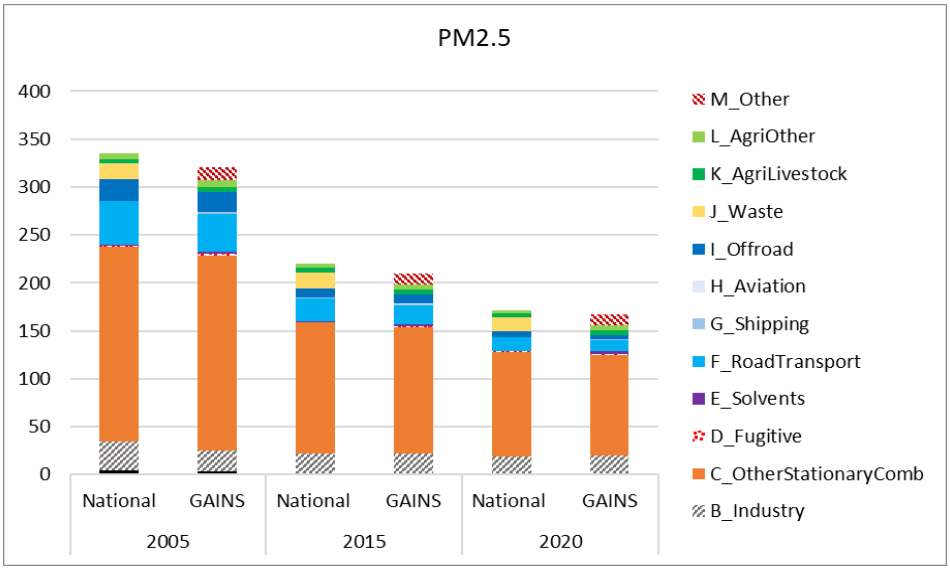
For **NMVOC**, the agreement is good, except differences for emissions from crops where national inventory includes natural sources in L_AgriOther, but this source is anyway not included in the NEC Directive and therefore the agreement in Table 3-10 is good.

Figure 8-39: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



France reports now condensable **$PM_{2.5}$** from residential sector. These emissions are larger than previous GAINS estimates (with condensables, as reported in the dedicated sensitivity scenario in CAO3) and rely on own emission factor measurements. These are now considered in GAINS and this result in good consistency between GAINS and the current national inventory.

Figure 8-40: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



GERMANY

Table 8-11: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	473	467	-1.3%	334	344	3.0%	241	225	-6.9%
NOx	1497	1413	-5.6%	1240	1205	-2.8%	866	853	-1.5%
PM2.5	135	154	13.7%	103	122	19.0%	81	102	24.8%
NH3	612	577	-5.8%	644	630	-2.2%	530	527	-0.6%
VOC	1184	1160	-2.1%	832	852	2.3%	732	730	-0.3%

Overall, acceptable match with only few estimates different slightly by more than 5%, apart from **$PM_{2.5}$** where GAINS includes condensable and Germany keeps reporting filterable PM – discussed and confirmed during consultations. For other pollutants, specifically **SO_2**, national totals close but there are some smaller sectoral differences, e.g., for iron and steel and cement production. For **NH_3,** slightly higher discrepancies in 2005 due to slightly higher discrepancies in manure nitrogen application.

Figure 8-41: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

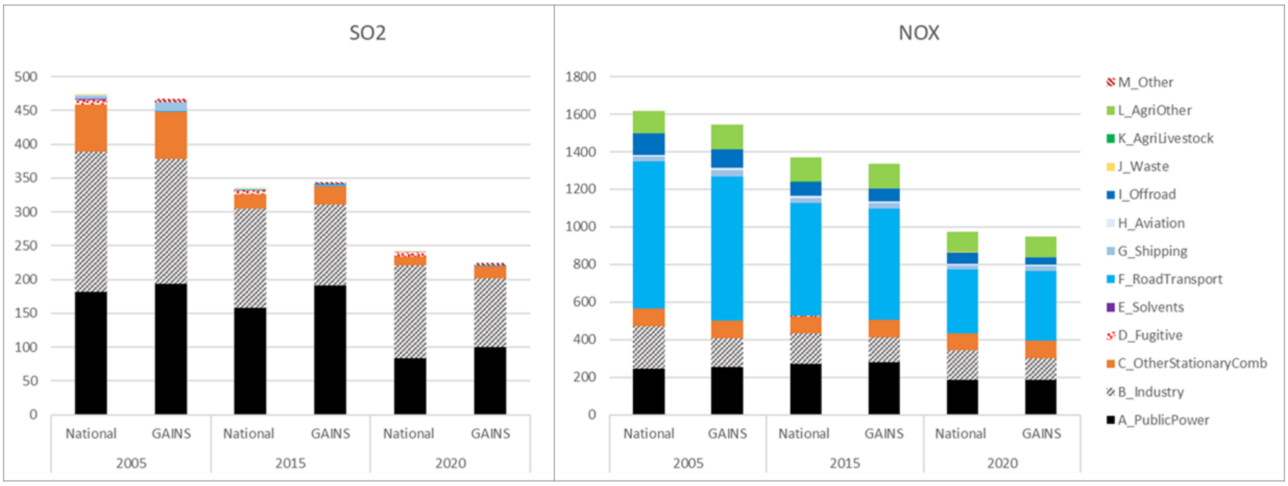


Figure 8-42: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

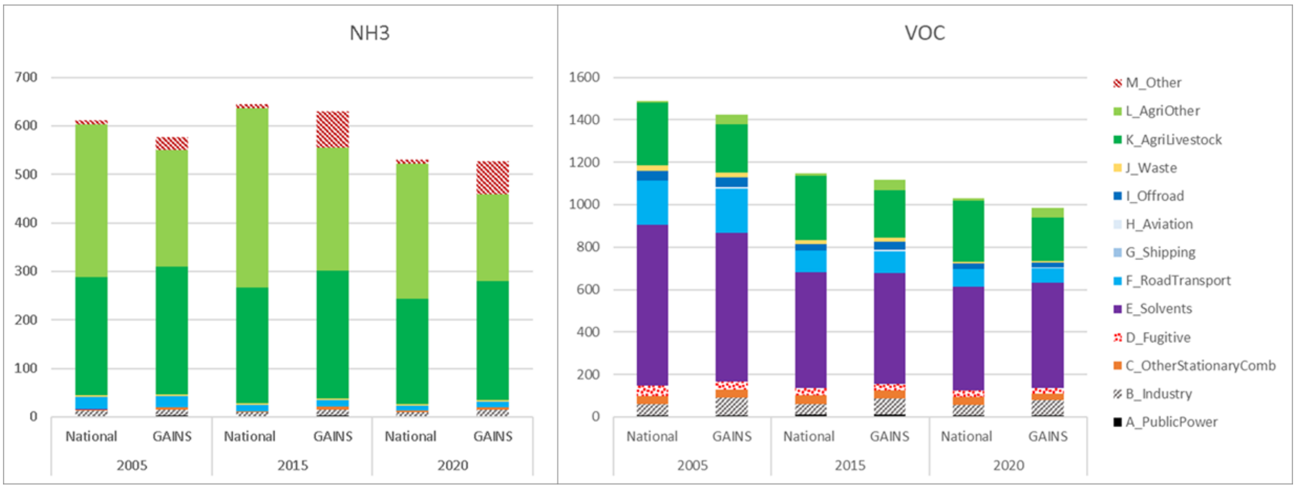
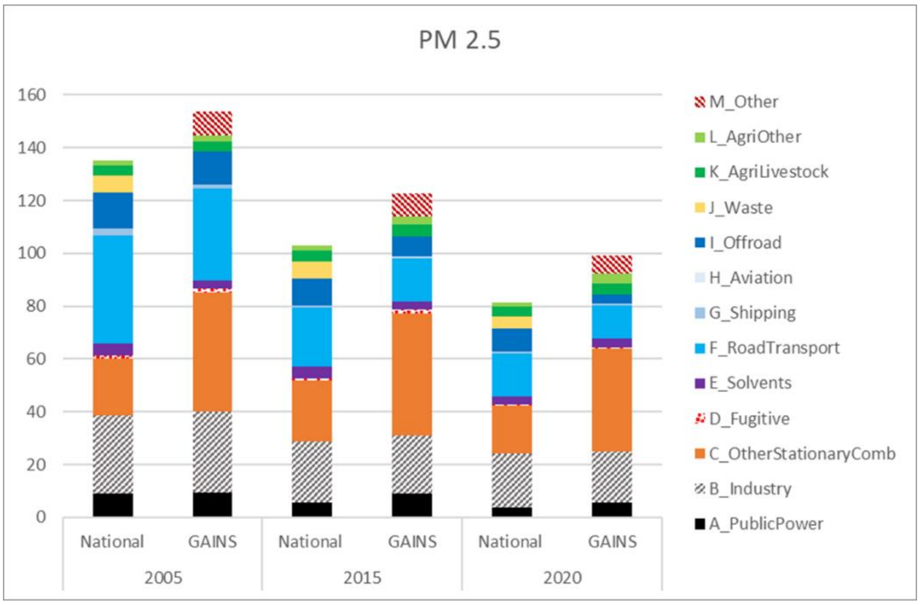


Figure 8-43: Comparison of the 2023 MS inventory submission for PM$_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



GREECE

Table 8-12: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	585	573	-2.2%	102	100	-1.7%	49	51	4.6%
NOx	462	435	-6.0%	246	234	-5.1%	204	174	-14.3%
PM2.5	68	72	6.0%	42	46	8.9%	34	37	7.7%
NH3	75	76	1.7%	64	65	1.3%	64	66	4.2%
VOC	320	320	0.0%	153	155	1.3%	125	120	-3.8%

Overall, very good match for **SO$_2$**, **NH$_3$**, and **NMVOC**. Somewhat larger differences for **NOx** in 2020 due to slightly lower GAINS implied emission factors for coal power plants and assumptions for road transport; both were discussed and harmonized to the possible extant with national experts. For **PM$_{2.5}$** GAINS estimates higher for all years and this a result of higher estimates for the open burning of agricultural residues. Open burning plays an important role in Greece emissions, also because disposal/burning of orchard trimming results in large emissions and might be partially also included in the remote sensing data that GAINS relies on.

Figure 8-44: Comparison of the 2023 MS inventory submission for SO$_2$ and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

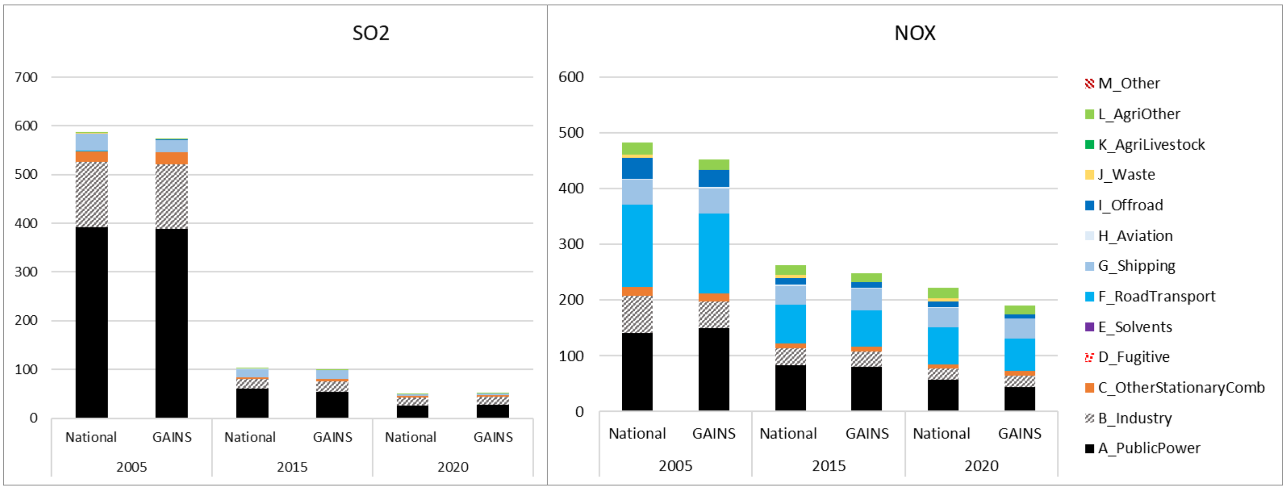


Figure 8-45: Comparison of the 2023 MS inventory submission for NH$_3$ and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

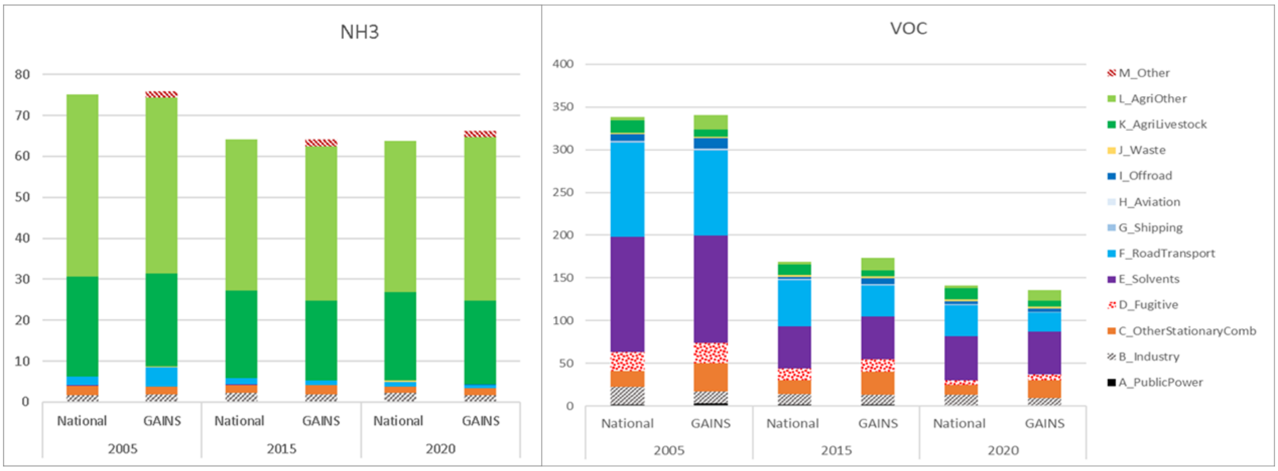
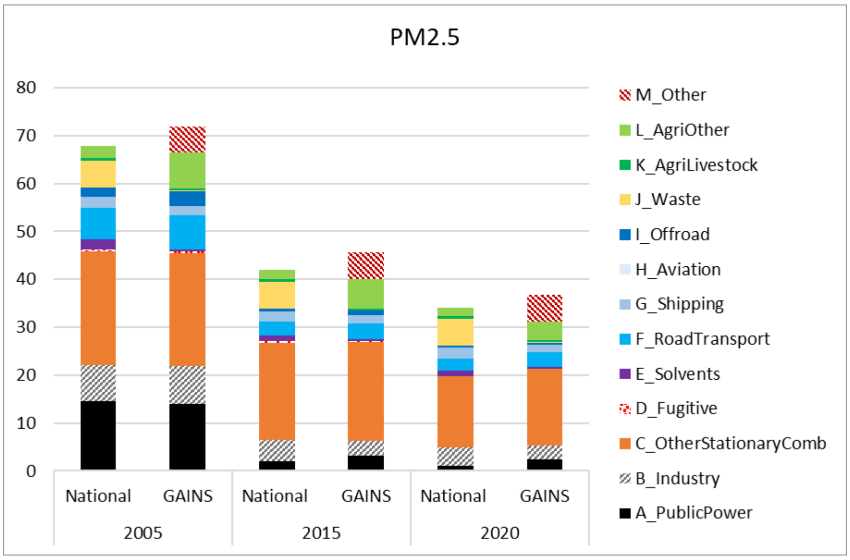


Figure 8-46: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



HUNGARY

Table 8-13: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	43	43	0.0%	24	23	-2.5%	16	15	-7.8%
NOx	163	162	-0.6%	107	116	8.9%	84	88	5.2%
PM2.5	40	47	16.8%	51	54	5.2%	37	39	6.3%
NH3	80	81	0.8%	76	77	0.8%	77	76	-1.0%
VOC	143	150	4.7%	97	112	15.8%	84	91	8.3%

Overall, acceptable match for **SO_2, NOx**, and **NMVOCs** for 2005, but differences are increasing for 2015 and 2020. Larger discrepancies for **$PM_{2.5}$** in 2005 are due to GAINS higher estimates for agricultural burning (3F) but it is importance declines over time owing to successful policies reducing its extent. For **NMVOC**, discrepancy in 2015 and 2020 emissions mostly due to slightly higher GAINS estimates for residential sector.

Figure 8-47: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

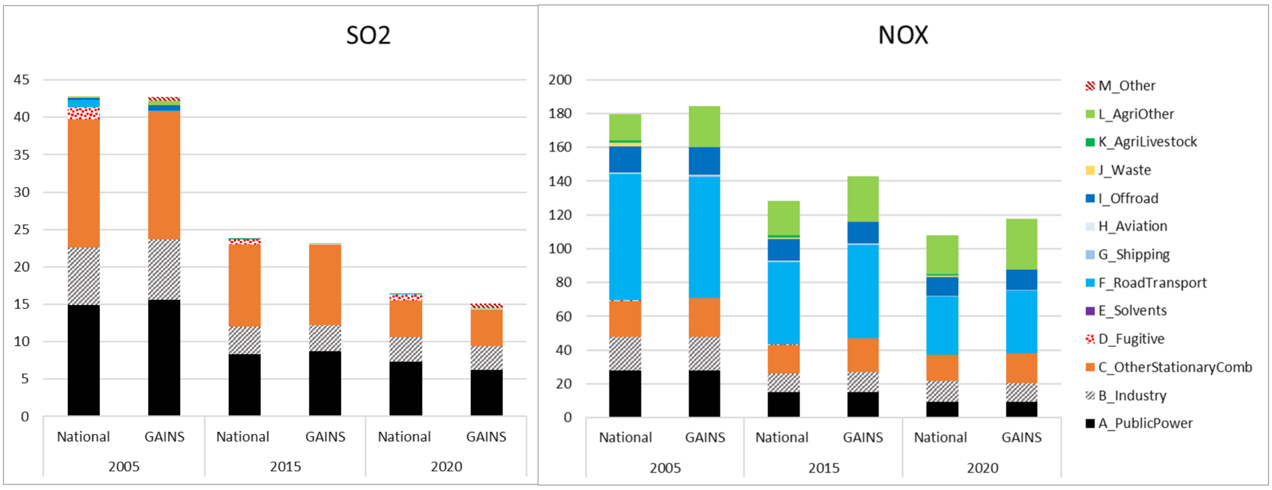


Figure 8-48: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

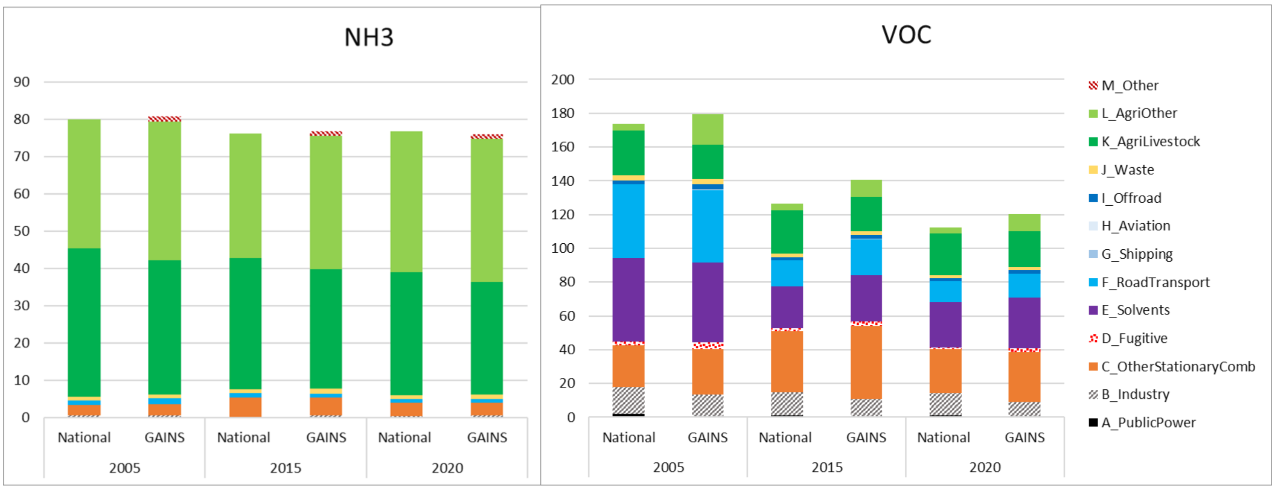
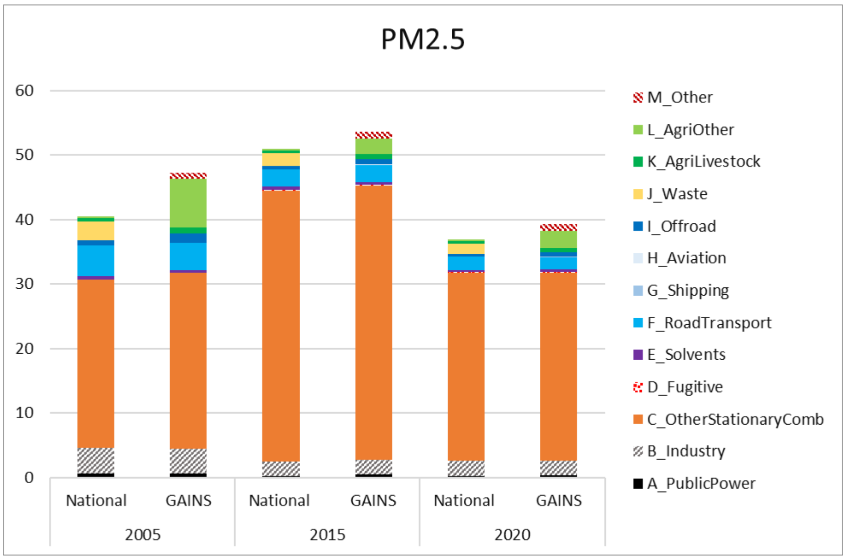


Figure 8-49: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



IRELAND

Table 8-14: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	73	72	-1.2%	16	17	3.9%	11	12	12.3%
NOx	142	145	2.1%	82	89	8.6%	62	59	-3.8%
PM2.5	19	20	3.2%	14	15	2.5%	13	13	0.2%
NH3	120	125	4.2%	120	123	2.8%	124	128	3.8%
VOC	81	82	1.4%	69	67	-3.2%	68	67	-2.7%

Overall, very good agreement for **NH_3, $PM_{2.5}$, and NMVOC** as well as for other pollutants for most years. Slightly larger differences remain for **NOx** in 2015 due to road-transport sector where emission factor assumptions are slightly different and for **SO_2** in 2020 where higher GAINS are due some differences in coal use in residential sector as well as SO2 from fuelwood, but these are small in absolute terms and are expected to decline in the future.

Figure 8-50: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

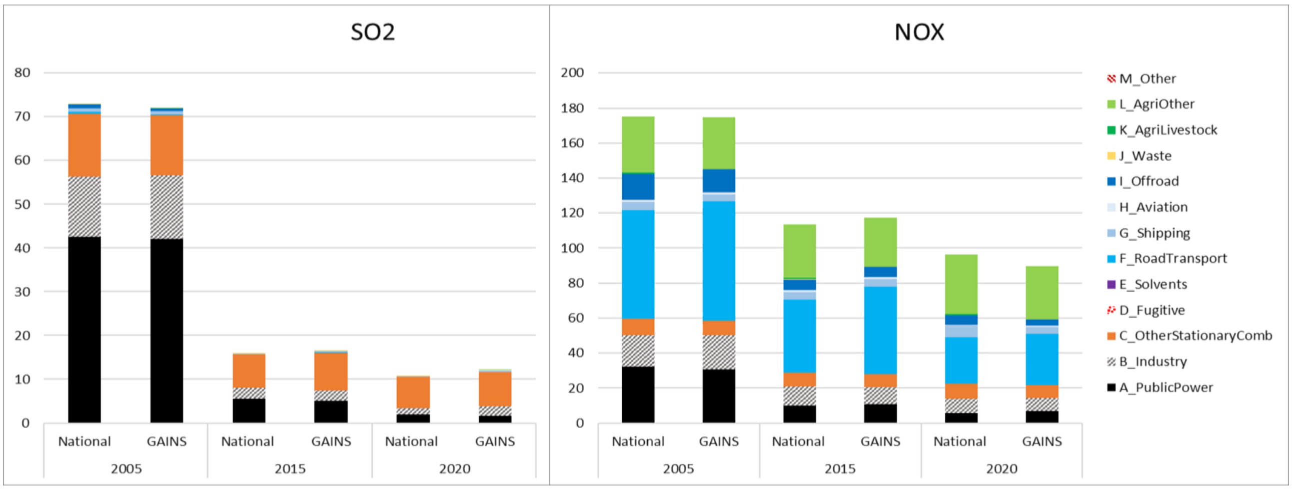


Figure 8-51: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

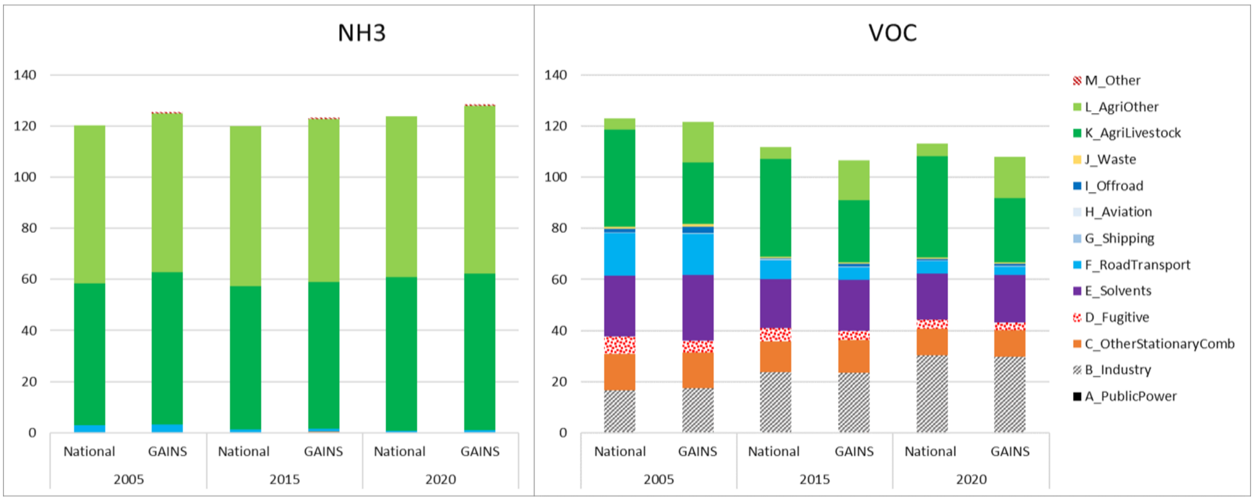
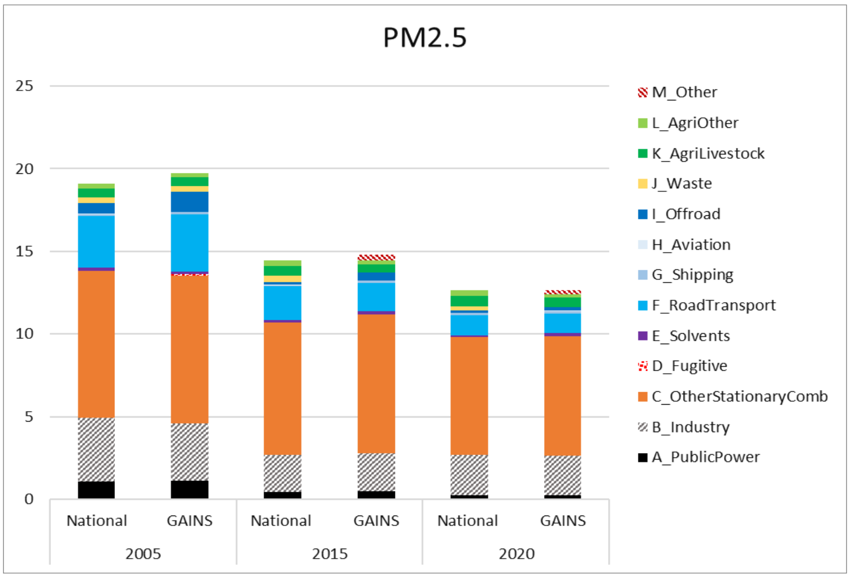


Figure 8-52: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



ITALY

Table 8-15: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	411	412	0.2%	128	125	-1.6%	85	80	-6.1%
NOx	1231	1230	-0.1%	679	732	7.9%	542	494	-8.9%
PM2.5	186	186	-0.4%	169	162	-4.2%	144	135	-6.1%
NH3	421	416	-1.3%	357	368	3.0%	362	363	0.4%
VOC	1202	1202	0.0%	778	758	-2.6%	717	675	-6.0%

Overall, very good match for 2005 for all pollutants. Differences are slightly increasing in 2020. Differences for **SO_2**, **NOx** and **NMVOC** in 2020 is linked to lower emissions in GAINS for shipping. Small differences for **$PM_{2.5}$** in 2015 and 2020 are linked to lower estimation in the residential sector and shipping sector.

Figure 8-53: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

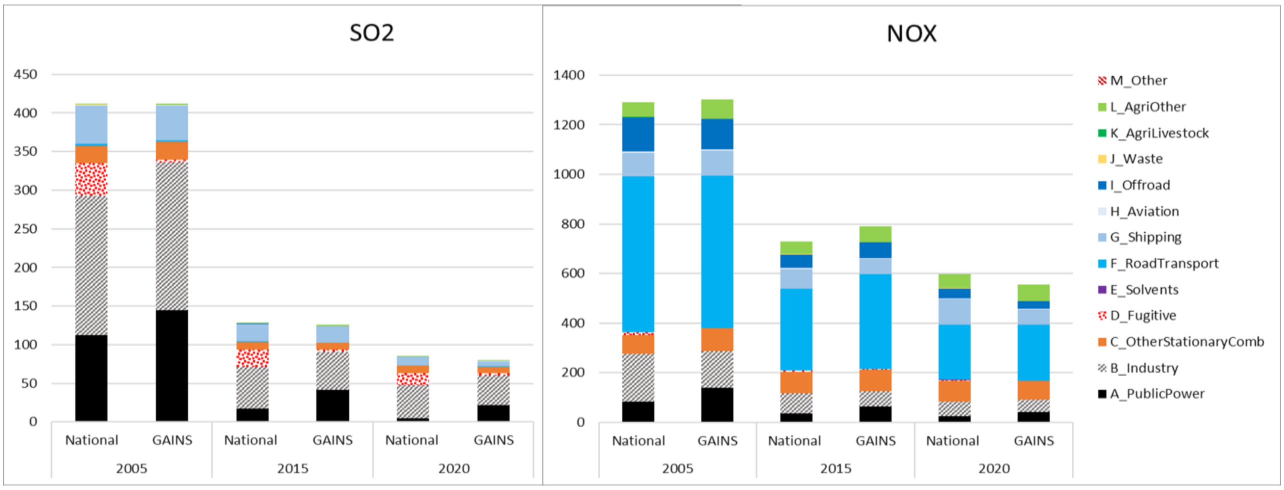


Figure 8-54: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

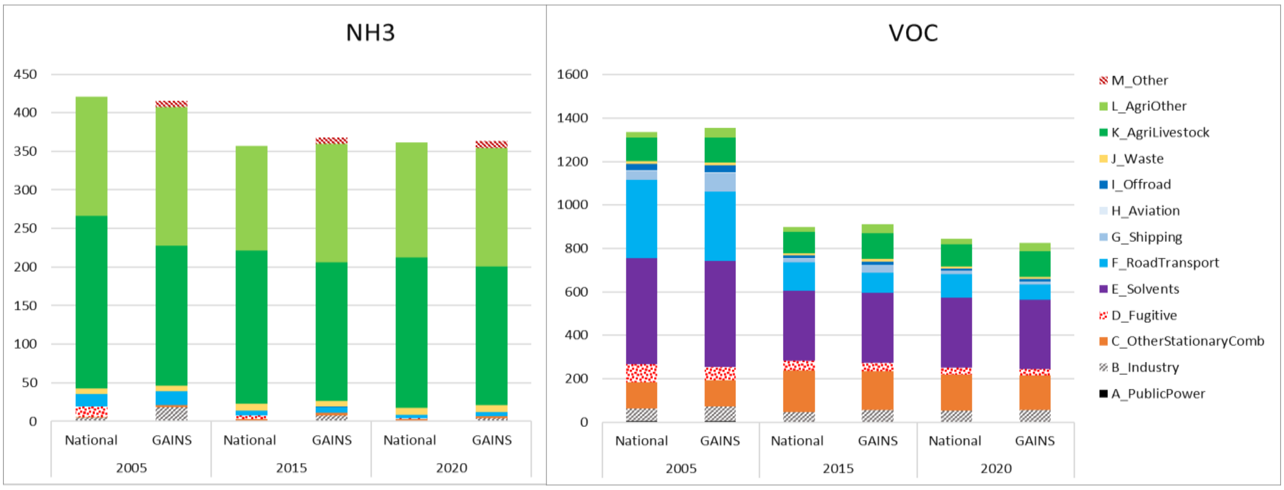
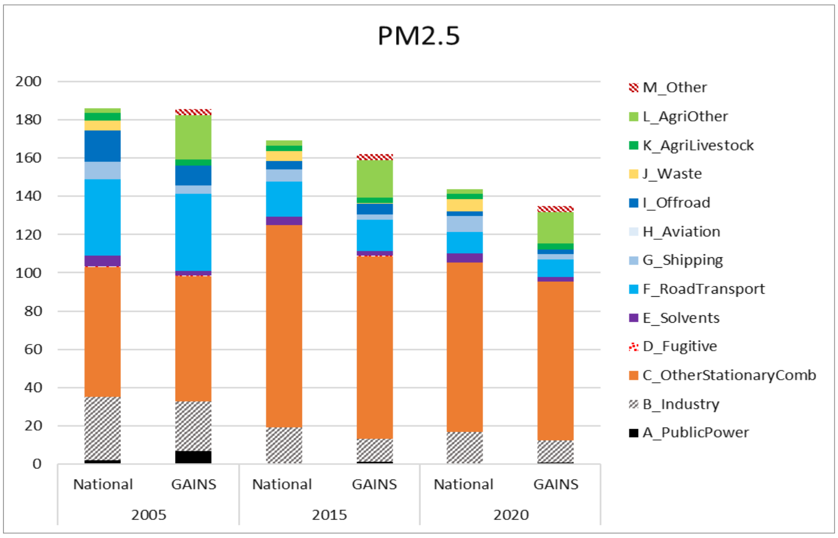


Figure 8-55: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



LATVIA

Table 8-16: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**
	[kt]	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**
SO2	9	9	6.9%	4	3	-12.4%	4	3	-14.8%
NOx	43	39	-9.2%	33	32	-3.0%	28	29	3.1%
PM2.5	27	28	2.9%	16	17	3.8%	17	16	-4.5%
NH3	15	16	3.9%	16	17	3.9%	16	17	4.6%
VOC	42	45	4.8%	28	30	7.3%	28	30	5.9%

Overall, very good match for **$PM_{2.5}$** and **NH_3**. For **NOx** and **NMVOC** the differences are also acceptable with some larger discrepancies for road transport estimates for 2005 (NOx) and residential sector in 2015/2020 for NMVOC. For **SO_2** the key difference after 2005 originates from discrepancy for non-road sector and is linked to assumptions about S content of diesel fuel, which in GAINS follows EU legislation and is a low-S fuel; national inventory has higher estimate indicating that the assumption about sulphur content was not adjusted.

Figure 8-56: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

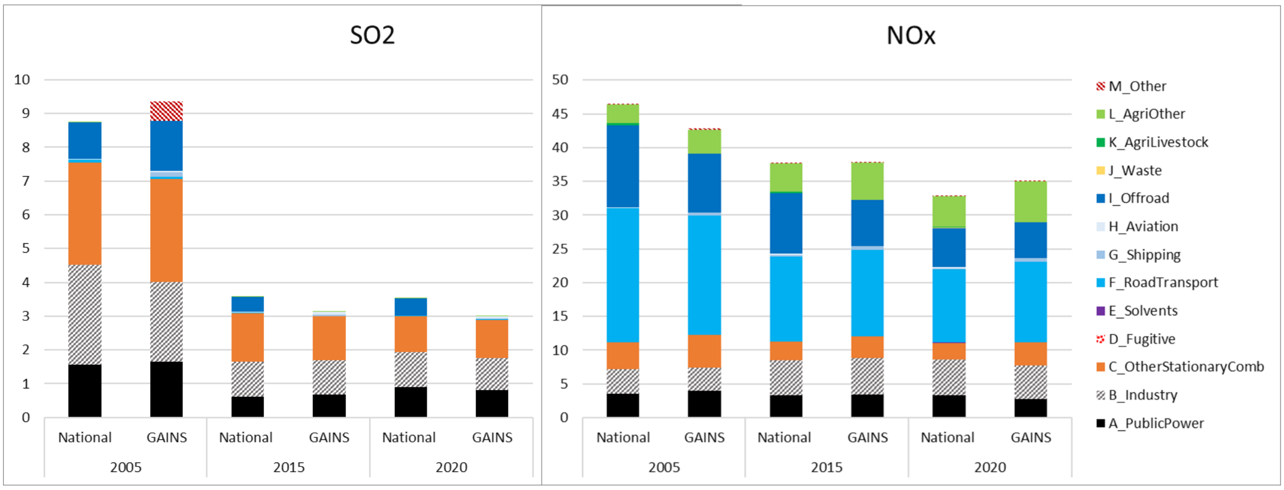


Figure 8-57: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

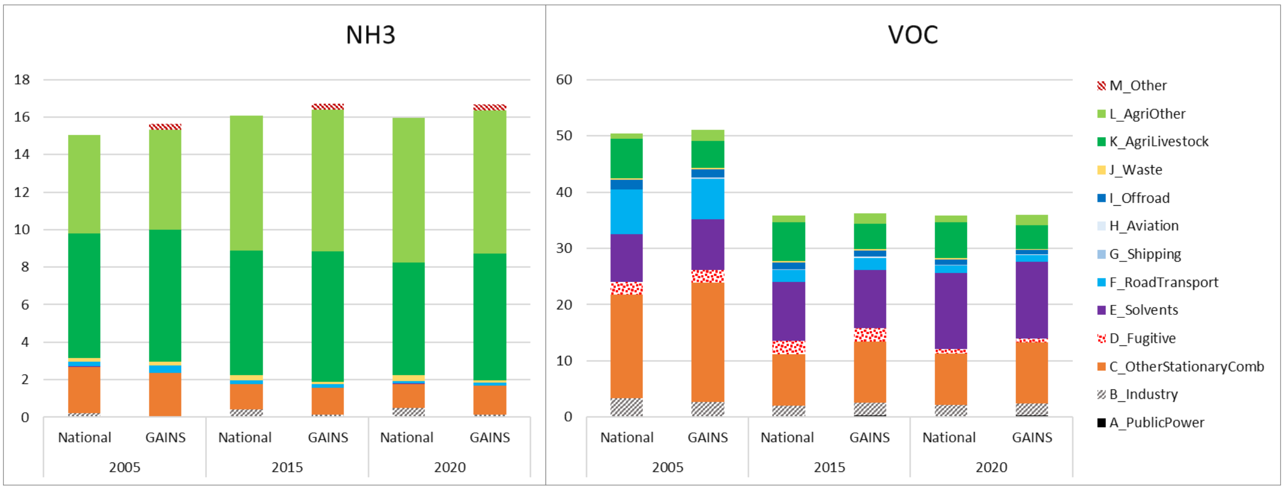
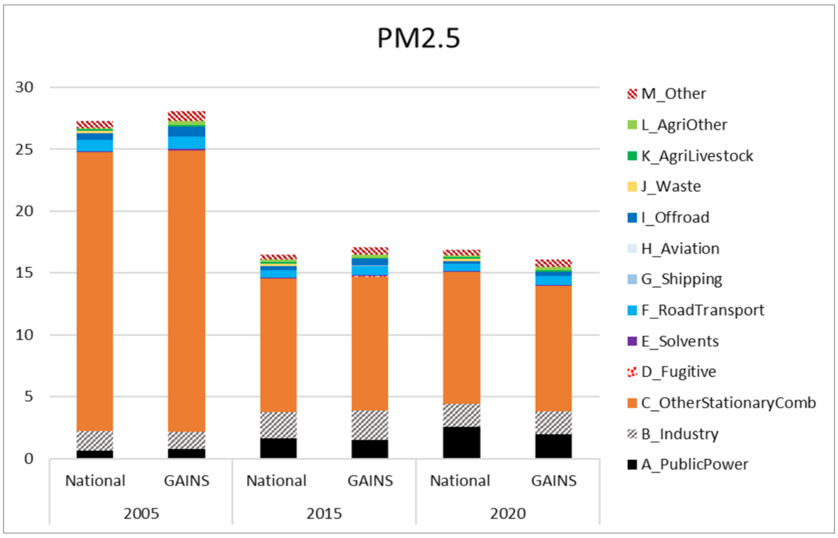


Figure 8-58: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



LITHUANIA

Table 8-17: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	28	28	0.8%	15	15	-1.2%	11	11	-3.6%
NOx	56	55	-2.6%	48	49	1.1%	42	42	-1.8%
PM2.5	9	19	102.0%	9	15	59.5%	7	12	63.1%
NH3	39	40	1.8%	40	37	-6.0%	40	37	-7.2%
VOC	46	49	7.3%	36	36	0.1%	34	33	-2.5%

Overall, good match for **SO_2,NOx** and **NMVOC** where only for 2005 a slightly elevated difference occurs due to road transport which becomes much less relevant over time. For **NH_3** several updates were made using the IIR and CRF (UNFCCC) information and the overall match is reasonable, but some differences remain showing faster decline of emissions in GAINS owing to implementation of IED; it has been challenging to validate the assumptions as the respective information about measure implementation is scarce or not available.

The largest differences however are for **$PM_{2.5}$** (up to a factor of two) where residential sector is dominating. Key reason is inclusion of condensables in GAINS and use of Tier II method rather than Tier I without condensables as in the national inventory. Furthermore, GAINS includes higher emissions from open burning of agricultural waste,

Figure 8-59: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

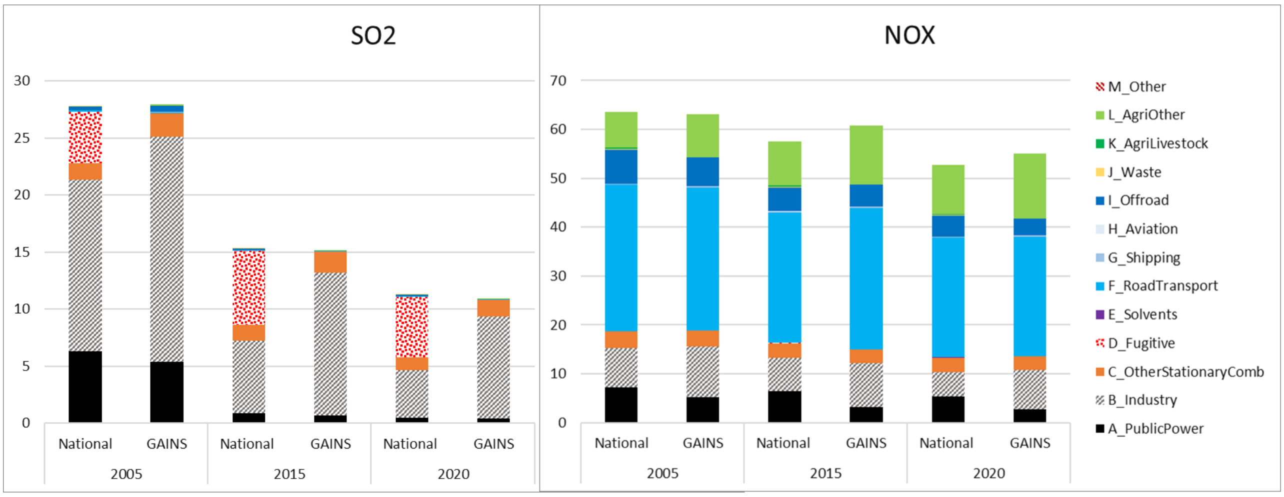


Figure 8-60: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

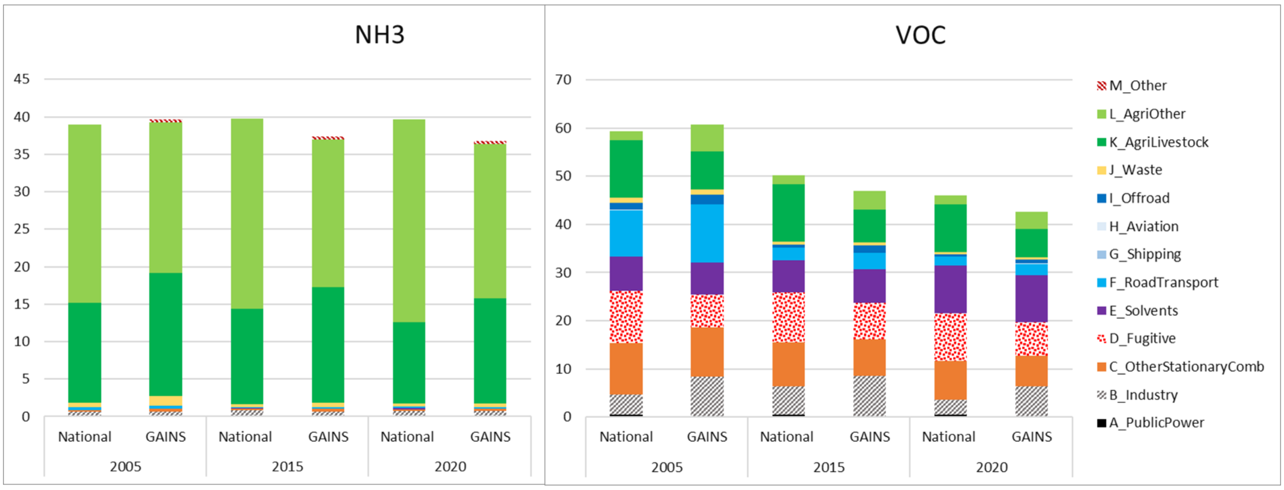
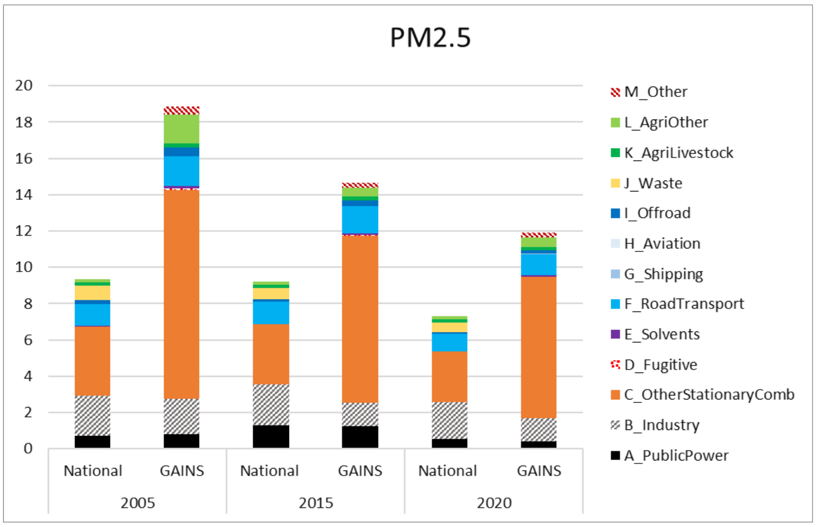


Figure 8-61: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



LUXEMBOURG

Table 8-18: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the preliminary GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	3	3	-0.2%	1	1	-8.1%	1	1	-18.4%
NOx	56	56	-0.2%	28	26	-8.0%	14	12	-12.2%
PM2.5	3	3	13.0%	1	2	16.7%	1	1	-11.4%
NH3	6	5	-14.5%	6	5	-17.1%	7	5	-28.1%
VOC	12	12	-0.1%	7	8	6.3%	7	7	-0.2%

Differences tend to increase towards 2020, apart from **NMVOC** where overall emissions compare well. In spite of the discussions following consultations some differences remain, and the reasons vary across pollutants. Emission from industrial sources are generally low and challenging to estimate as often linked to very few sources for which specific data is difficult to obtain. Even small differences in assumptions about mitigation measures actual efficiency lead to observed discrepancies for industrial emissions of **SO_2**, **NOx**, and **$PM_{2.5}$**. While for NOx, industrial sources contribute little, for SO_2 they represent currently nearly all emissions and so the difference is linked to one source. For $PM_{2.5}$, the difference is also linked to apparent error in the estimates or power sector in the national report and these emissions will be updated in the 2024 submission and then showing a good agreement with GAINS.

Larger differences for **NH_3** remain throughout the whole period although the livestock numbers, excretion rates and implementation of polices were discussed and updated in GAINS drawing on the information available in the IIR as well as CRF (reporting to UNFCCC) in discussion with national experts. GAINS estimates a more optimistic outcome for implemented policies showing lower emissions than in national inventory. There is also rather large set of emissions from industry and power plants in national reporting in 2020 which appears to be erroneous and will be corrected in 2024 submission leading to a better alignment with GAINS.

Figure 8-62: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

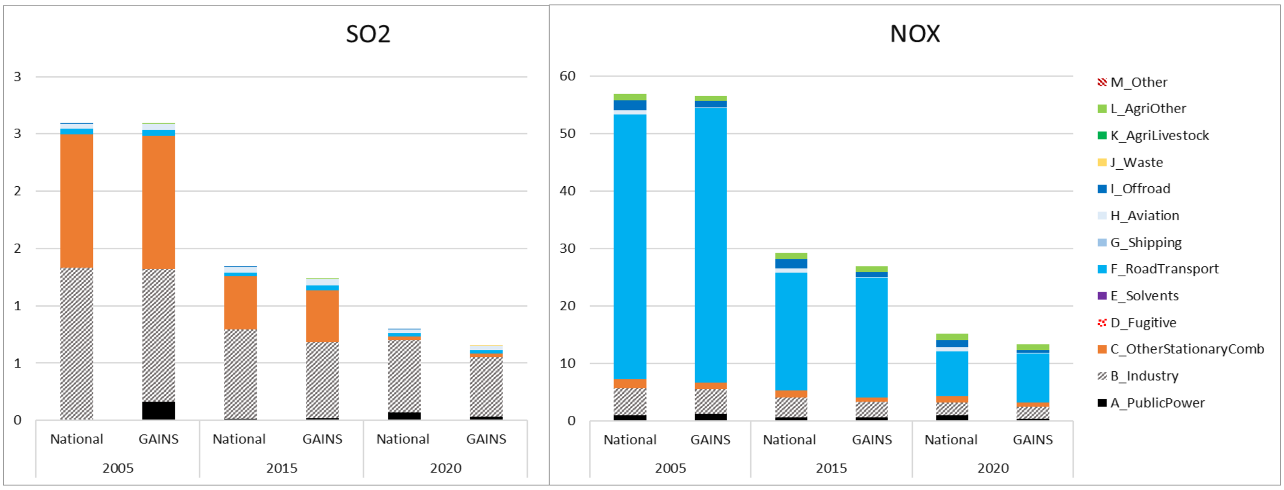


Figure 8-63: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

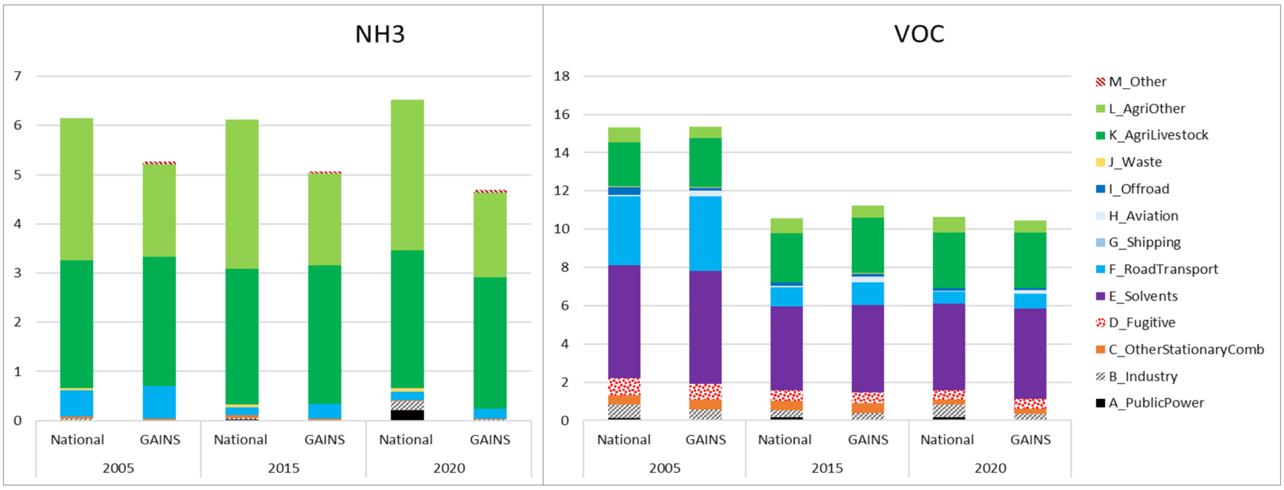
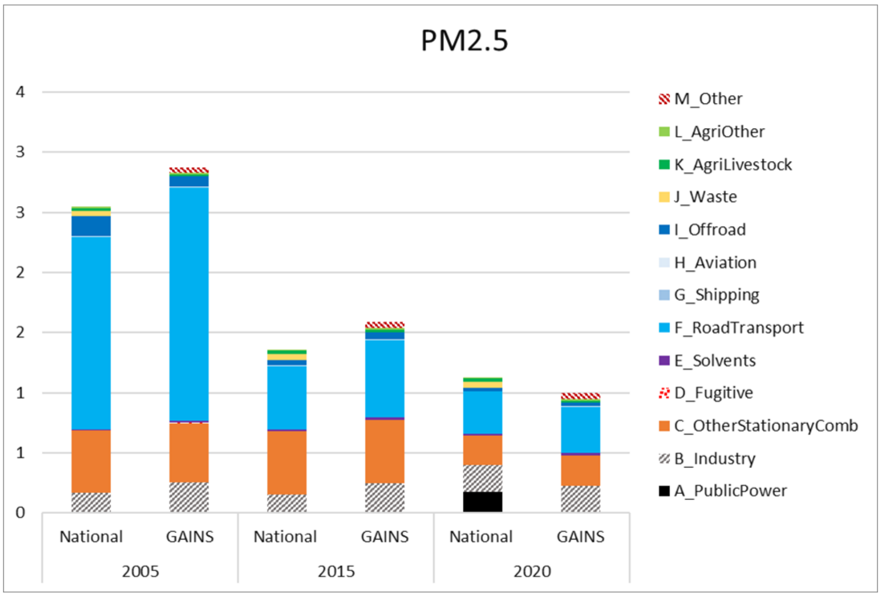


Figure 8-64: Comparison of the 2023 MS inventory submission for PM$_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



MALTA

Table 8-19: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	12	12	1.7%	2	2	0.8%	0	0	5.7%
NOx	10	9	-0.6%	6	5	-8.5%	4	3	-17.0%
PM2.5	1	1	13.2%	0	0	11.1%	0	0	12.5%
NH3	2	2	3.2%	1	1	1.5%	1	1	-4.4%
VOC	4	3	-2.8%	3	3	2.9%	2	2	-9.8%

Acceptable match for **SO$_2$** and **NH$_3$**. For **NOx**, large differences in emissions from non-road, including shipping and aviation although the latter two in absolute terms are smaller. Uncertainties in fuel amounts and type for different engines in industry and agriculture; there seem to be differences in balances in PRIMES/GAINS vs national dataset. Harmonization efforts was undertaken during consultations and the national team followed also the PRIMES modelling team - unfortunately, differences remain. Overall emissions of **PM$_{2.5}$** are rather small with remaining discrepancies for offroad sector (as for NOx) and to some extent the road transport sector which is slightly larger in GAINS relaying on PRIMES data on vehicle km driven and fuel use for which some differences were identified with national data and not all discrepancies were resolved.

Figure 8-65: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

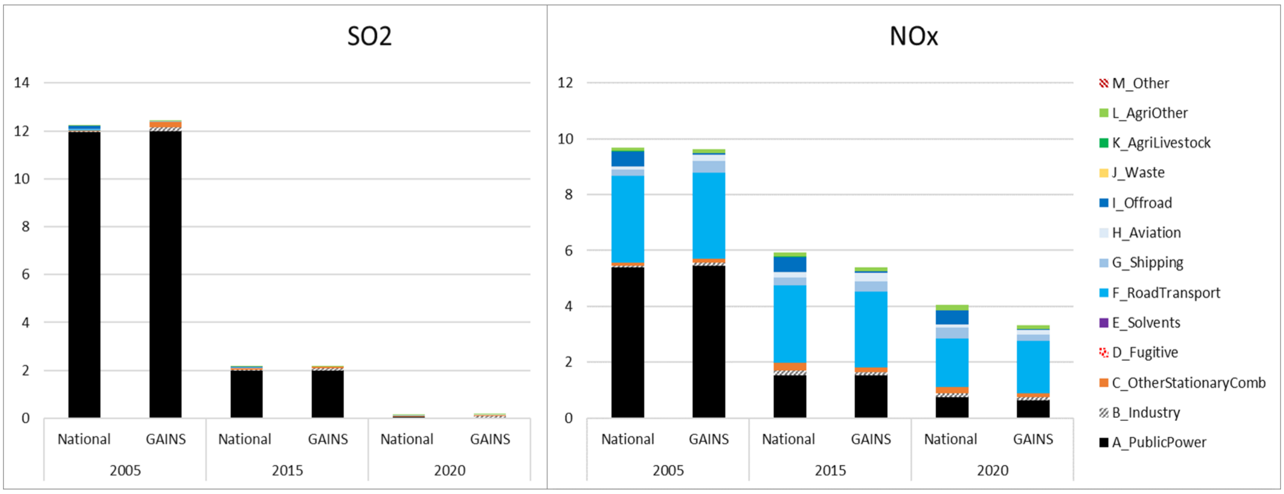


Figure 8-66: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

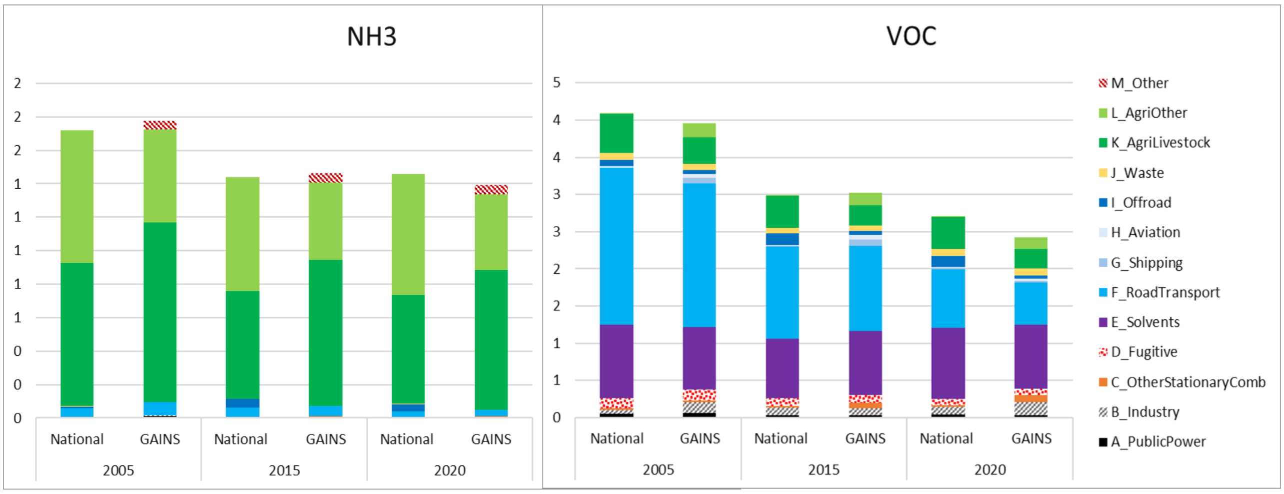
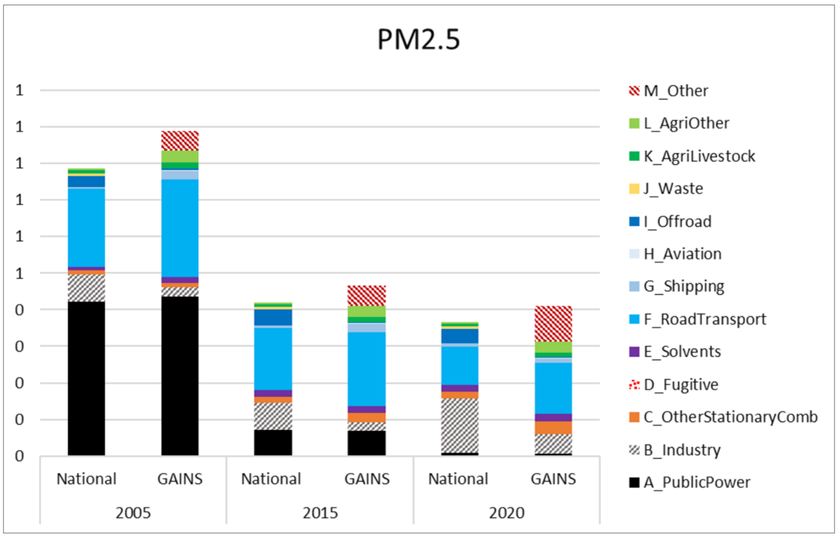


Figure 8-67: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



NETHERLANDS

Table 8-20: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**
	[kt]	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**
SO2	68	67	-2.2%	31	31	1.4%	20	19	-3.6%
NOx	405	383	-5.5%	248	224	-9.6%	182	162	-11.1%
PM2.5	29	30	2.6%	18	19	5.4%	15	16	10.2%
NH3	154	147	-4.9%	129	135	4.7%	123	123	-0.2%
VOC	208	198	-4.7%	163	153	-5.9%	183	175	-3.9%

Overall, acceptable match for **SO_2, NH_3,** and **NMVOC**. For **NOx**, GAINS is lower throughout due to remaining uncertainties for offroad sector, which include fuel allocation and actual emission factors. Most of the remaining differences for **$PM_{2.5}$** are also linked to the offroad sector uncertainties.

Figure 8-68: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

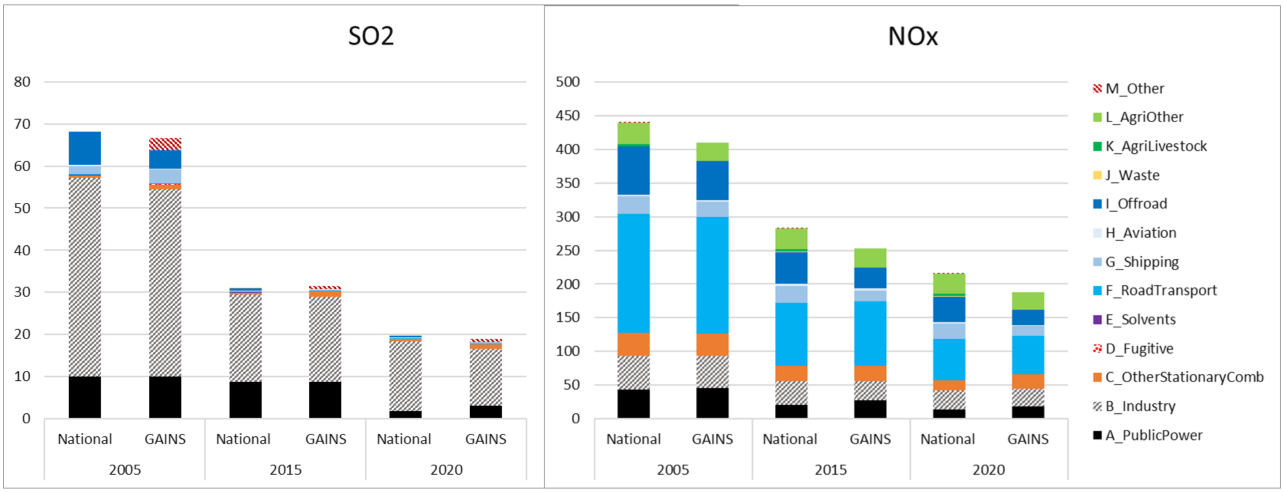


Figure 8-69: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

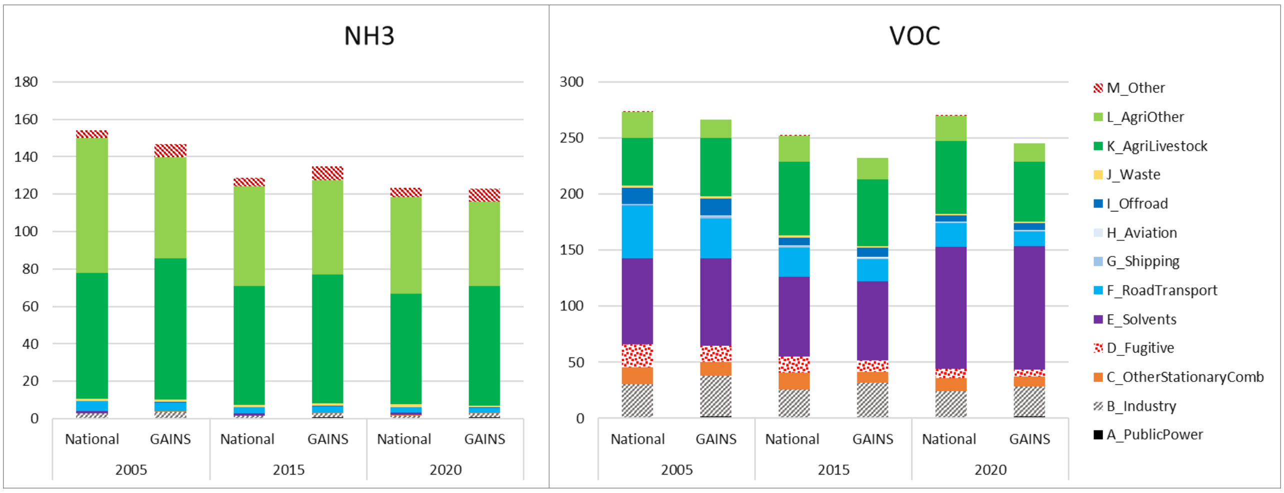
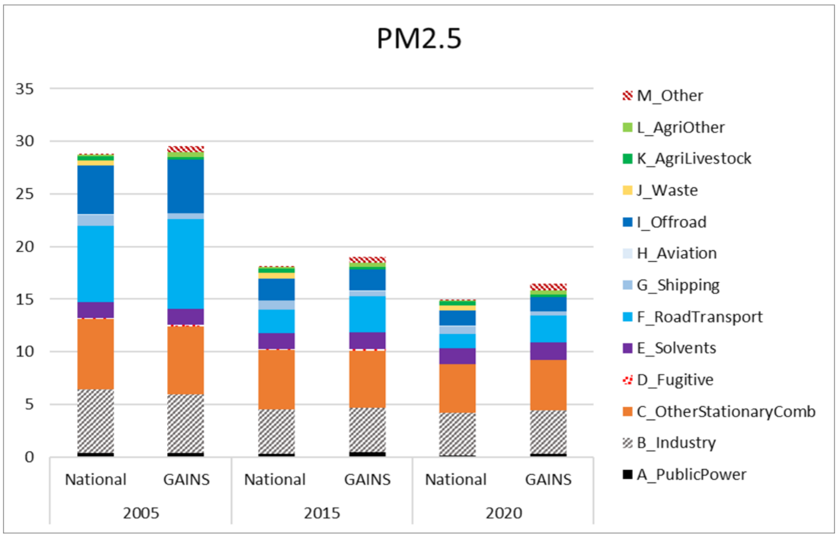


Figure 8-70: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



POLAND

Table 8-21: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	1129	1121	-0.7%	639	593	-7.1%	385	377	-2.1%
NOx	793	793	0.0%	653	656	0.5%	533	524	-1.8%
PM2.5	322	337	4.7%	297	317	6.5%	307	299	-2.3%
NH3	323	315	-2.4%	289	285	-1.4%	310	296	-4.5%
VOC	686	748	9.0%	630	652	3.5%	629	652	3.6%

Overall, good agreement at national and also sectoral level. Small differences are remaining mostly for **$PM_{2.5}$** and **NMVOC** and are for off-road transport sources. Poland has revised $PM_{2.5}$ from residential sector based on the new emission factor measurements and data about structure of installations. These apply both for fuelwood and coal. After discussion with the national team, GAINS and the national inventory compare well.

Figure 8-71: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

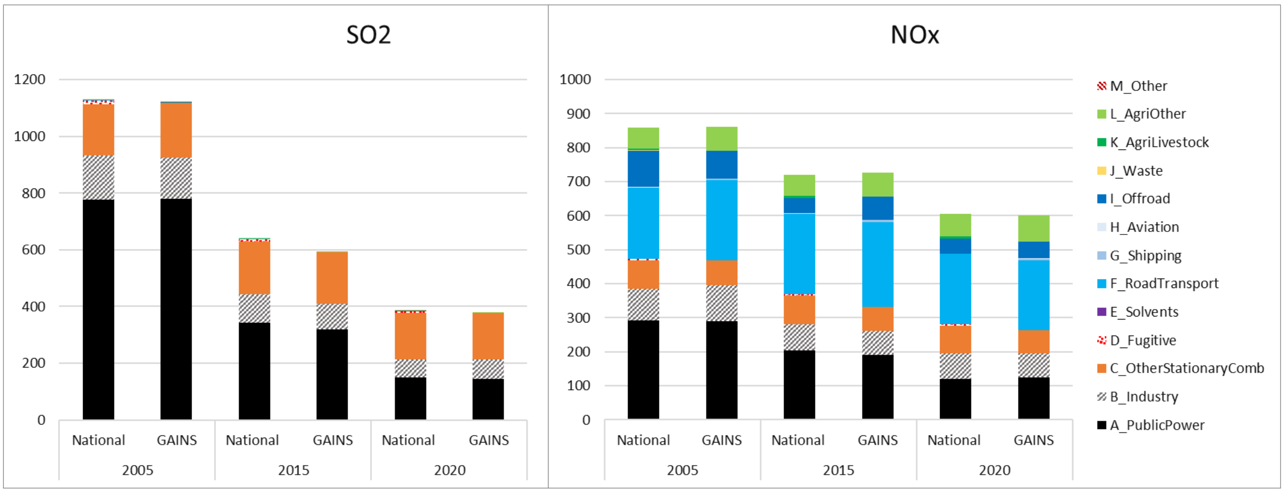


Figure 8-72: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

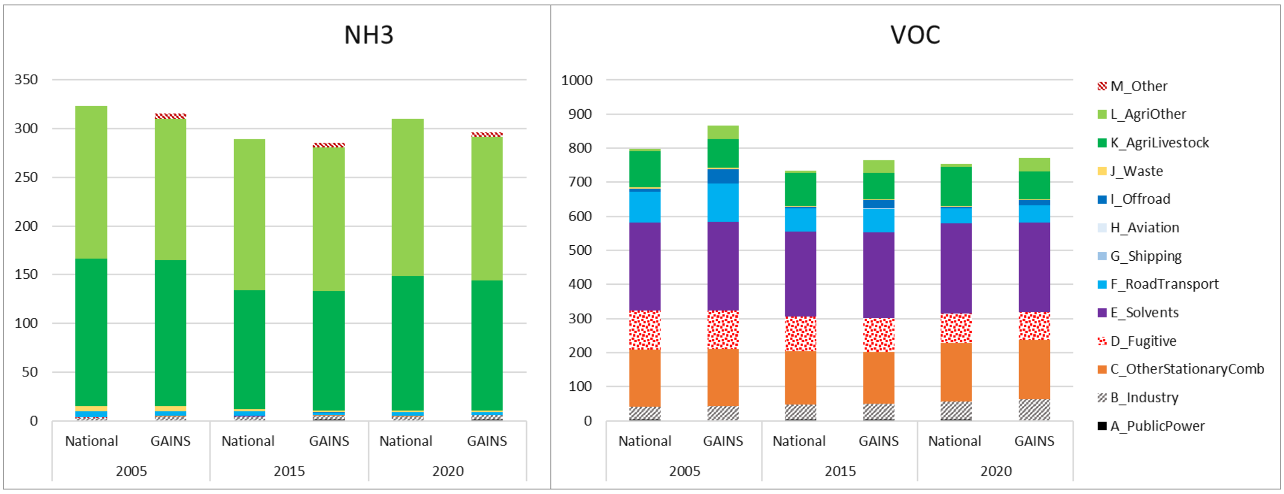
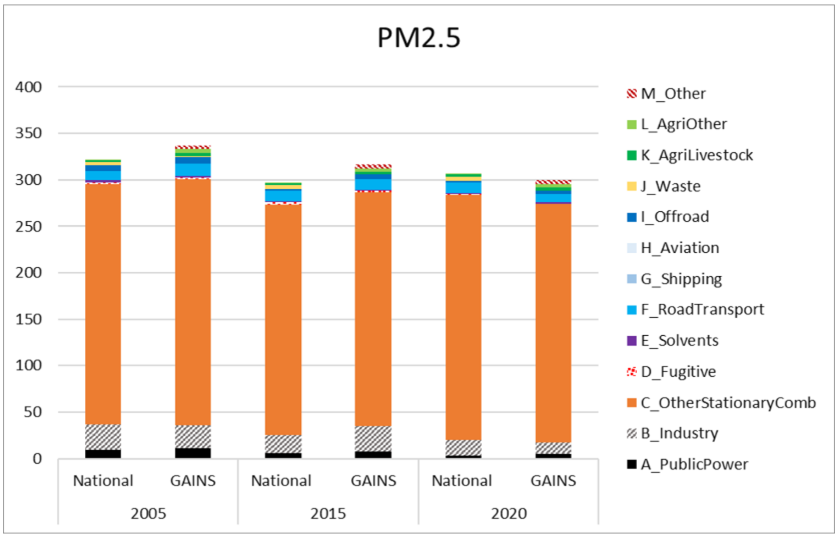


Figure 8-73: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



PORTUGAL

Table 8-22: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	189	191	0.8%	45	48	6.3%	38	31	-18.2%
NOx	274	288	5.4%	160	177	10.9%	125	120	-4.3%
PM2.5	58	58	-0.4%	47	47	-0.9%	44	44	-0.9%
NH3	62	58	-6.4%	58	55	-4.5%	61	57	-7.7%
VOC	170	172	1.4%	128	130	1.8%	134	136	2.0%

Overall, very good match for **$PM_{2.5}$** and **NMVOC**. For **SO_2** the key difference are due to the Power sector where we assume the level control remains as in 2015; it seems that implied emission factor actually worsens in the national estimates, i.e., older plans have larger fuel use but such detailed information was not directly available to validate such possibility (importance will be declining due to decarbonization in the Baseline scenario). For **NOx**, larger differences for 2005 and 2015 are driven by higher estimation in the road transport sector, i.e., the share and emission factors for older vehicles and the split between light and heavy duty; the assumptions in GAINS were updated with information from IIR and consultations but remain slightly different, however the differences decline by 2020. GAINS estimates slightly lower **NH_3** but there was not enough information about penetration of mitigation measures to justify further revisions.

Figure 8-74: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

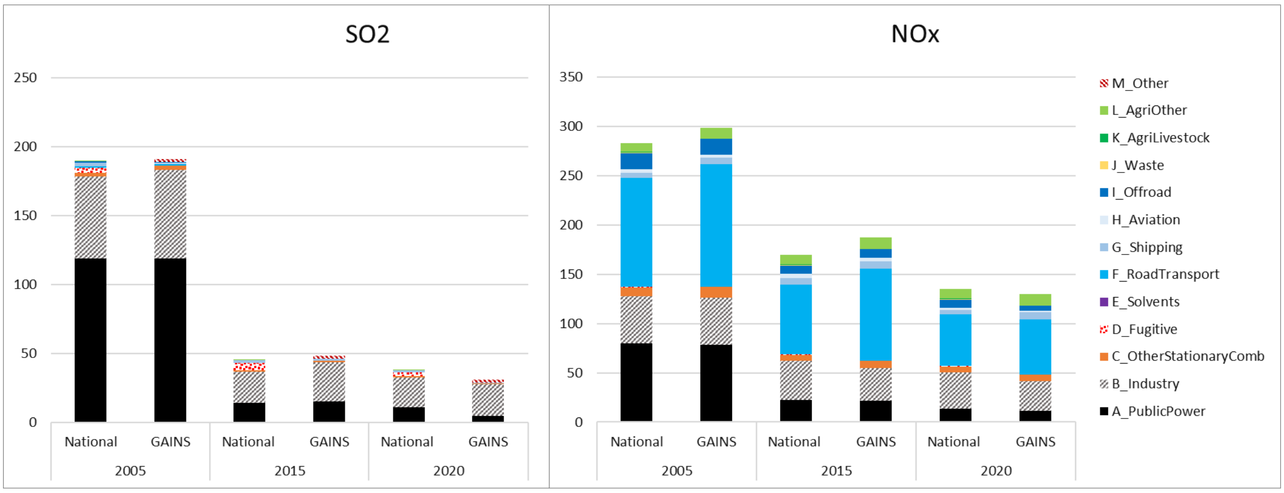


Figure 8-75: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

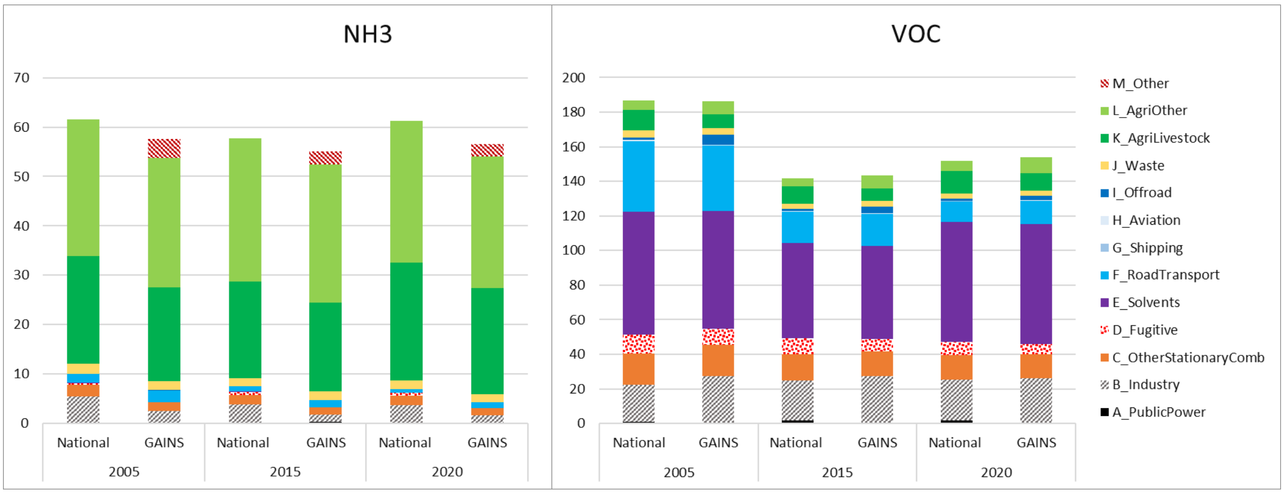
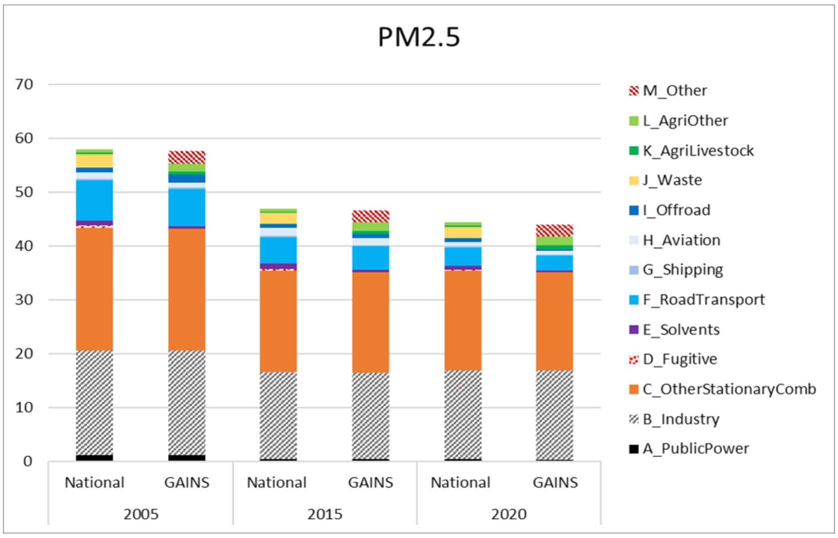


Figure 8-76: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



ROMANIA

Table 8-23: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	603	599	-0.8%	149	146	-1.6%	61	59	-2.5%
NOx	306	300	-1.8%	194	218	11.9%	175	173	-1.0%
PM2.5	120	144	19.9%	109	126	16.5%	110	126	14.7%
NH3	194	188	-3.1%	170	163	-3.7%	156	152	-2.4%
VOC	250	288	15.4%	181	213	17.9%	175	206	18.1%

Overall, good match for **SO_2** and **NH_3**. For **NOx**, still differences are remaining in the offroad sector. The key difference for **$PM_{2.5}$** and **NMVOC** are due to the agricultural burning. As highlighted earlier for some other countries, GAINS relies on estimates and trends from the remote sensing product (FINN), unless there is well documented bottom-up data available. National inventory has much lower estimates of open agricultural burning.

Figure 8-77: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

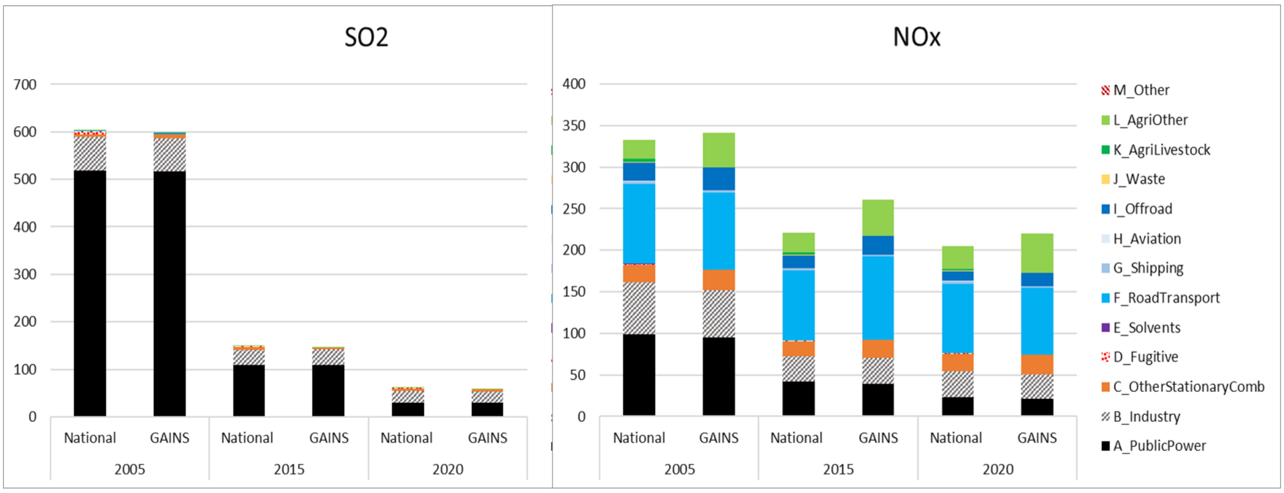


Figure 8-78: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

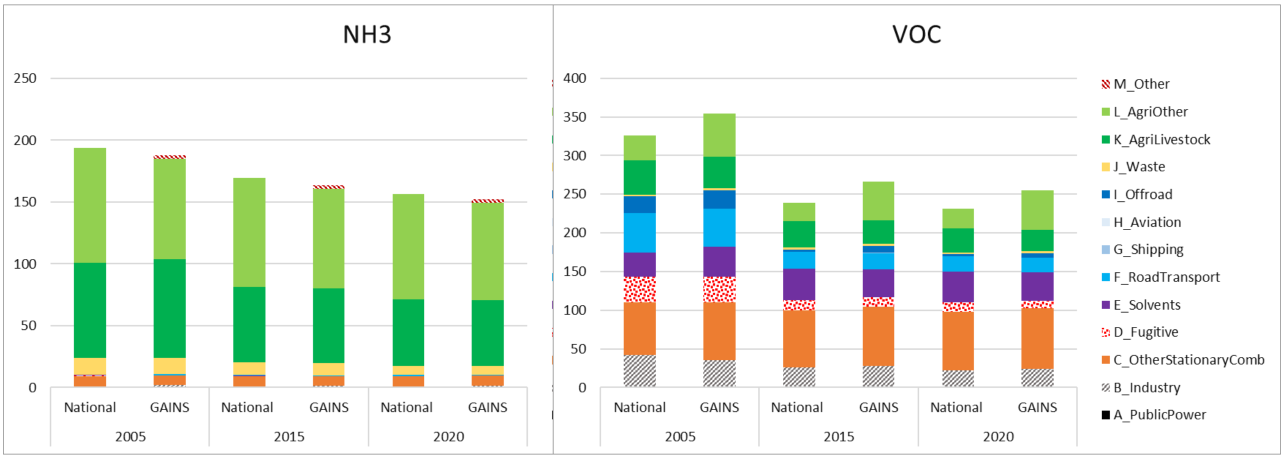
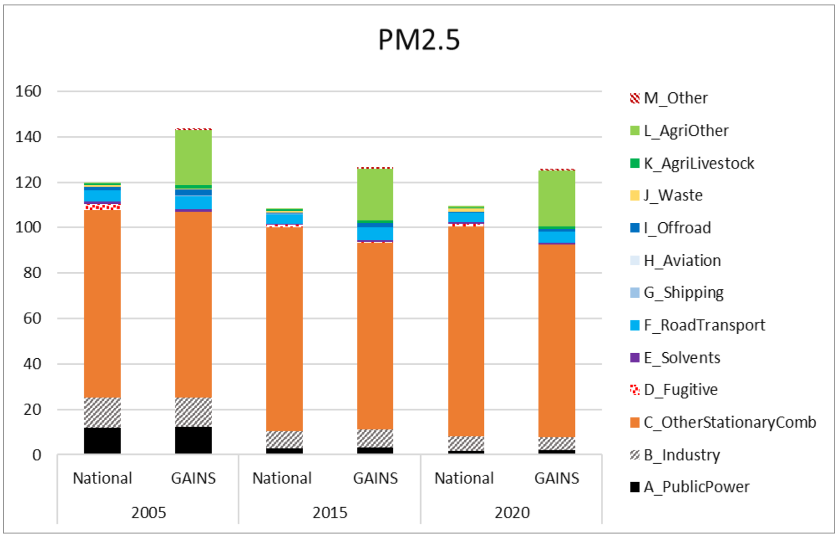


Figure 8-79: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



SLOVAKIA

Table 8-24: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**
	[kt]	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**
SO2	86	85	-1.2%	67	65	-2.8%	13	14	1.9%
NOx	100	95	-4.6%	61	63	4.4%	49	46	-6.5%
PM2.5	36	36	2.0%	21	22	4.7%	17	17	-2.1%
NH3	32	30	-6.6%	28	27	-4.2%	27	27	-0.6%
VOC	131	128	-2.2%	96	95	-1.6%	81	81	-0.4%

Overall, acceptable match for all pollutants. Small differences for **NOx** are from lower estimation in the off-road sector.

Figure 8-80: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

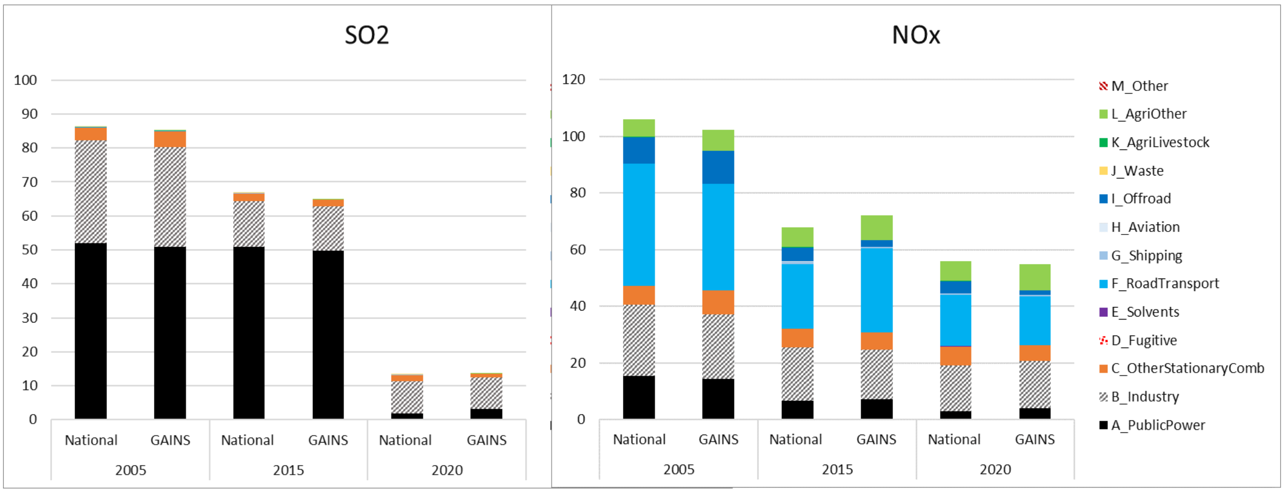


Figure 8-81: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

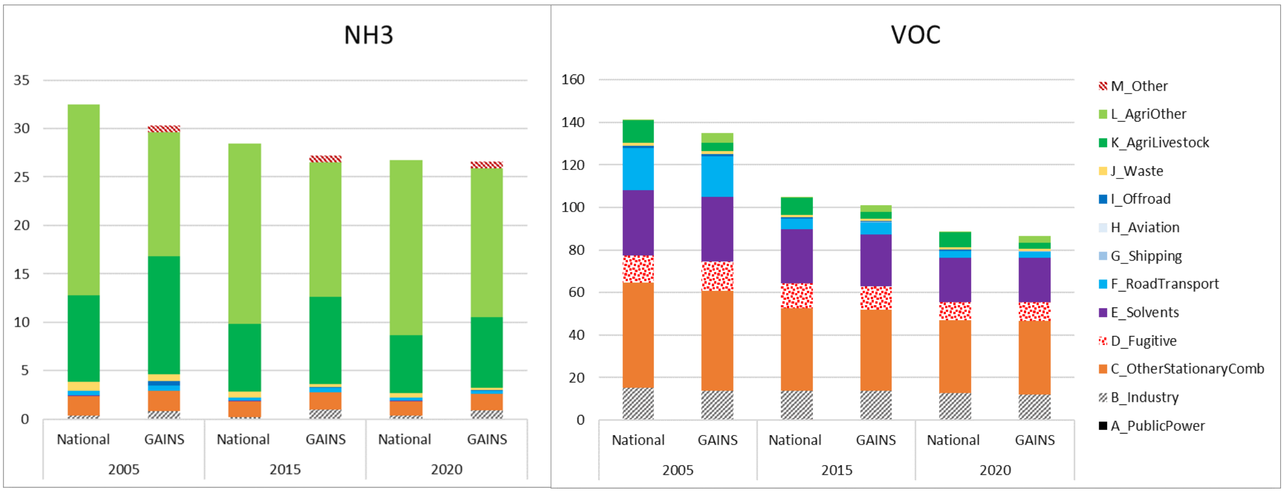
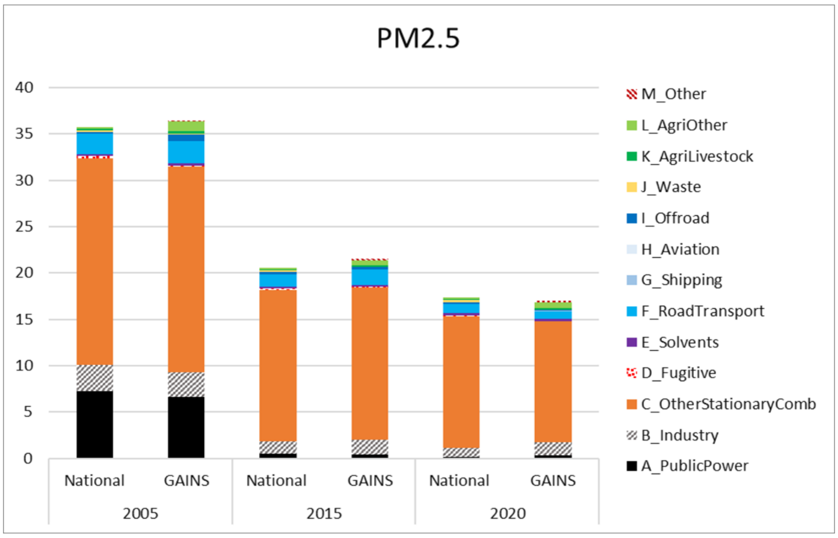


Figure 8-82: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the preliminary GAINS estimates for 2005, 2015, and 2020.



SLOVENIA

Table 8-25: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	40	40	1.2%	6	6	1.1%	4	4	11.5%
NOx	53	49	-7.1%	33	34	4.2%	23	23	1.0%
PM2.5	16	16	-1.3%	13	13	0.6%	10	10	-3.8%
NH3	21	21	0.0%	19	19	0.6%	18	19	2.2%
VOC	42	44	3.1%	27	27	1.4%	25	24	-3.6%

Overall, acceptable match for all pollutants with few exceptions. Small remaining differences for **NOx** for 2005 are due to uncertainties in data for off-road sector and residential combustion. For **SO_2** in 2020, differences are possibly due to different emission factor for coal power with FGD; the numbers are small and the national emission factor seem to be even beyond the BAT technology in GAINS .

Figure 8-83: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

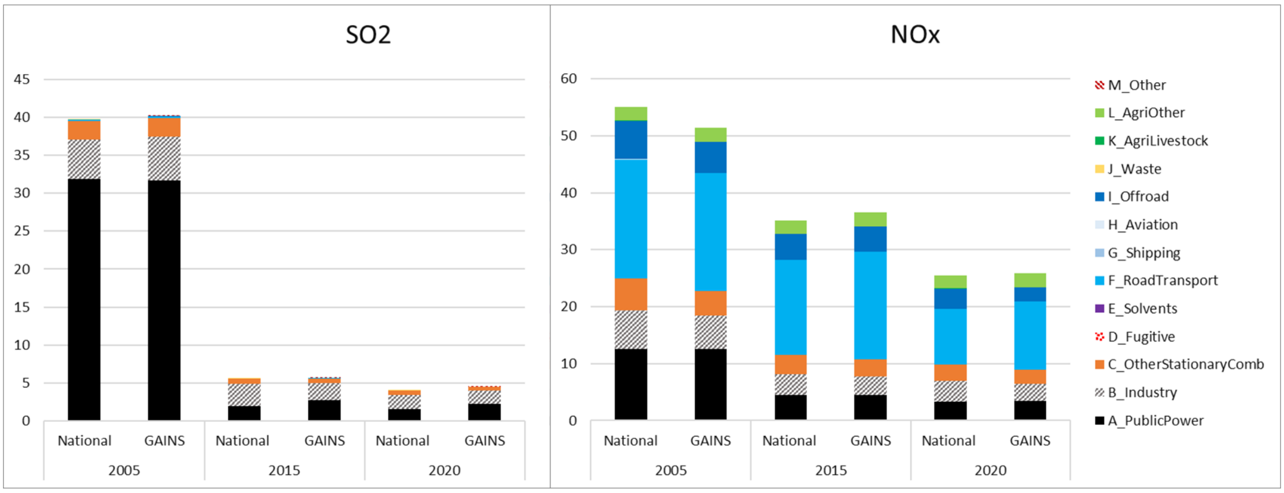


Figure 8-84: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

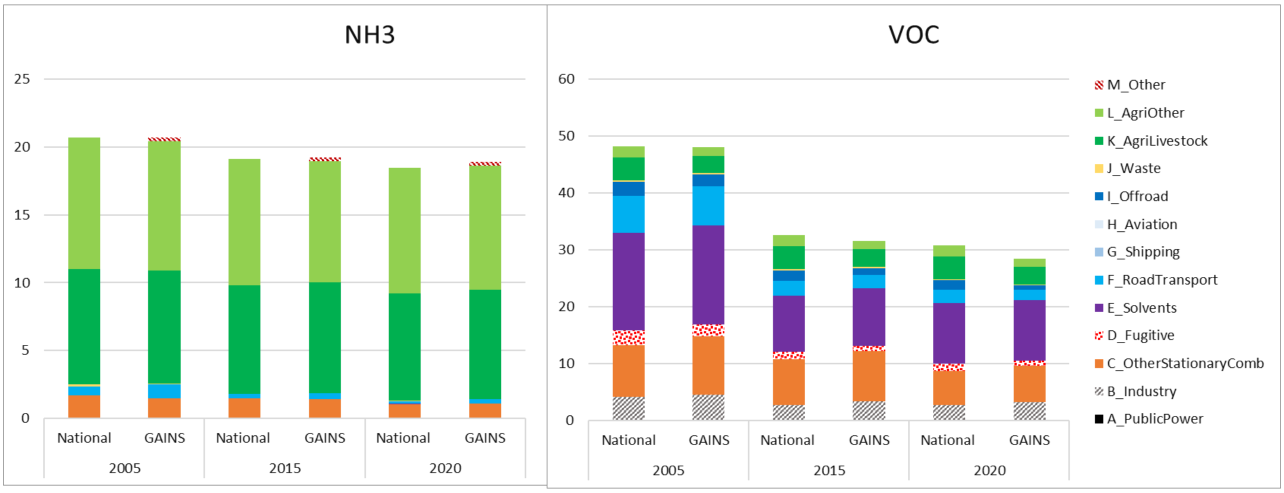
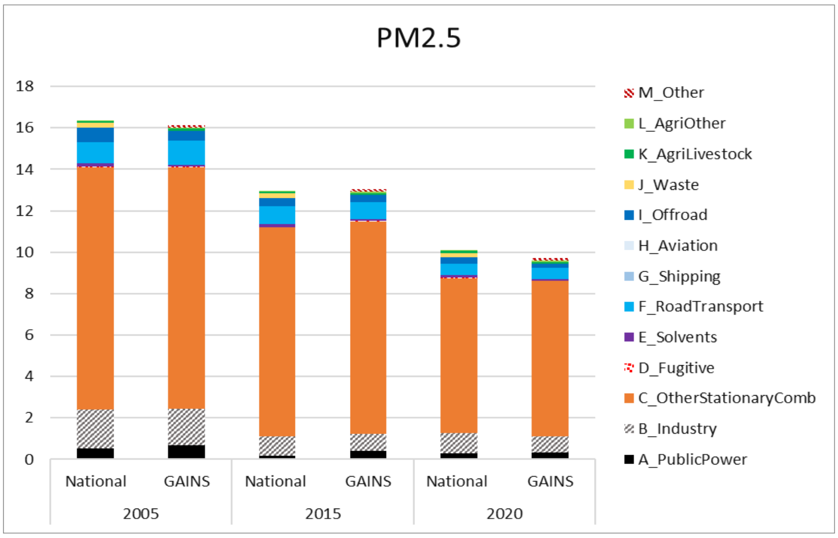


Figure 8-85: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



SPAIN

Table 8-26: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference	National inventory 2023	GAINS estimate	Difference
	[kt]	[kt]	[%]	[kt]	[kt]	[%]	[kt]	[kt]	[%]
SO2	1207	1205	-0.2%	260	247	-5.2%	128	104	-18.5%
NOx	1244	1323	6.4%	731	802	9.7%	516	494	-4.3%
PM2.5	167	164	-1.9%	153	137	-10.4%	133	126	-5.5%
NH3	509	508	-0.2%	471	494	4.9%	491	515	4.9%
VOC	621	635	2.3%	442	451	2.0%	465	467	0.5%

NH_3 and **NMVOC** align well with nation estimation. For **NOx** and **$PM_{2.5}$**, overall, emissions very comparable for 2005 with somewhat increasing discrepancy towards 2015 and decreased differences in 2020. Main causes are uncertainties in estimating emissions from non-road sector and residential combustion sector structure. The chart showing comparison for **$PM_{2.5}$** indicates also a large difference between waste and agricultural burning, but this is the same thing, just allocated in the inventory and GAINS to different categories, i.e., the emissions from orchard trimming (burning of residues) are classified in the national inventory as waste while in GAINS are included in the open agricultural burning.

Figure 8-86: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

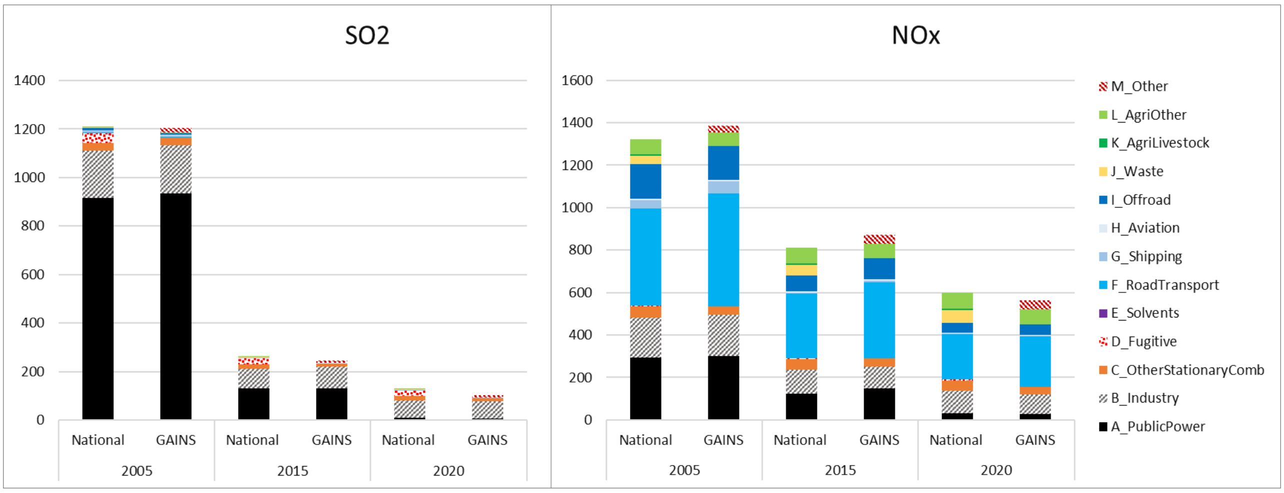


Figure 8-87: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

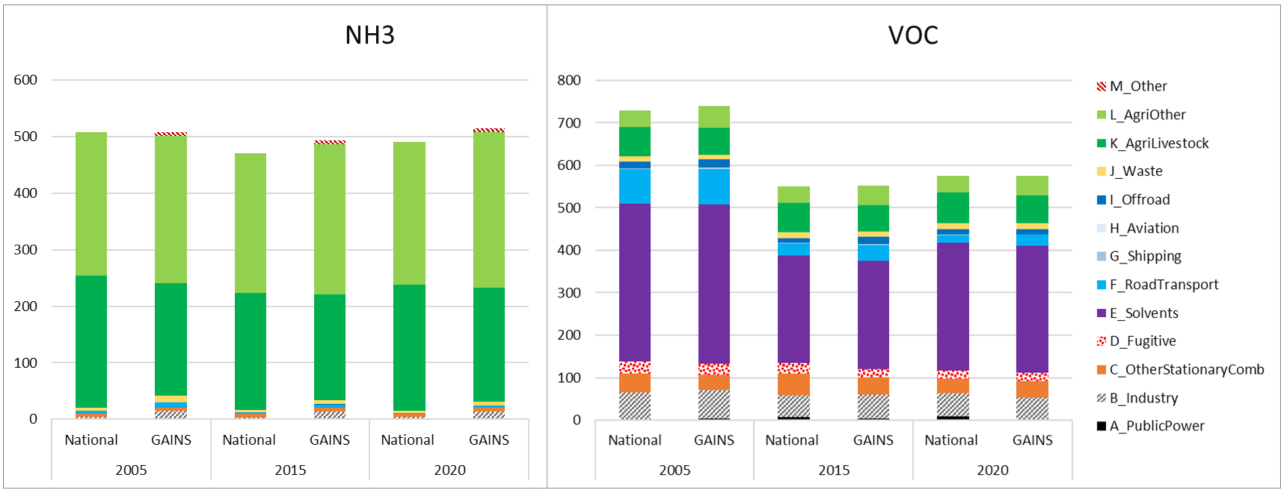
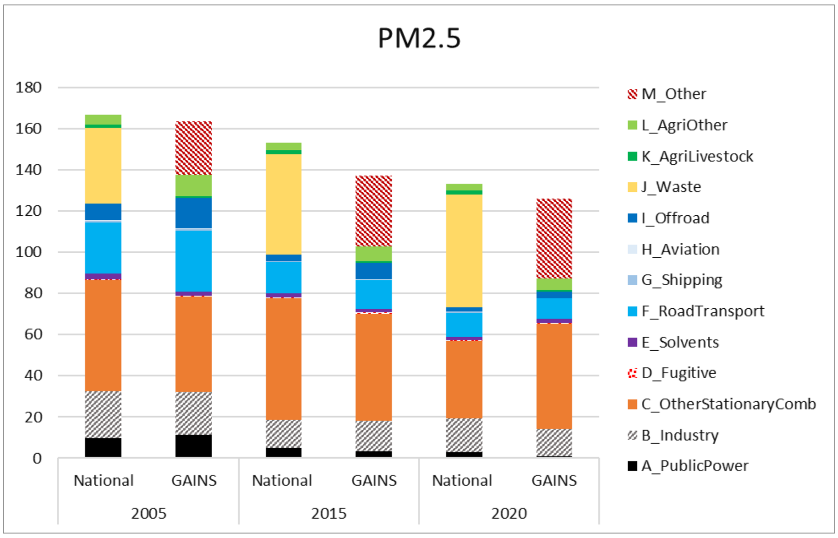


Figure 8-88: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



SWEDEN

Table 8-27: Comparison of the 2023 MS inventory submission (NEC relevant emission sources only) with the GAINS estimates for 2005, 2015, and 2020.

	2005			2015			2020		
	National inventory 2023	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**	**National inventory 2023**	**GAINS estimate**	**Difference**
	[kt]	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**	**[kt]**	**[kt]**	**[%]**
SO2	34	36	4.1%	17	18	7.5%	15	15	3.3%
NOx	181	189	4.3%	134	136	1.4%	103	102	-0.8%
PM2.5	31	34	7.9%	19	21	10.9%	17	18	5.5%
NH3	57	57	-0.2%	54	52	-3.0%	52	51	-1.8%
VOC	172	169	-2.1%	127	125	-1.4%	109	104	-4.4%

Overall, acceptable match for all pollutants. Remaining differences for **$PM_{2.5}$** are due to the offroad sector for which data are scarce.

Figure 8-89: Comparison of the 2023 MS inventory submission for SO_2 and NOx (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.

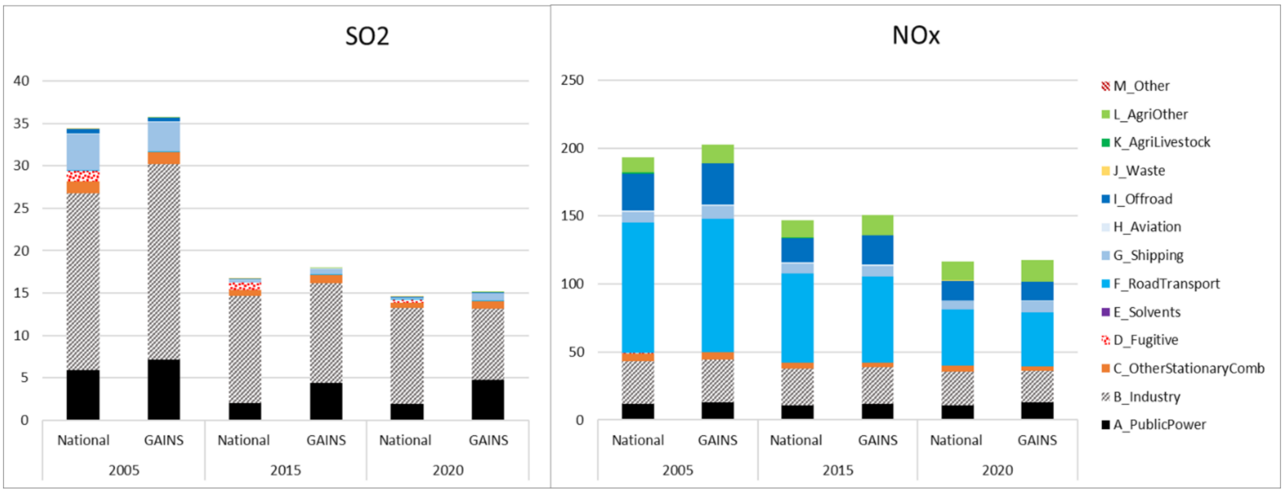


Figure 8-90: Comparison of the 2023 MS inventory submission for NH_3 and NMVOC (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020

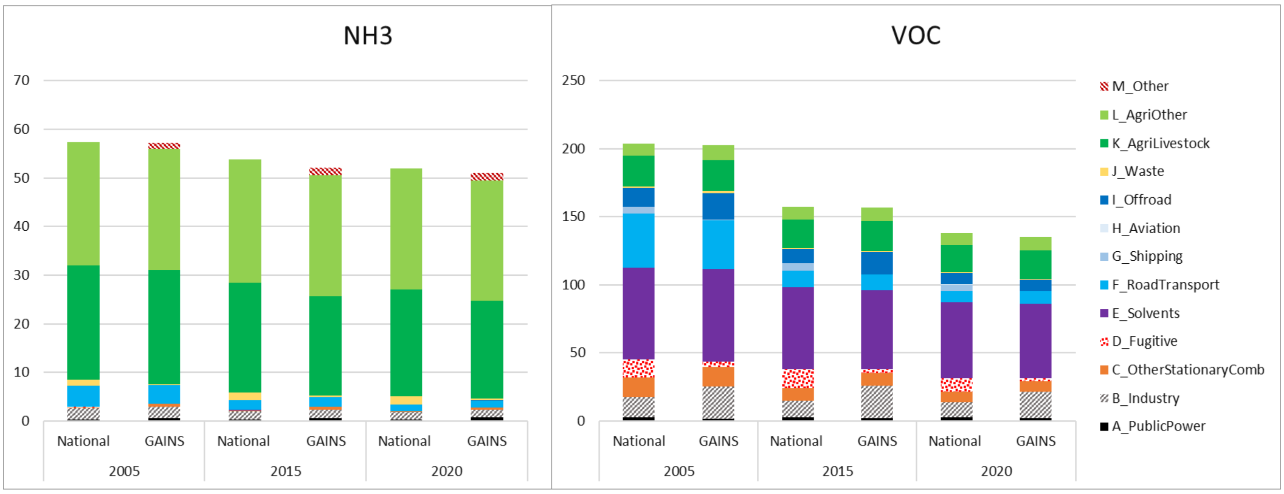
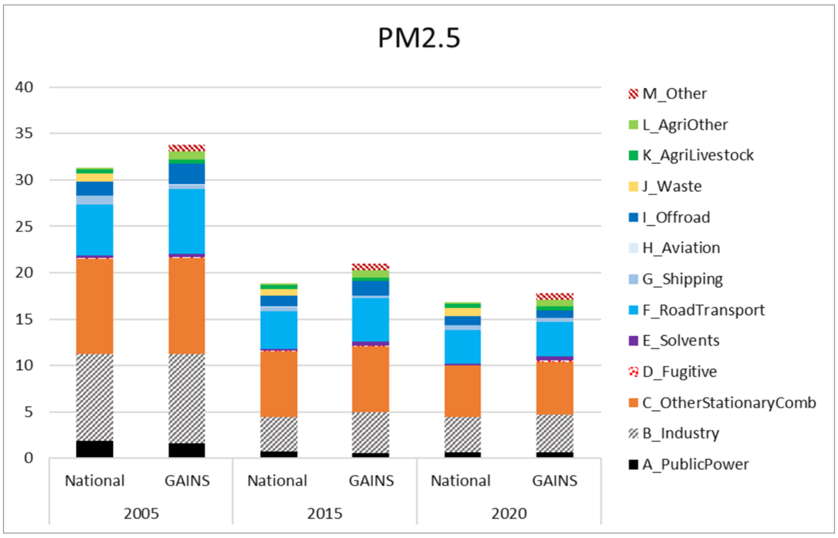


Figure 8-91: Comparison of the 2023 MS inventory submission for $PM_{2.5}$ (includes all anthropogenic emission sources) with the GAINS estimates for 2005, 2015, and 2020.



A3.4.2 Comparison of GAINS Baseline with WM and WaM projections

A comparison between the GAINS CAO4 baseline and the WM and WaM projections as submitted in 2023 by Member States is provided below. Based on the analysis of those, it appears that GAINS Baseline is often more ambitious in that emissions continue past reduction trends or even decline faster. National baselines, especially WM, is often more conservative slowing down the rate of change after 2020 or even showing increasing emissions. WaM, whenever provided, is more ambitious and clearly targets attainment of ERCs. During consultations IIASA has discussed what policies and measures are actually planned to attain projected reductions; such information has been considered useful to validate some of the GAINS assumptions about the remaining mitigation potential.

Among reasons causing GAINS baseline emissions declining faster is faster decarbonization of the economy, consistent with the objectives of the European Green Deal, and often much quicker reduction of fuelwood use in residential sector – many countries have similar, albeit less optimistic, assumptions about future development of biomass for residential uses. However, others have been pointing out that the actual change in fuelwood use is very slow and most of the rural users will likely remain using solid fuel stoves and boilers for quite some time. Whenever discussing assumptions about projections of installation stock exchange, the MS data shows that lifetimes for stoves and boilers are in order of 20-25 years and about 30-40 years for fireplaces; this is consistent with GAINS model assumptions.

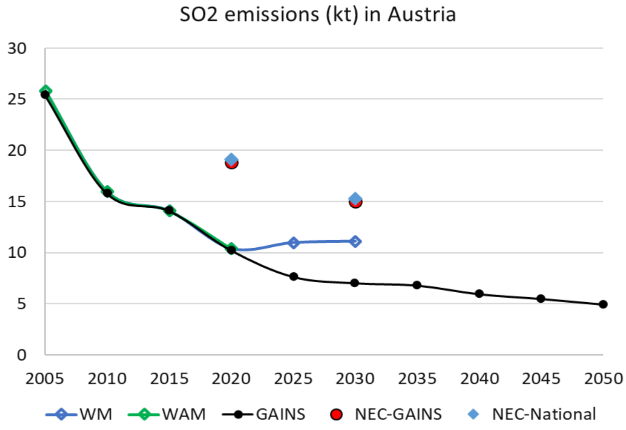
ERCs are not achieved in most cases for ammonia, and for some MS also for NOx and $PM_{2.5}$, while there were hardly projections of any violation of ERCs for SO_2.

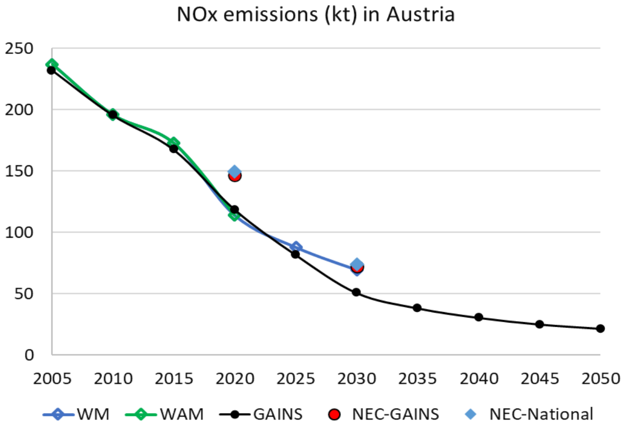
For some countries one can see an ‘offset’ (between GAINS and the Member States reporting) that is especially large for initial years (2005-2015) and is less visible in the projections. This is typically due to condensable particulate matter that are not always included and matter most when there is a lot of fuelwood used and especially in poor efficiency installations; consequently, becomes less pronounced in the future.

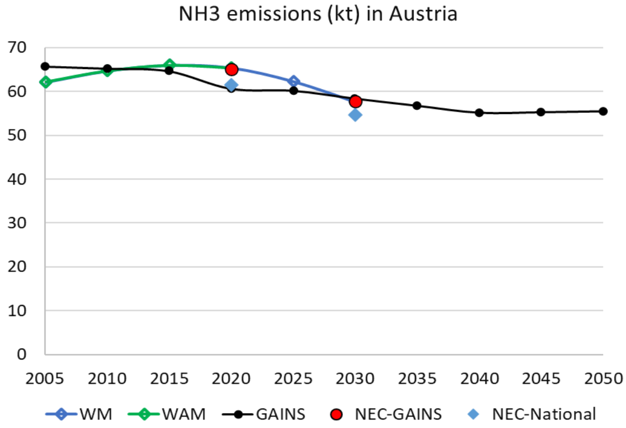
Discussion of reasons for remaining differences between GAINS and Member States estimates presented in the previous section highlights some of the reasons, which also propagate in the future and are visible in the overview presented below for each Member State. Additionally, the presentations prepared for the Member States consultations include some comments about reasons for potential or expected non-compliance.

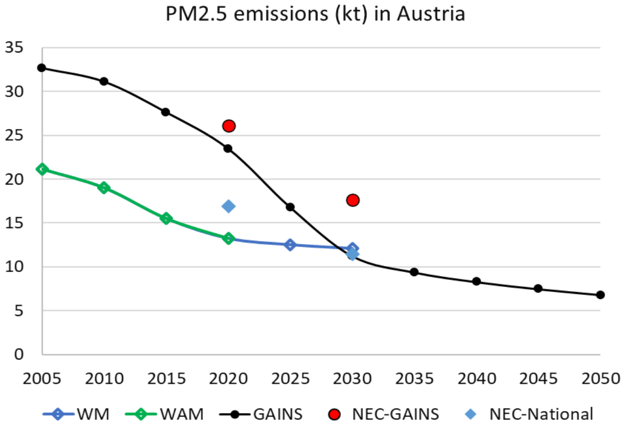
The following figures compare for each country the GAINS Baseline with the WM and WaM projections as well as illustration of compliance with the ERCs calculated against the GAINS [NEC-GAINS – shown as a red dot] and the national estimate [NEC-National – shown as the blue diamond] of 2005 emissions, respectively.

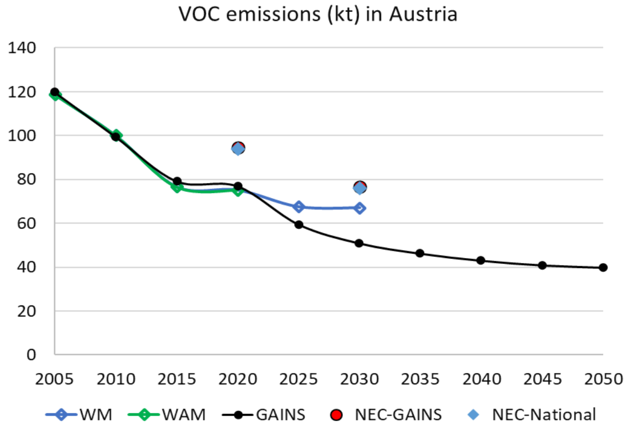
AUSTRIA


SO2 emissions (kt) in Austria

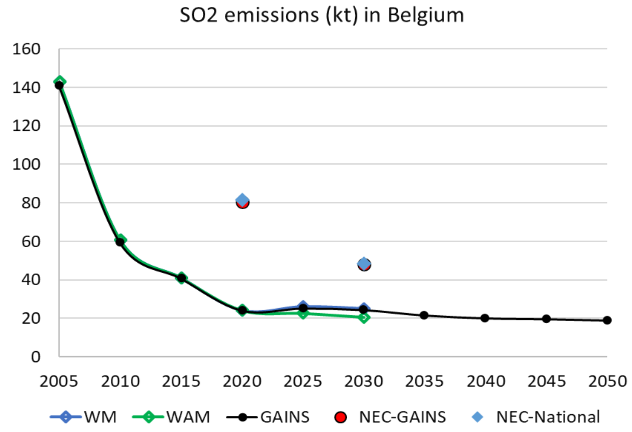

NOx emissions (kt) in Austria

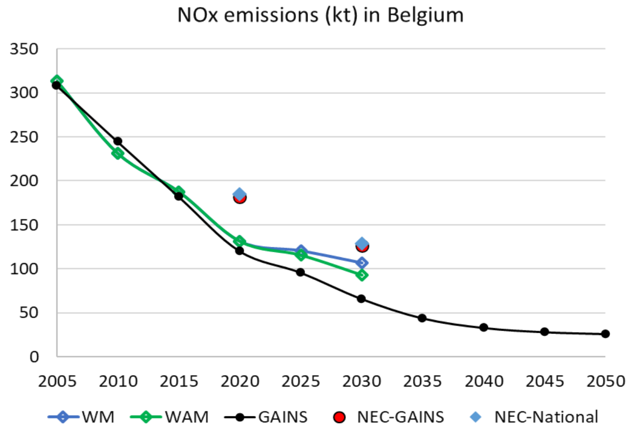

NH3 emissions (kt) in Austria

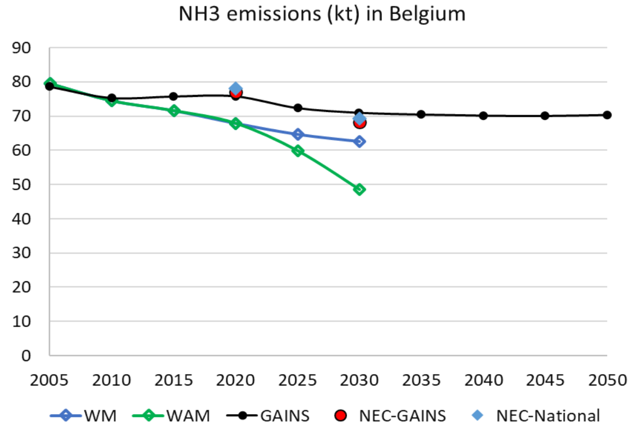

PM2.5 emissions (kt) in Austria

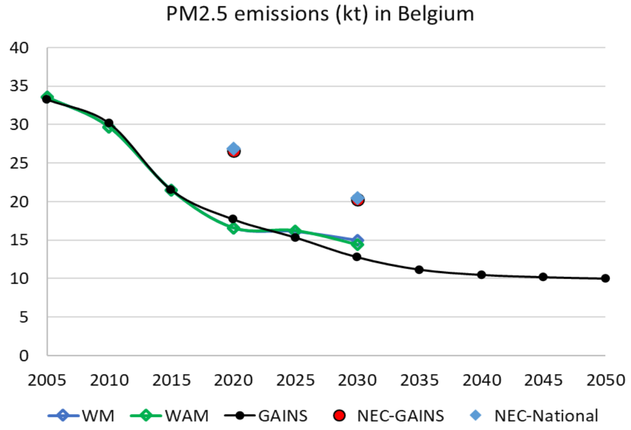

VOC emissions (kt) in Austria

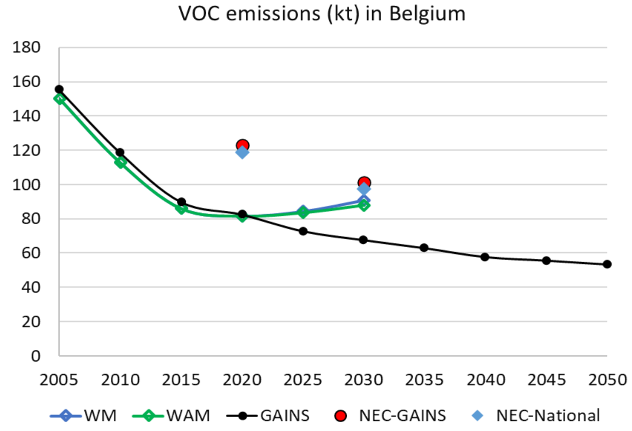
BELGIUM


SO2 emissions (kt) in Belgium

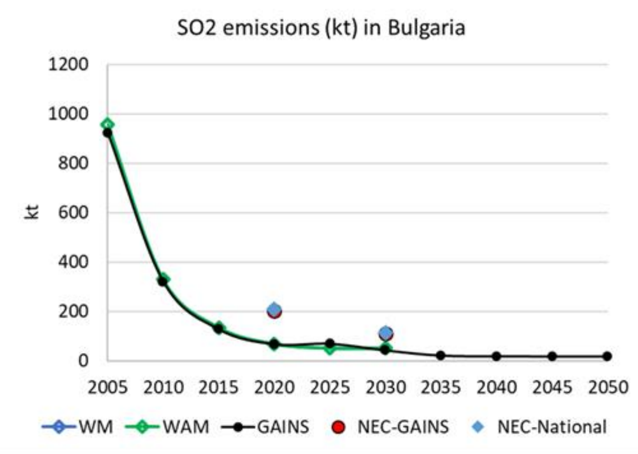

NOx emissions (kt) in Belgium

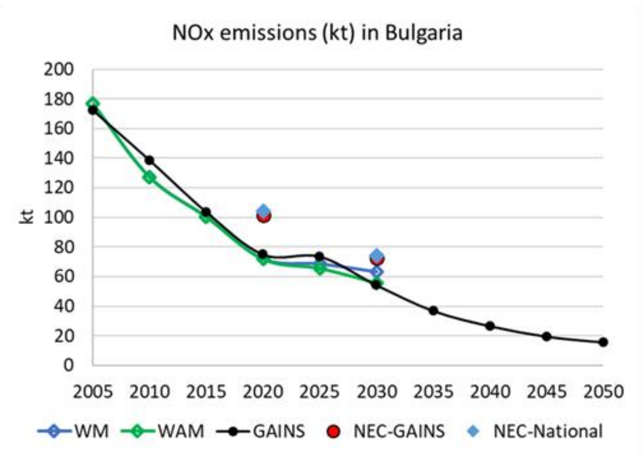

NH3 emissions (kt) in Belgium

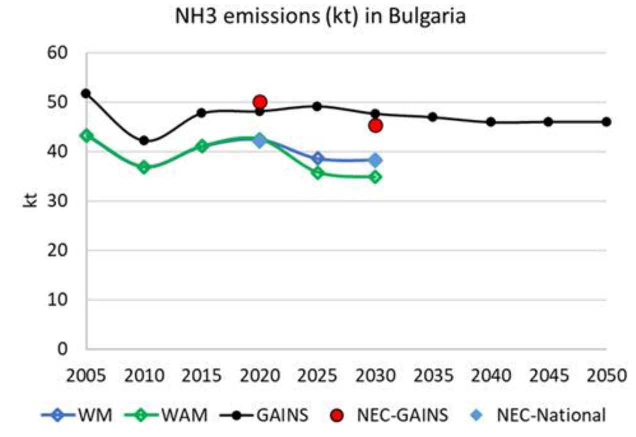

PM2.5 emissions (kt) in Belgium

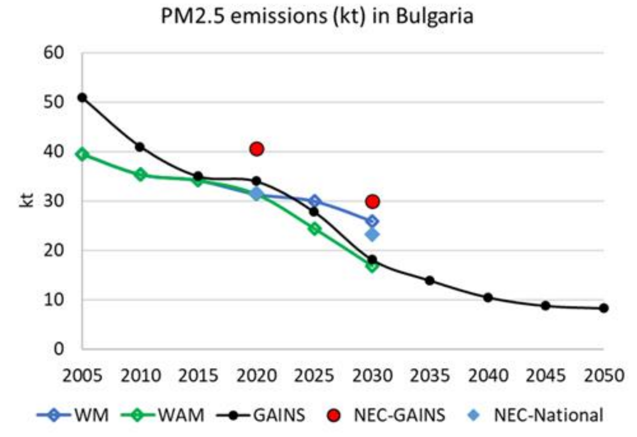

VOC emissions (kt) in Belgium

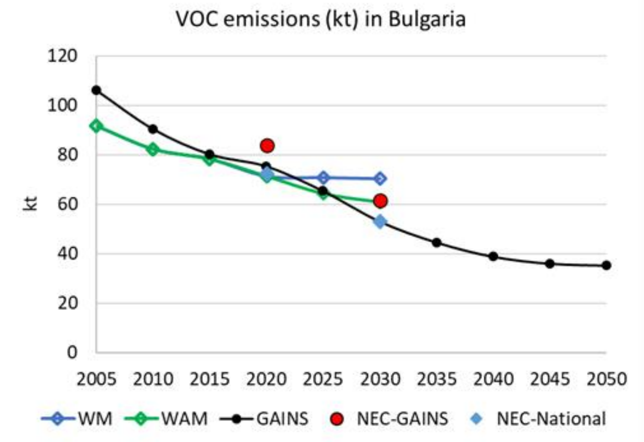
BULGARIA


SO2 emissions (kt) in Bulgaria
1200
1000
800
600
400
200
0
kt
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

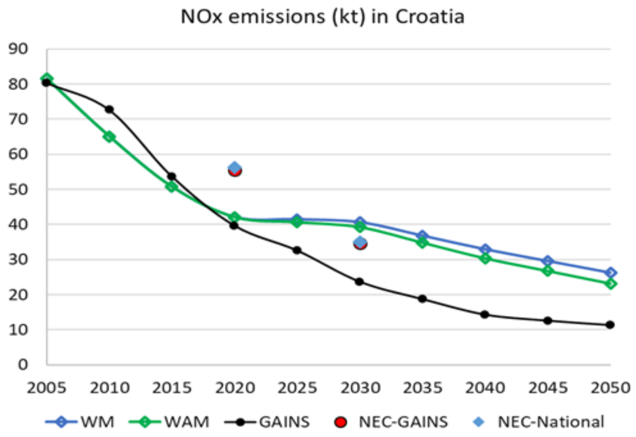

NOx emissions (kt) in Bulgaria
200
180
160
140
120
100
80
60
40
20
0
kt
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

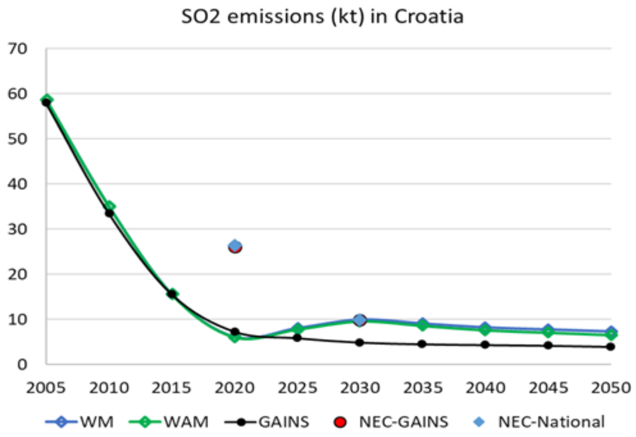

NH3 emissions (kt) in Bulgaria
60
50
40
30
20
10
0
kt
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

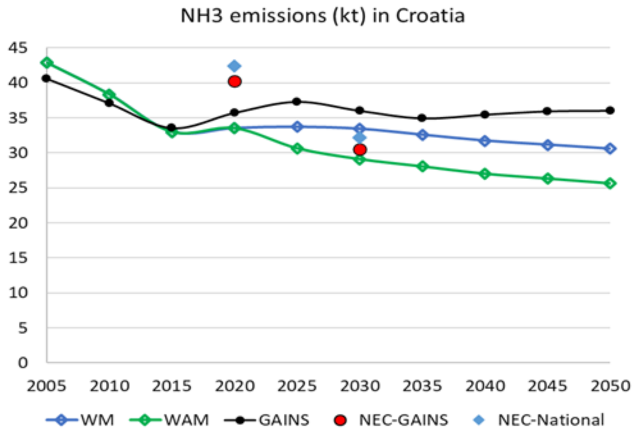

PM2.5 emissions (kt) in Bulgaria
60
50
40
30
20
10
0
kt
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

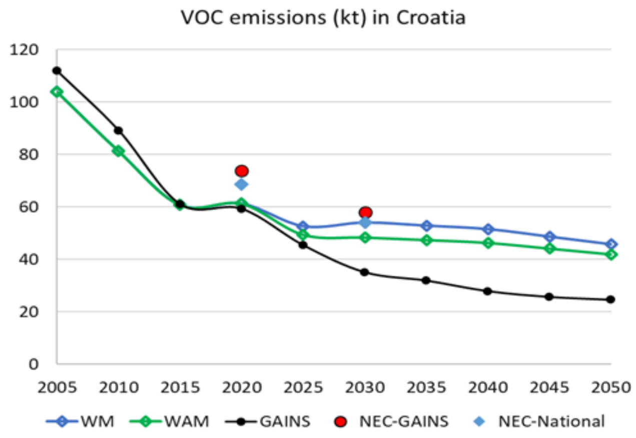

VOC emissions (kt) in Bulgaria
120
100
80
60
40
20
0
kt
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

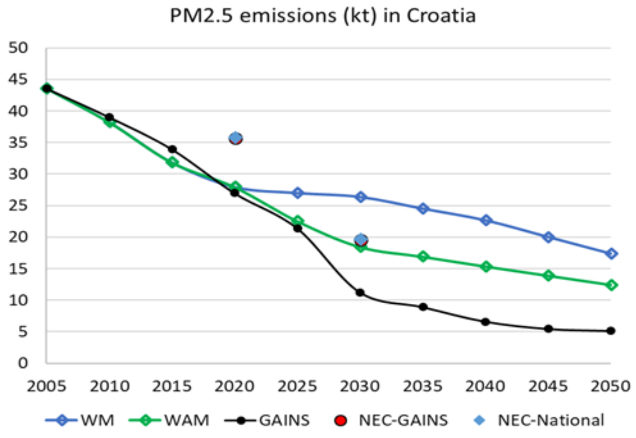
CROATIA


NOx emissions (kt) in Croatia
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

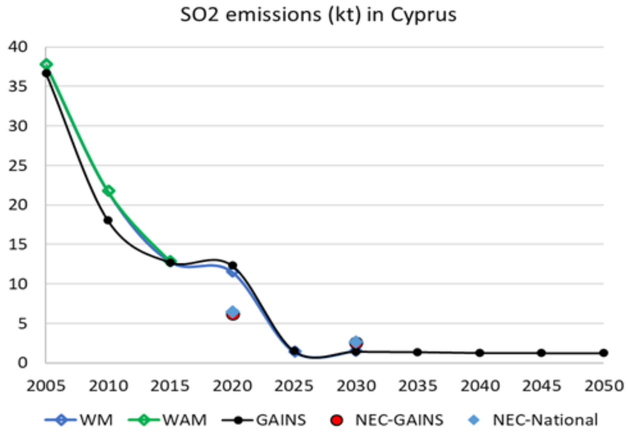

SO2 emissions (kt) in Croatia
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

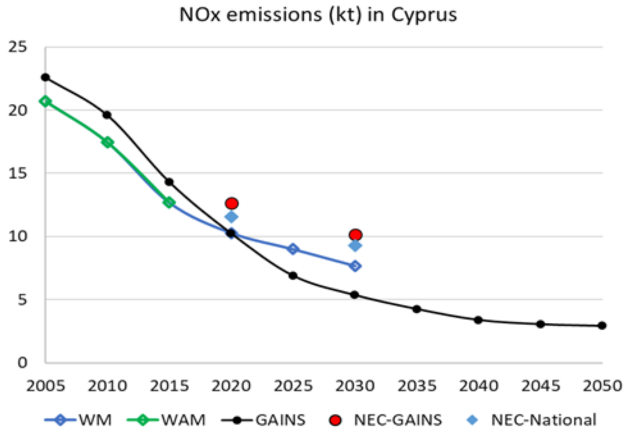

NH3 emissions (kt) in Croatia
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

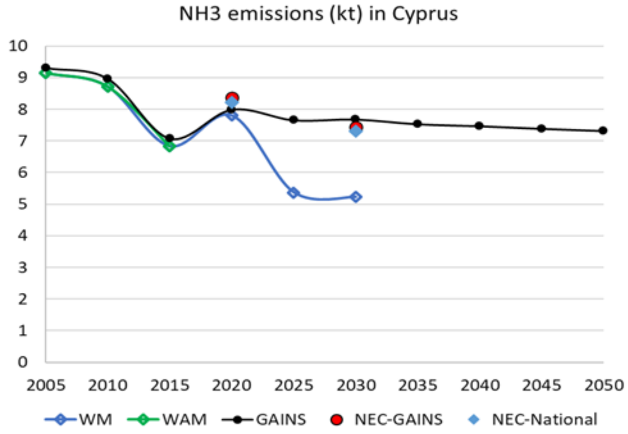

VOC emissions (kt) in Croatia
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

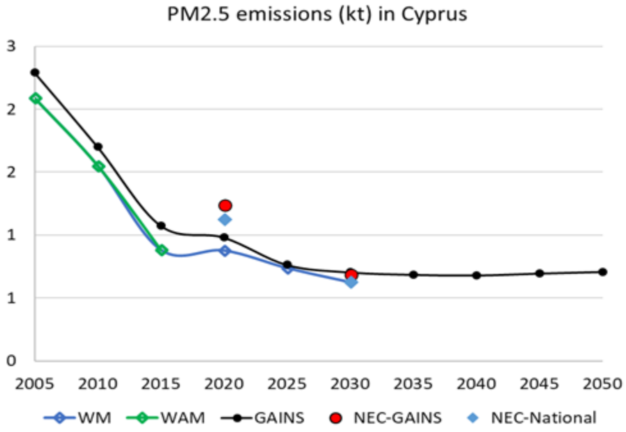

PM2.5 emissions (kt) in Croatia
50
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

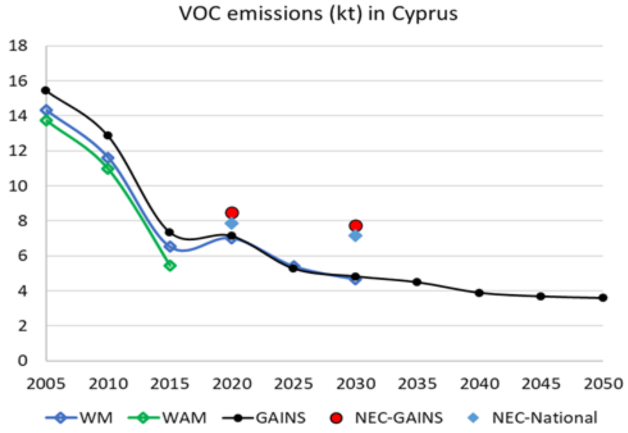
CYPRUS


SO2 emissions (kt) in Cyprus
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

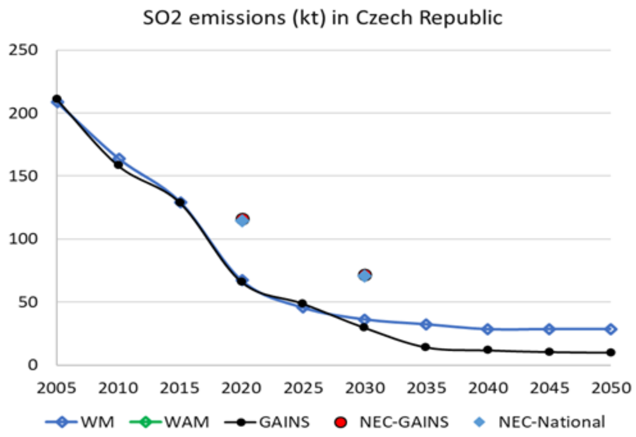

NOx emissions (kt) in Cyprus
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

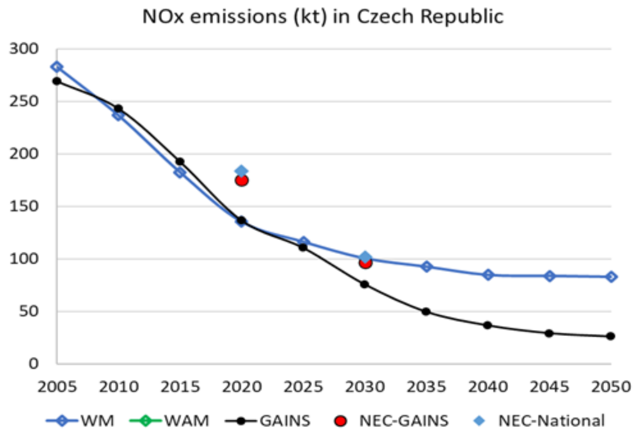

NH3 emissions (kt) in Cyprus
10
9
8
7
6
5
4
3
2
1
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

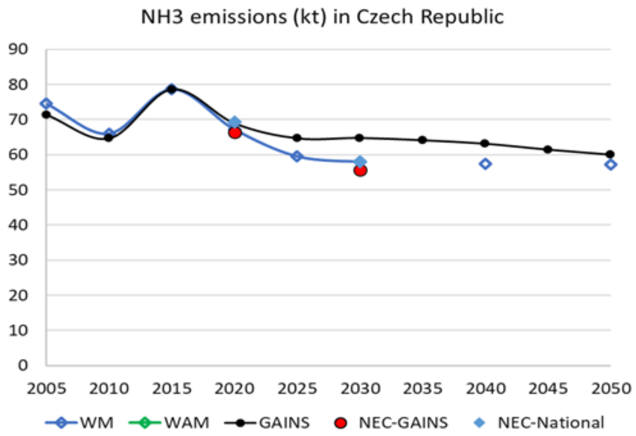

PM2.5 emissions (kt) in Cyprus
3
2
2
1
1
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

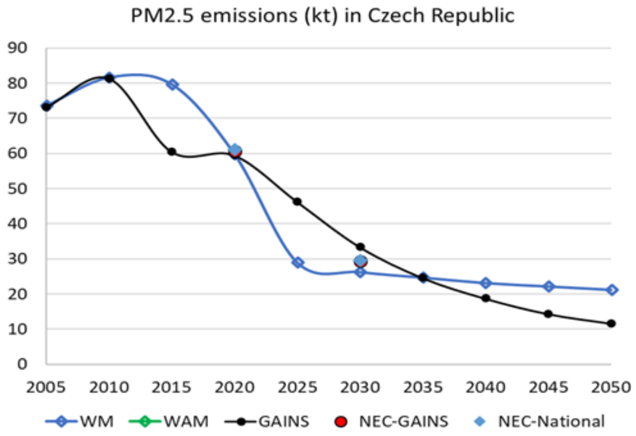

VOC emissions (kt) in Cyprus
18
16
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

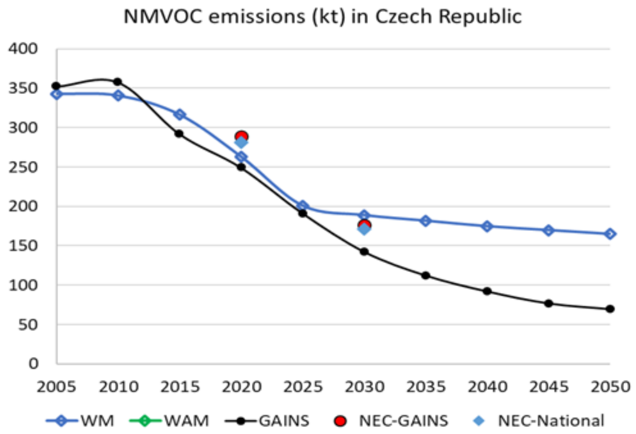
CZECH REPUBLIC



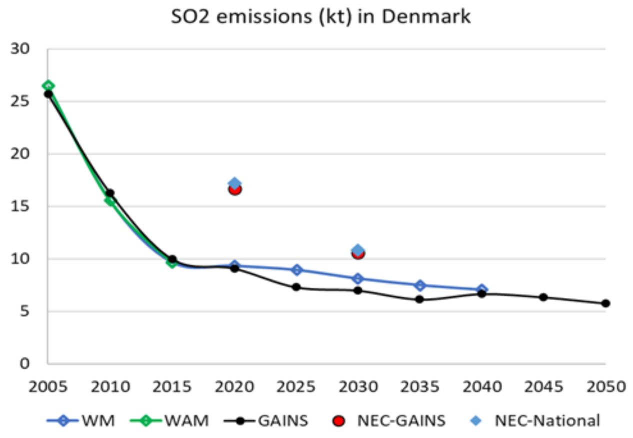


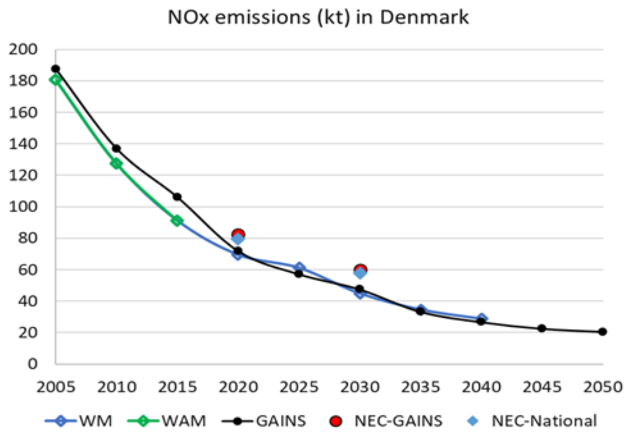


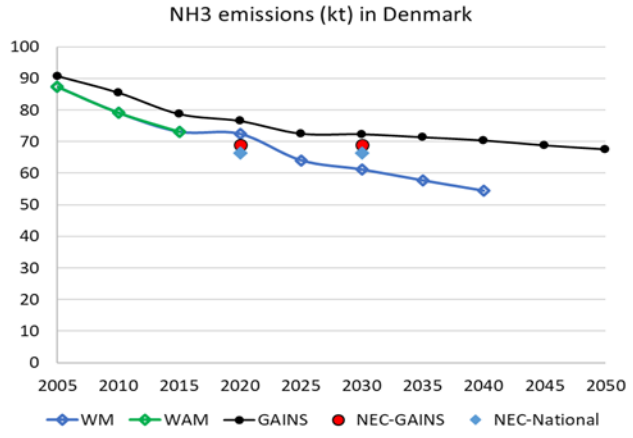


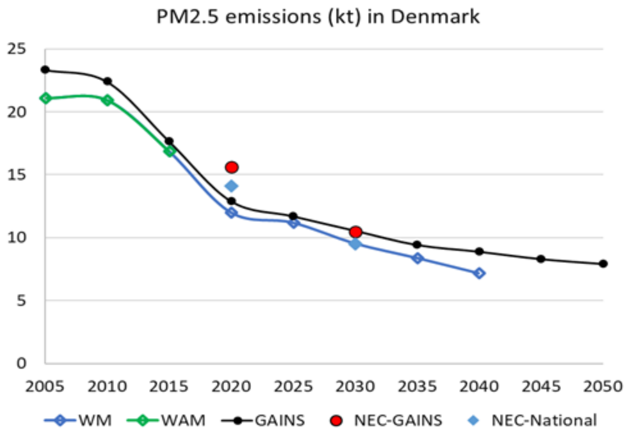


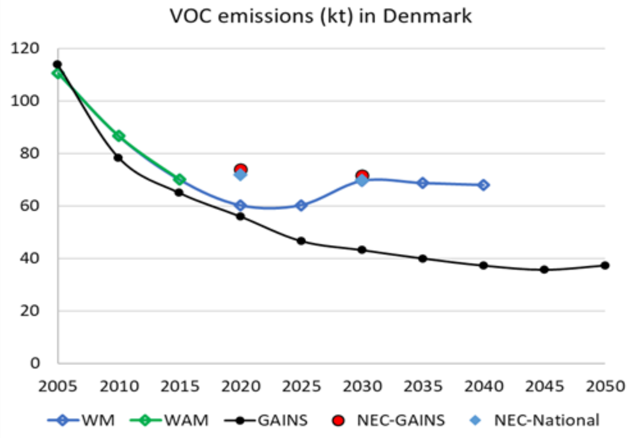
DENMARK


SO2 emissions (kt) in Denmark
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

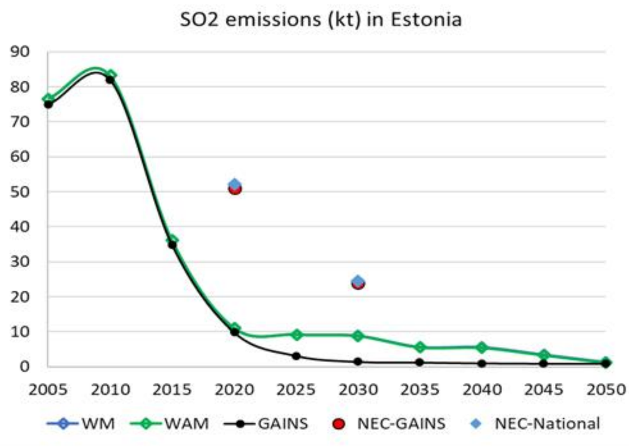

NOx emissions (kt) in Denmark
200
180
160
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

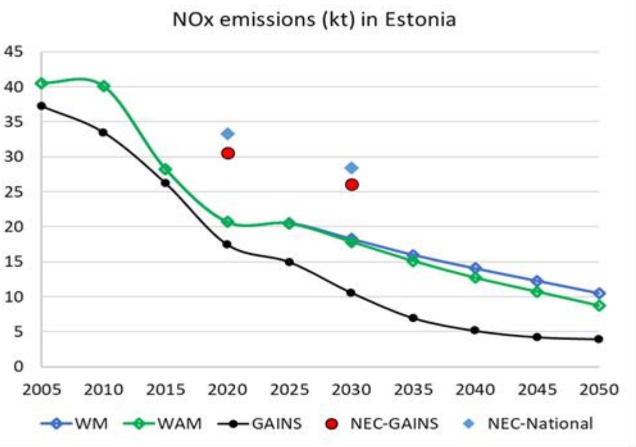

NH3 emissions (kt) in Denmark
100
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

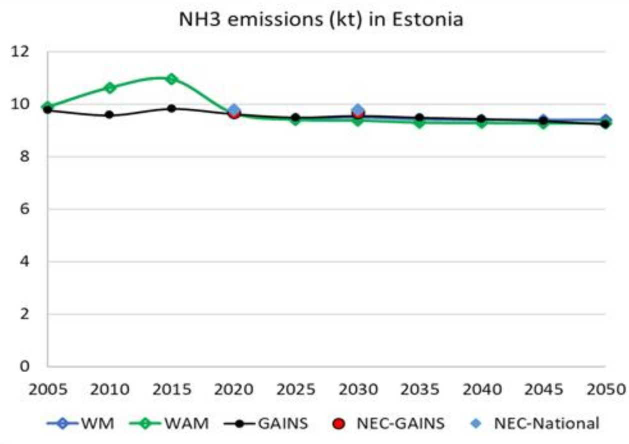

PM2.5 emissions (kt) in Denmark
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

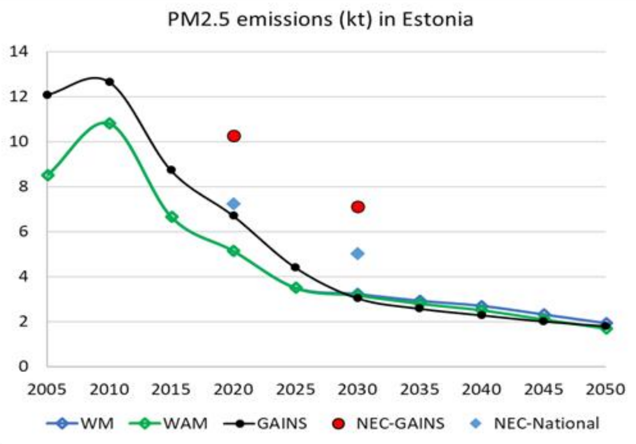

VOC emissions (kt) in Denmark
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

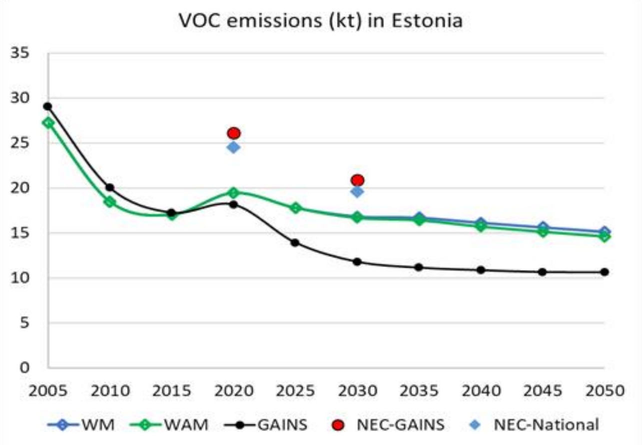
ESTONIA


SO2 emissions (kt) in Estonia
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

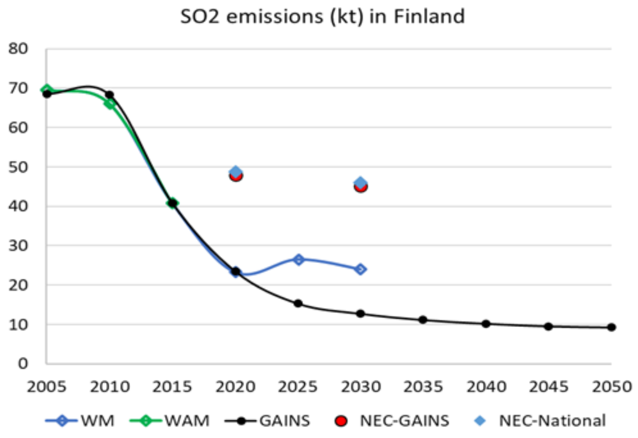

NOx emissions (kt) in Estonia
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

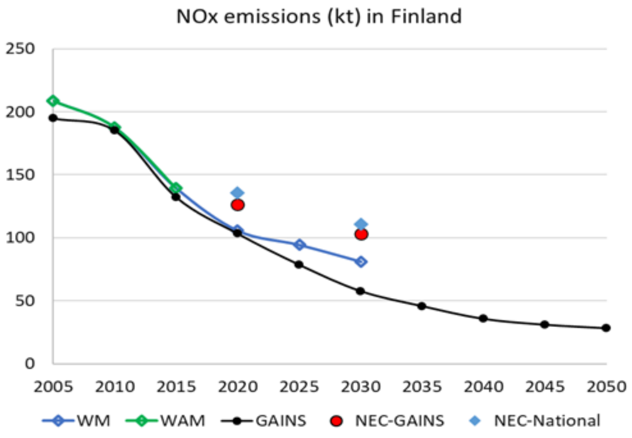

NH3 emissions (kt) in Estonia
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

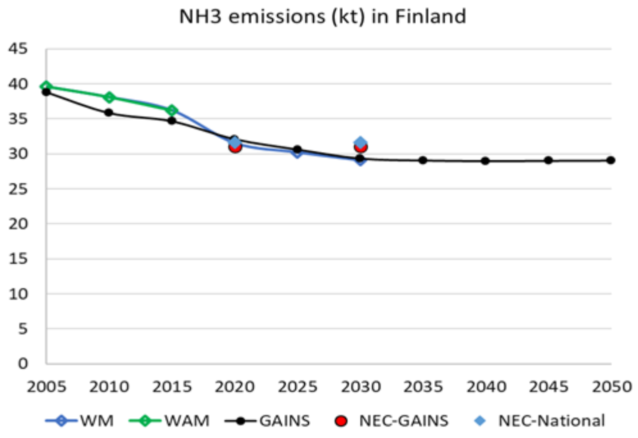

PM2.5 emissions (kt) in Estonia
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

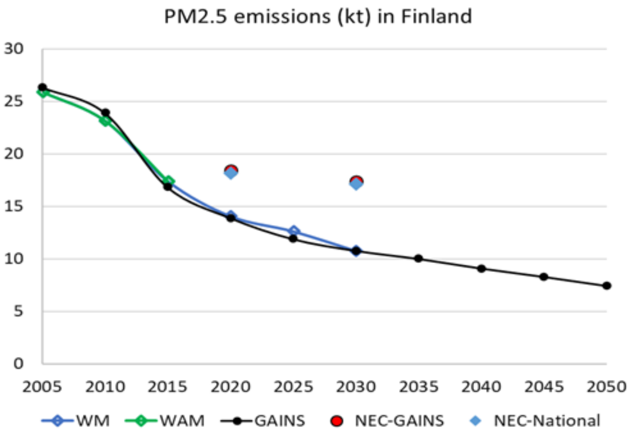

VOC emissions (kt) in Estonia
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

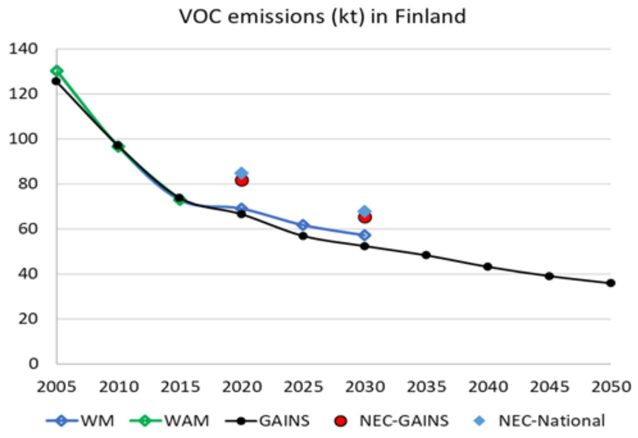
FINLAND


SO2 emissions (kt) in Finland
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

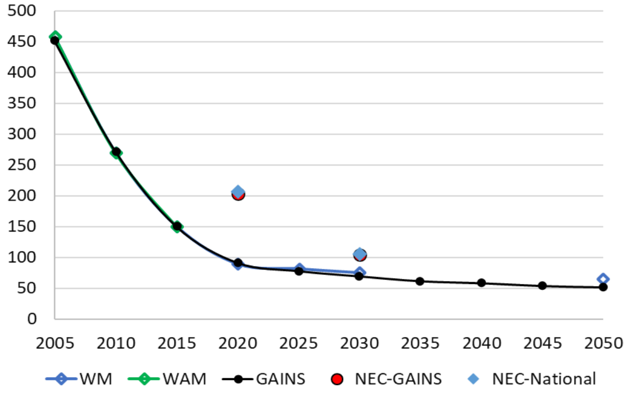

NOx emissions (kt) in Finland
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

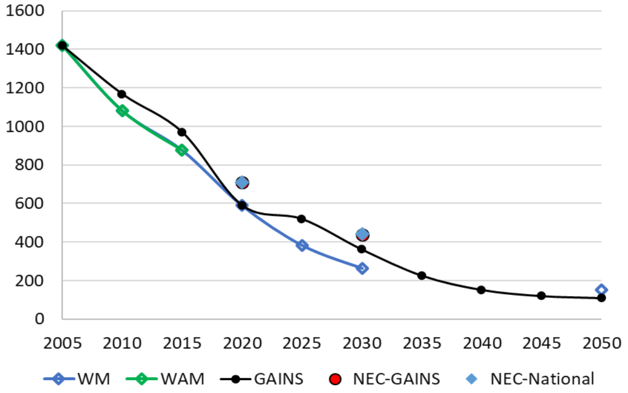

NH3 emissions (kt) in Finland
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

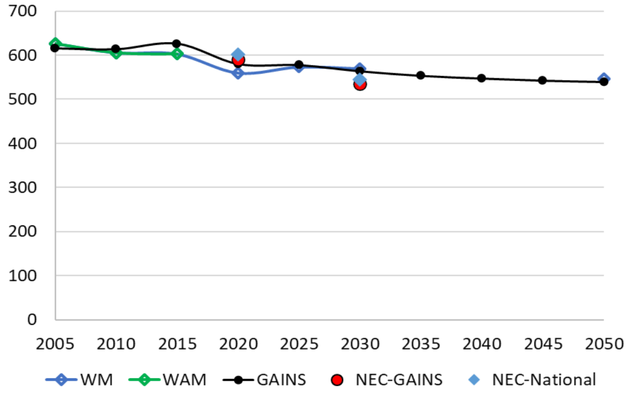

PM2.5 emissions (kt) in Finland
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

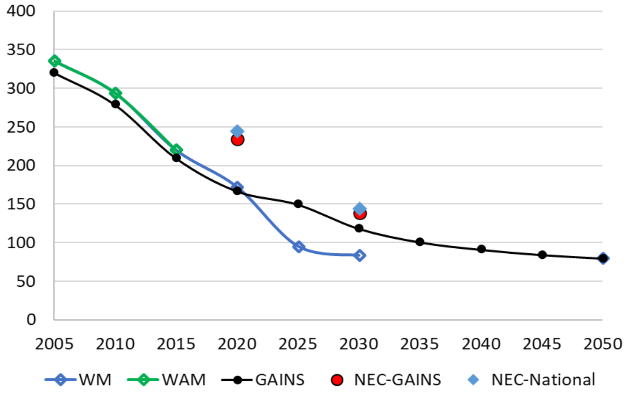

VOC emissions (kt) in Finland
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

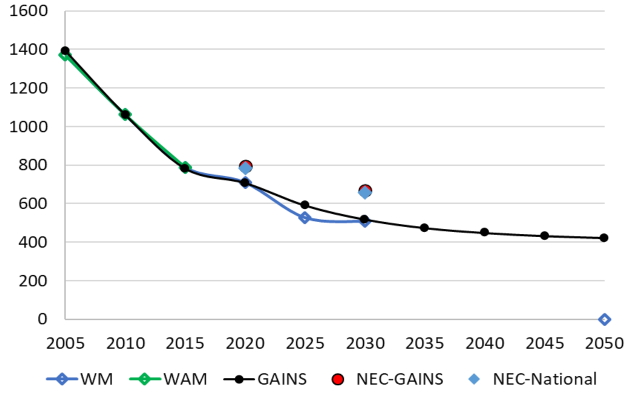
FRANCE


SO2 emissions (kt) in France

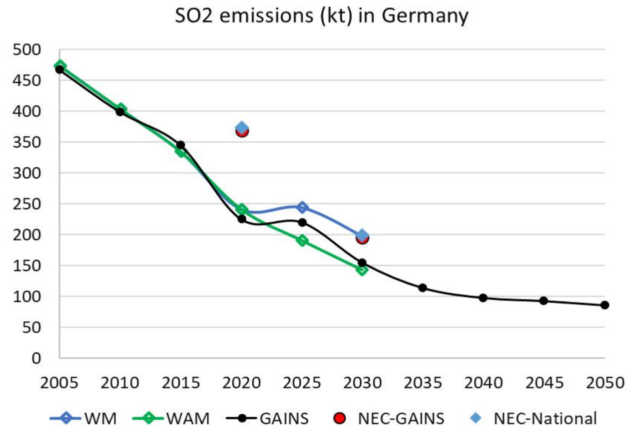

NOx emissions (kt) in France

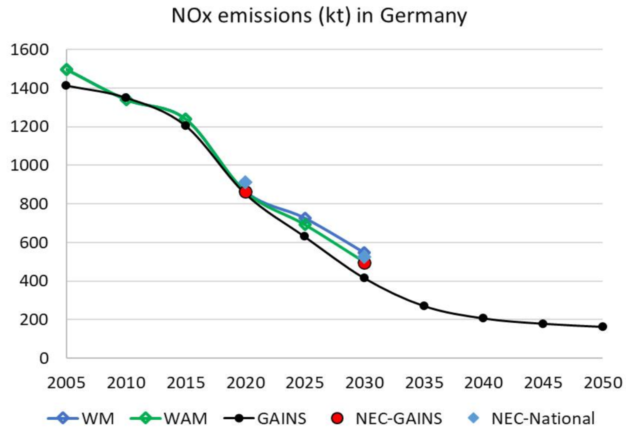

NH3 emissions (kt) in France

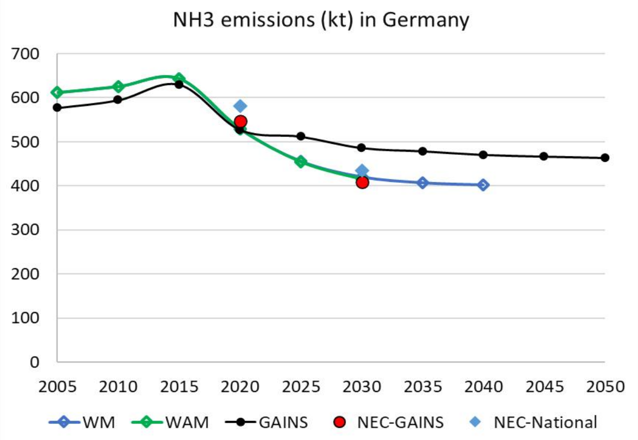

PM2.5 emissions (kt) in France

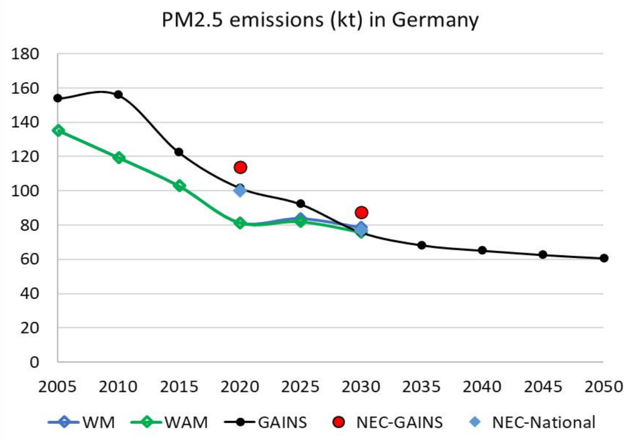

VOC emissions (kt) in France

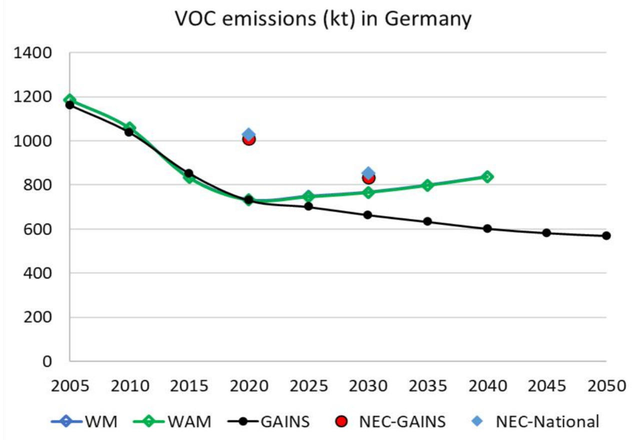
GERMANY


SO2 emissions (kt) in Germany
500
450
400
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

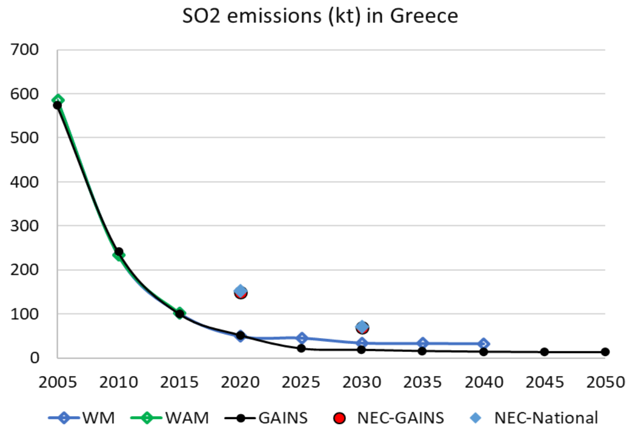

NOx emissions (kt) in Germany
1600
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

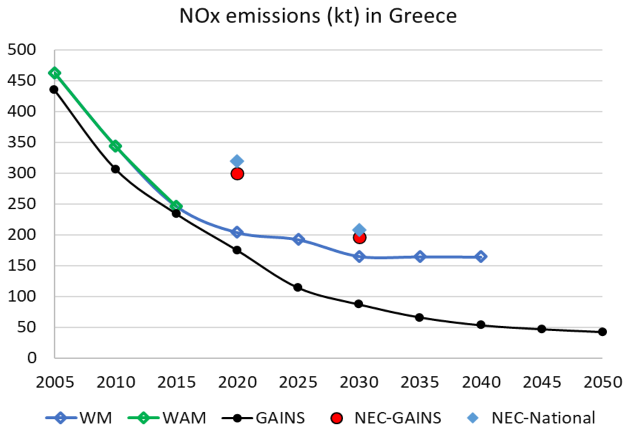

NH3 emissions (kt) in Germany
700
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

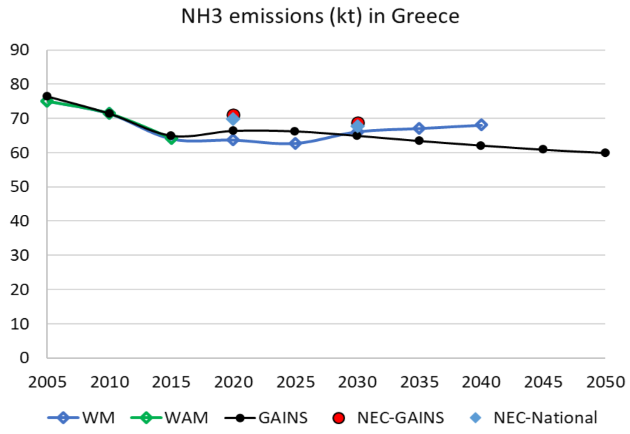

PM2.5 emissions (kt) in Germany
180
160
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

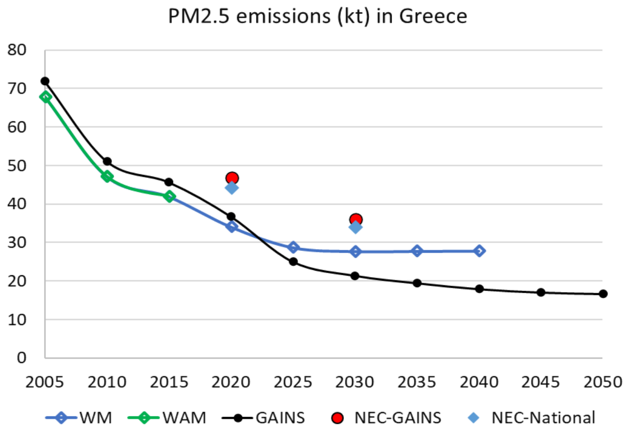

VOC emissions (kt) in Germany
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

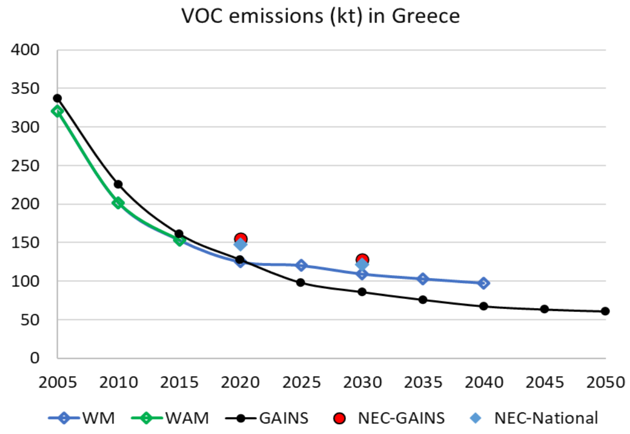
GREECE


SO2 emissions (kt) in Greece
700
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

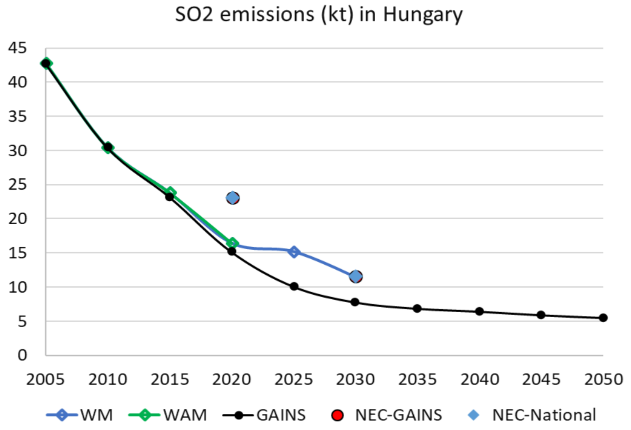

NOx emissions (kt) in Greece
500
450
400
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

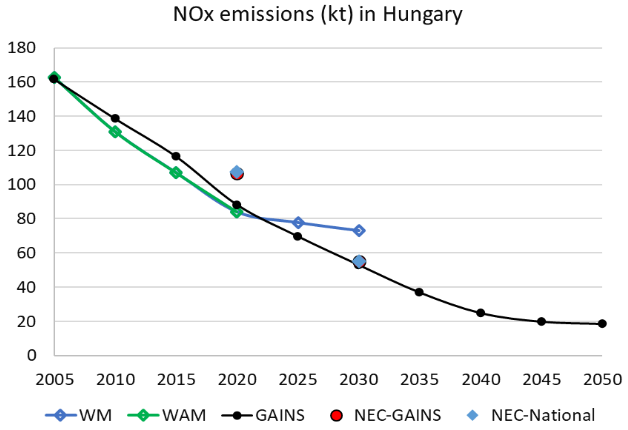

NH3 emissions (kt) in Greece
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

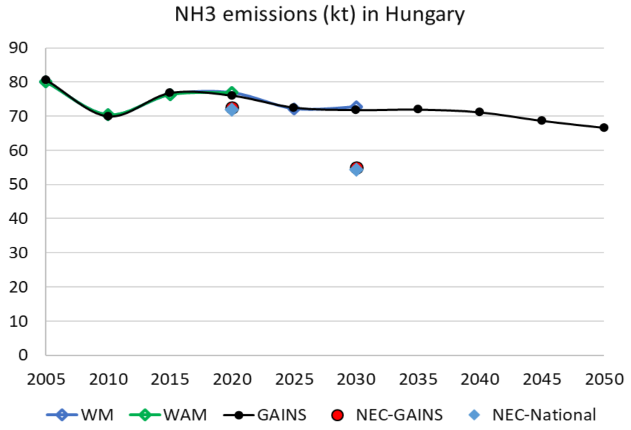

PM2.5 emissions (kt) in Greece
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

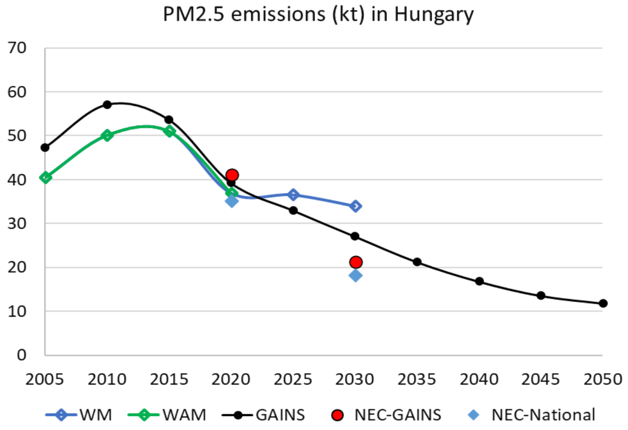

VOC emissions (kt) in Greece
400
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

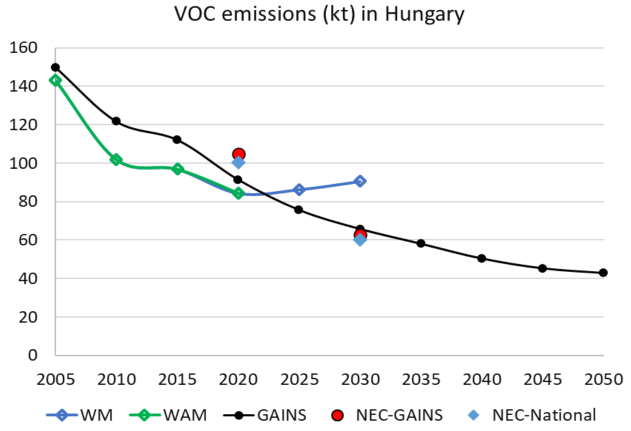
HUNGARY


SO2 emissions (kt) in Hungary

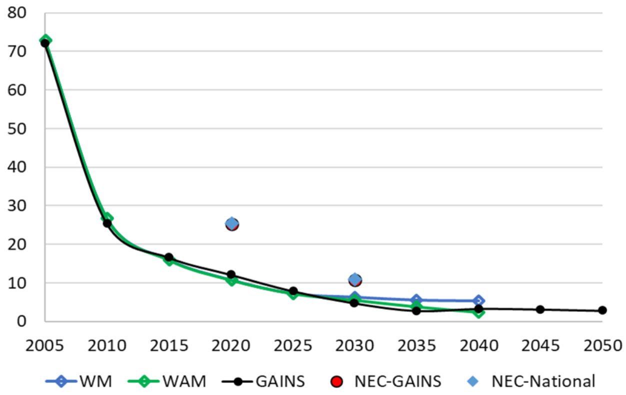

NOx emissions (kt) in Hungary

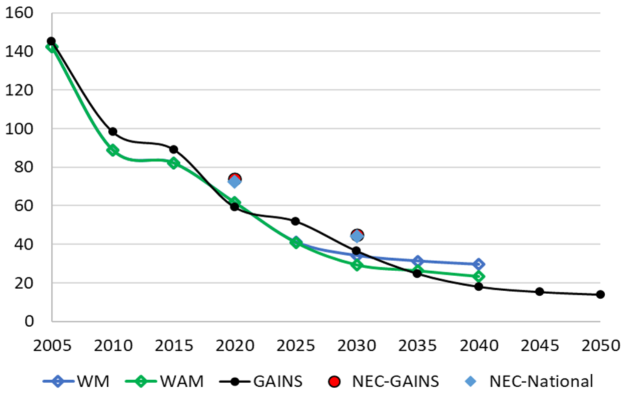

NH3 emissions (kt) in Hungary

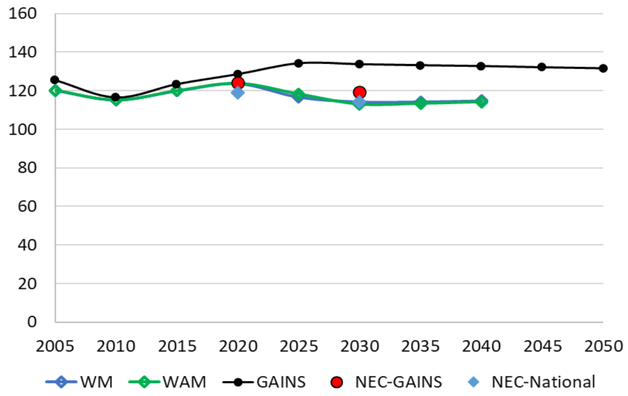

PM2.5 emissions (kt) in Hungary

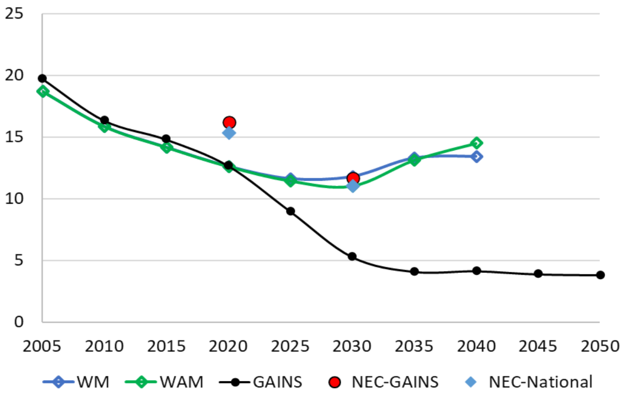

VOC emissions (kt) in Hungary

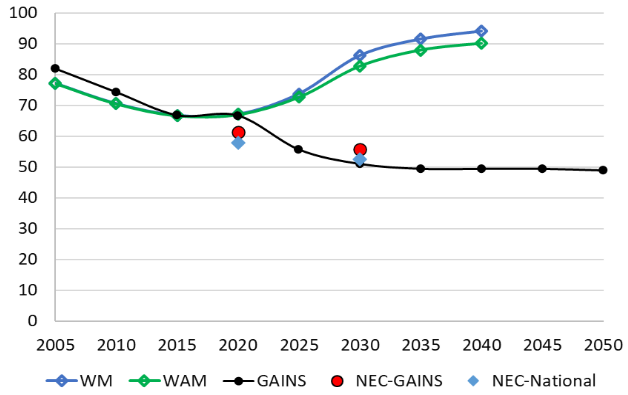
IRELAND


SO2 emissions (kt) in Ireland

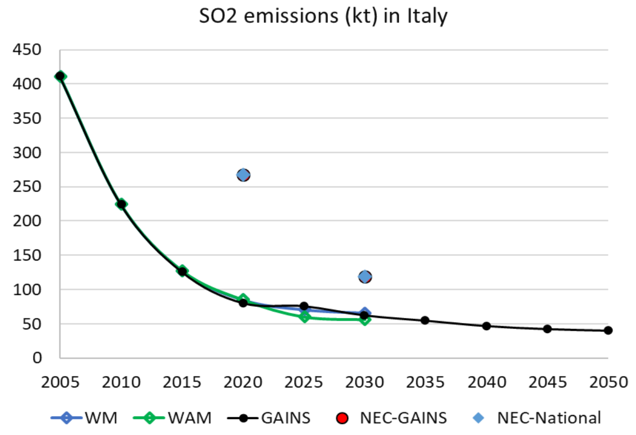

NOx emissions (kt) in Ireland

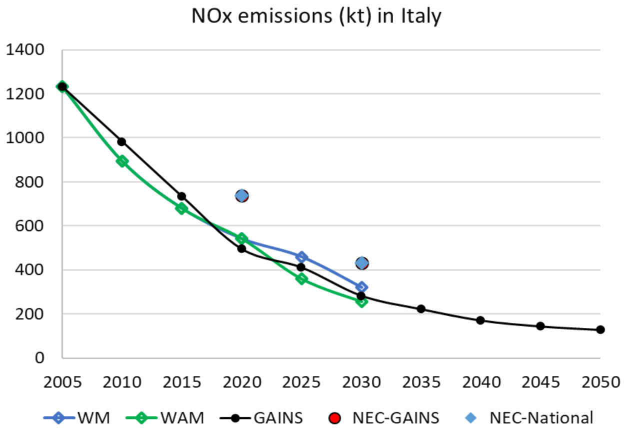

NH3 emissions (kt) in Ireland

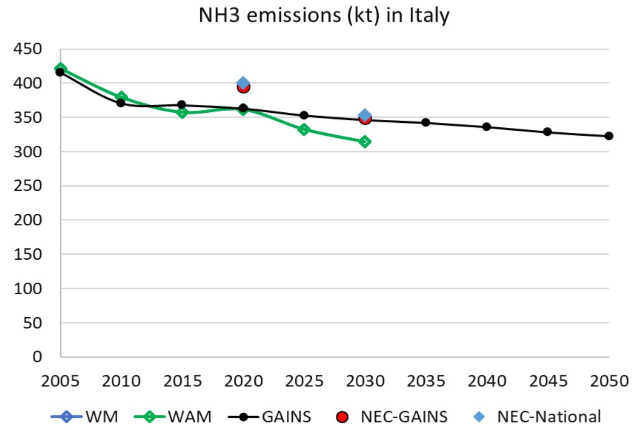

PM2.5 emissions (kt) in Ireland

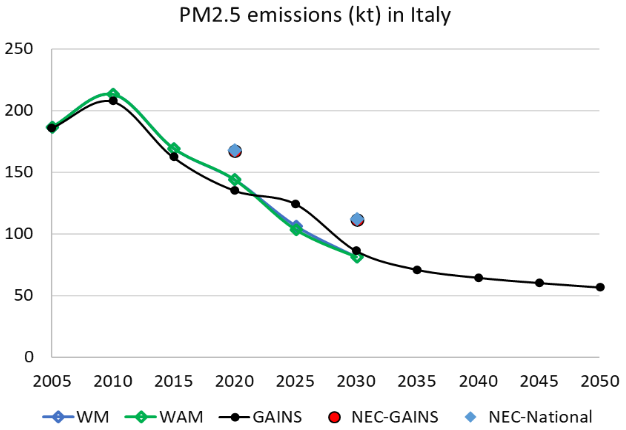

VOC emissions (kt) in Ireland

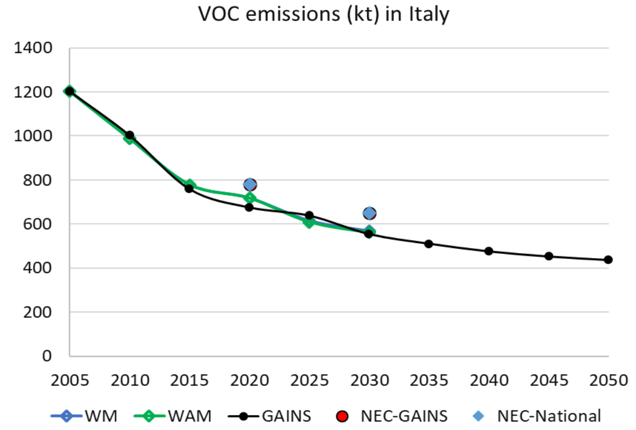
ITALY


SO2 emissions (kt) in Italy
450
400
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

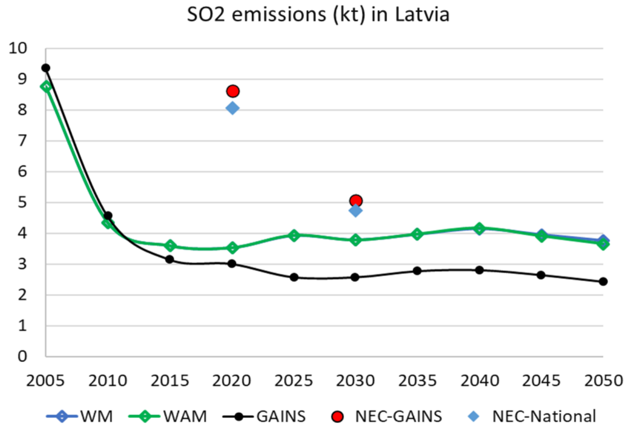

NOx emissions (kt) in Italy
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

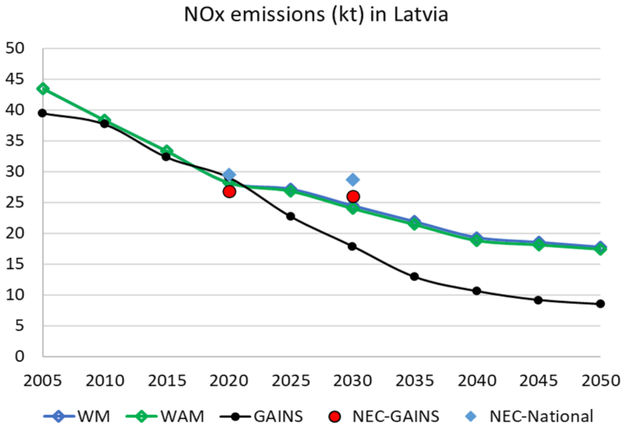

NH3 emissions (kt) in Italy
450
400
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

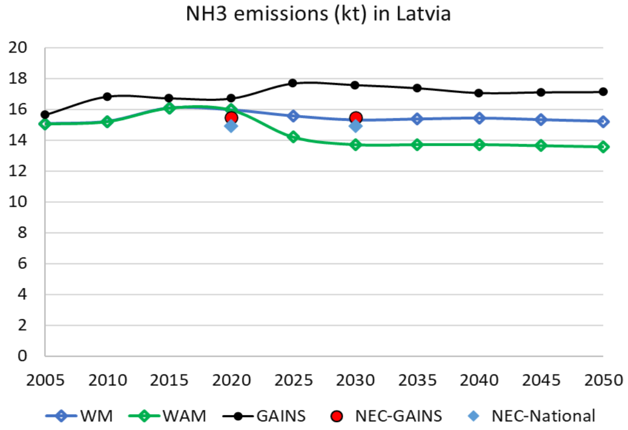

PM2.5 emissions (kt) in Italy
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

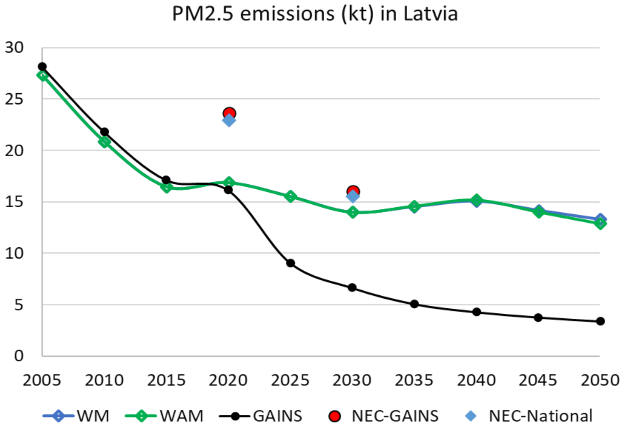

VOC emissions (kt) in Italy
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

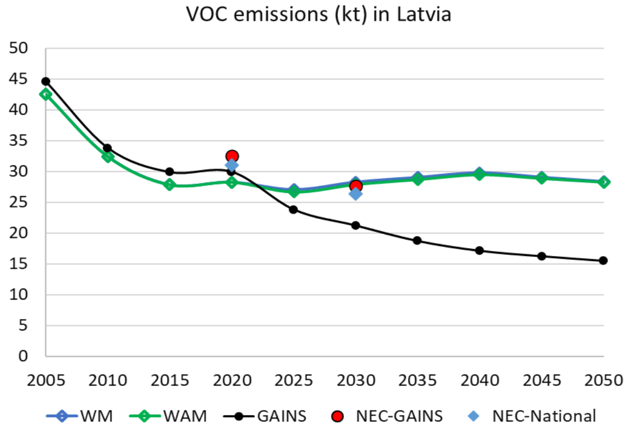
LATVIA


SO2 emissions (kt) in Latvia
10
9
8
7
6
5
4
3
2
1
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

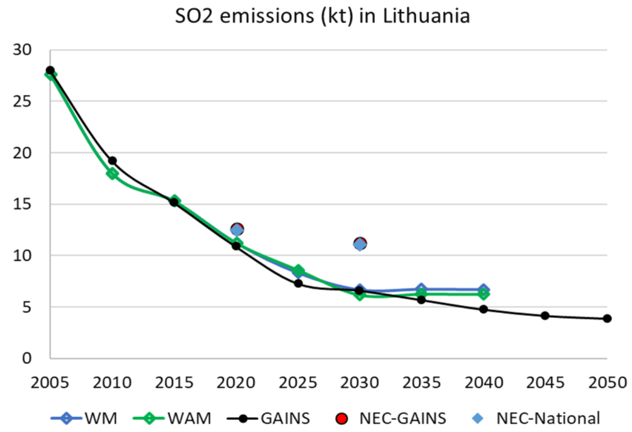

NOx emissions (kt) in Latvia
50
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

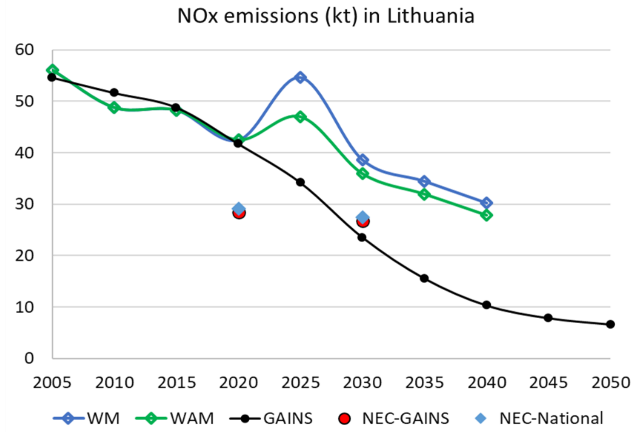

NH3 emissions (kt) in Latvia
20
18
16
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

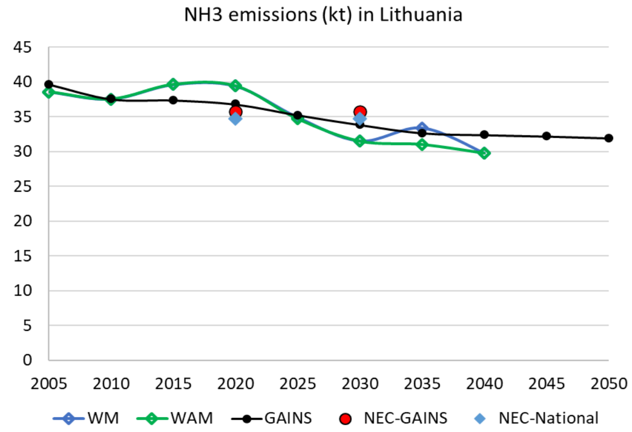

PM2.5 emissions (kt) in Latvia
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

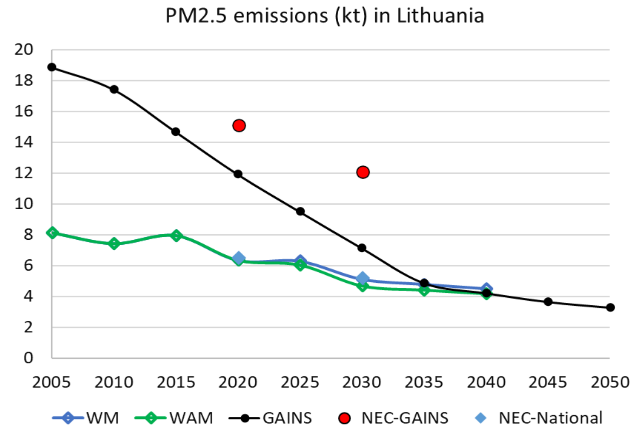

VOC emissions (kt) in Latvia
50
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

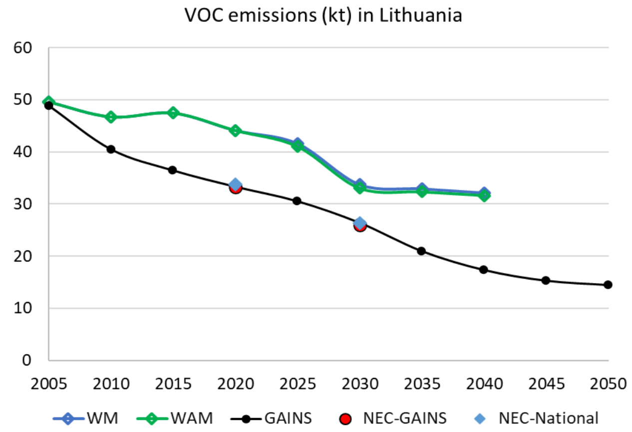
LITHUANIA


SO2 emissions (kt) in Lithuania
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

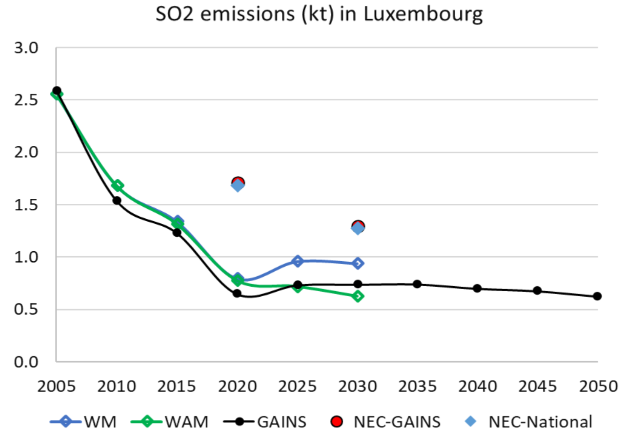

NOx emissions (kt) in Lithuania
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

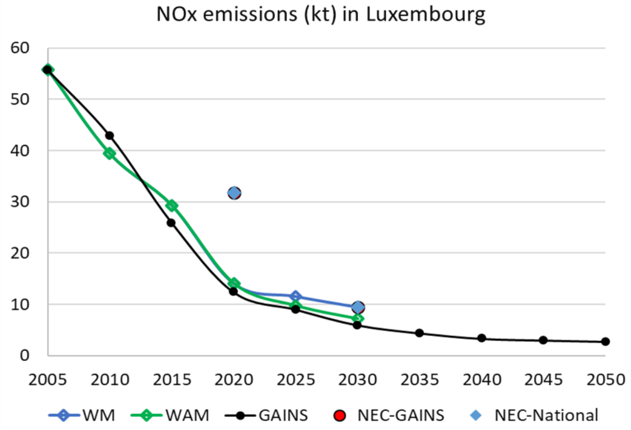

NH3 emissions (kt) in Lithuania
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

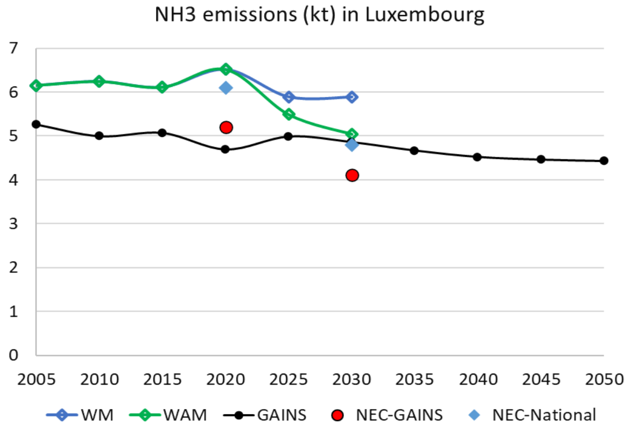

PM2.5 emissions (kt) in Lithuania
20
18
16
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

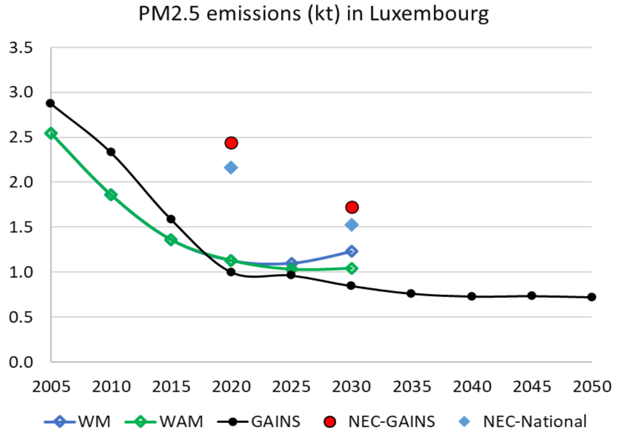

VOC emissions (kt) in Lithuania
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

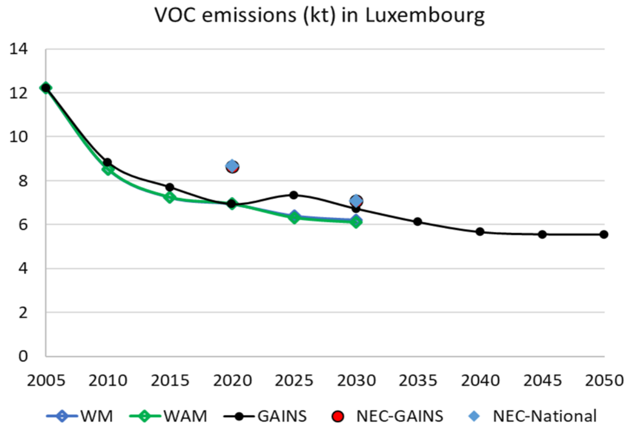
LUXEMBOURG


SO2 emissions (kt) in Luxembourg
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

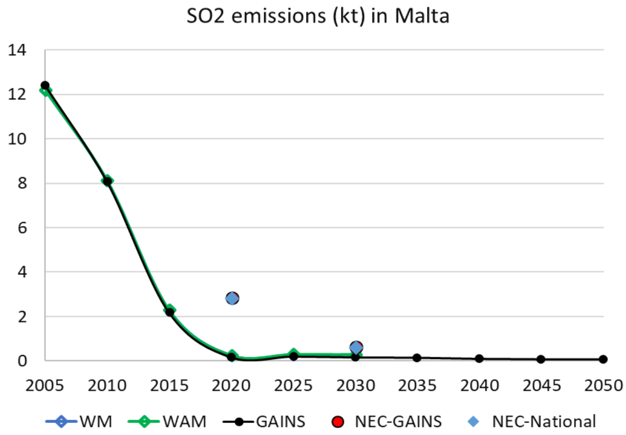

NOx emissions (kt) in Luxembourg
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

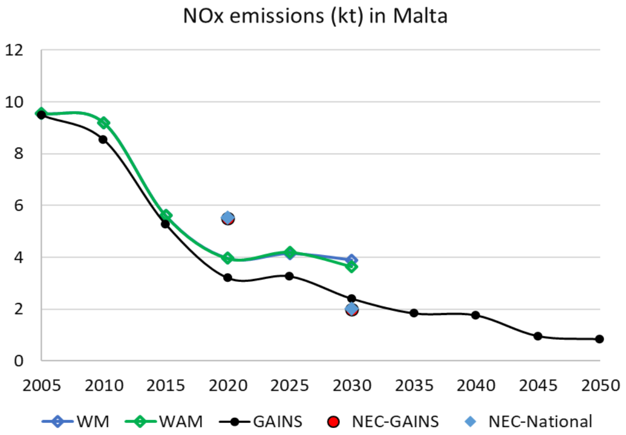

NH3 emissions (kt) in Luxembourg
7
6
5
4
3
2
1
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

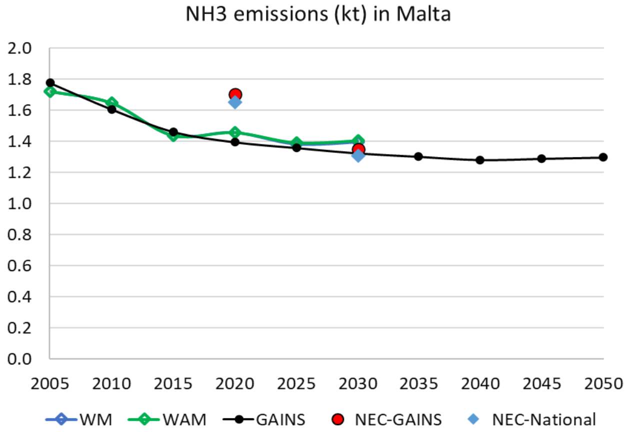

PM2.5 emissions (kt) in Luxembourg
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

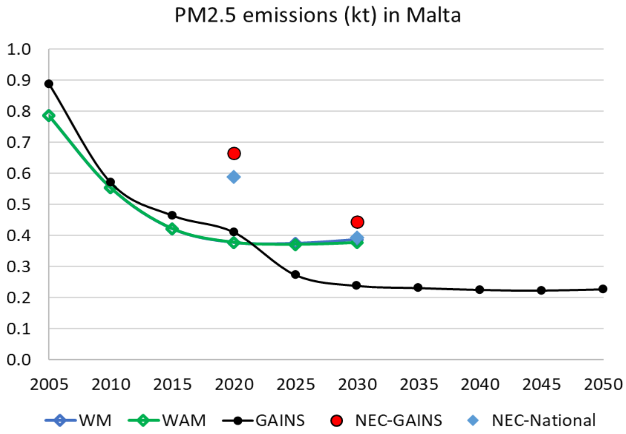

VOC emissions (kt) in Luxembourg
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

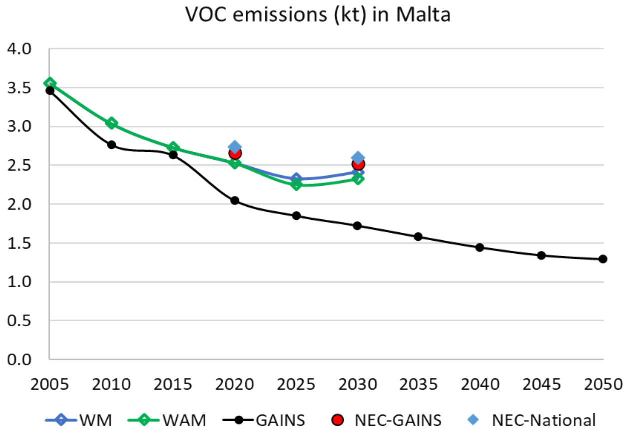
MALTA


SO2 emissions (kt) in Malta
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

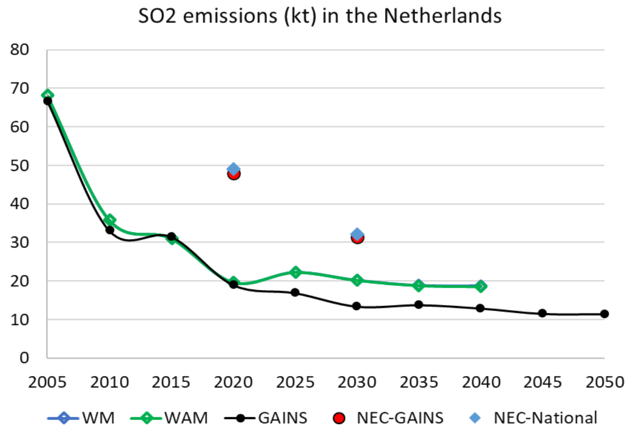

NOx emissions (kt) in Malta
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

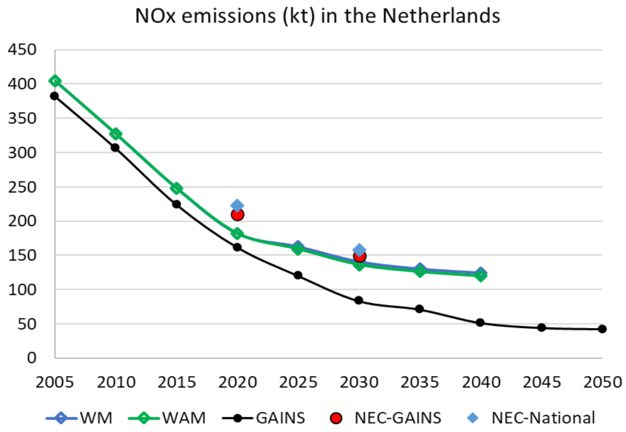

NH3 emissions (kt) in Malta
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

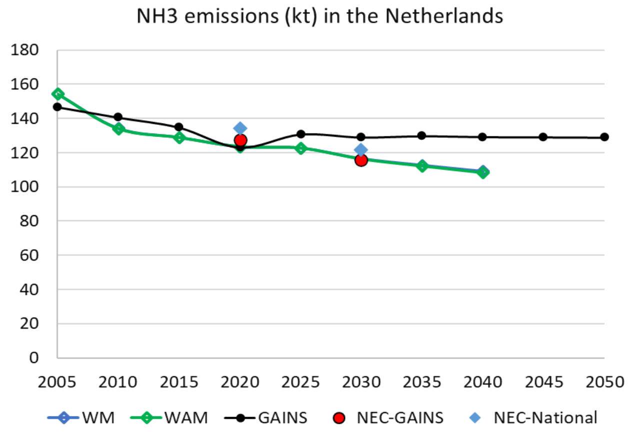

PM2.5 emissions (kt) in Malta
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

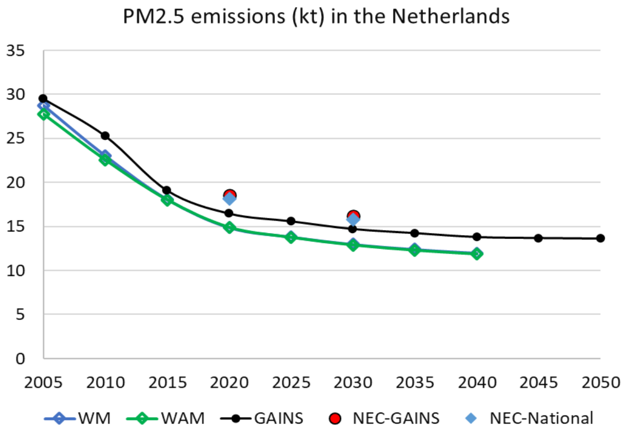

VOC emissions (kt) in Malta
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

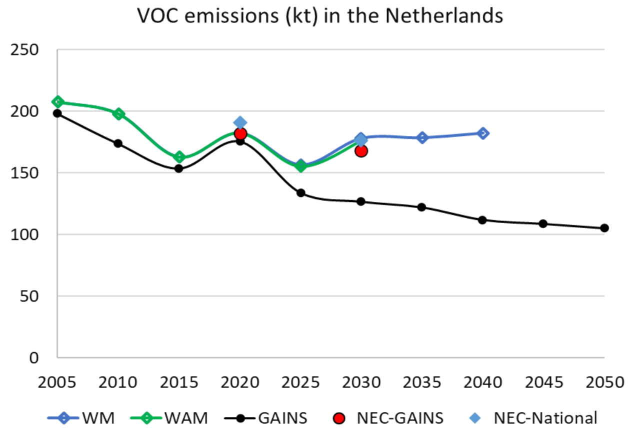
NETHERLANDS


SO2 emissions (kt) in the Netherlands

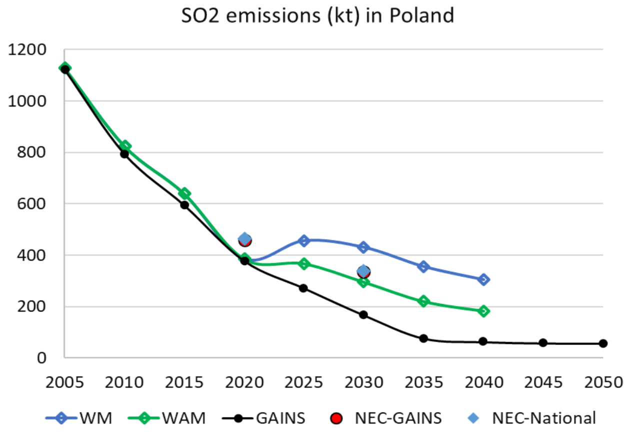

NOx emissions (kt) in the Netherlands

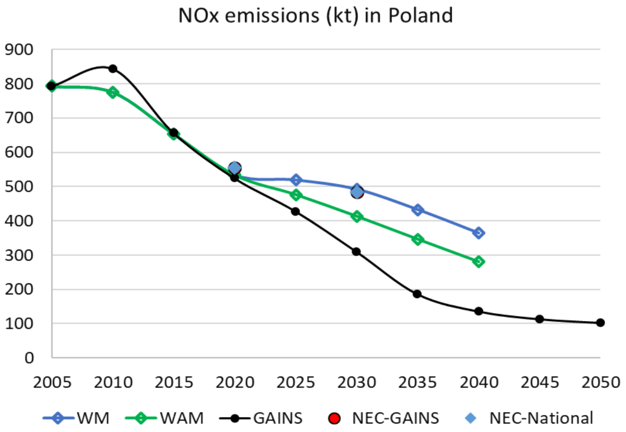

NH3 emissions (kt) in the Netherlands

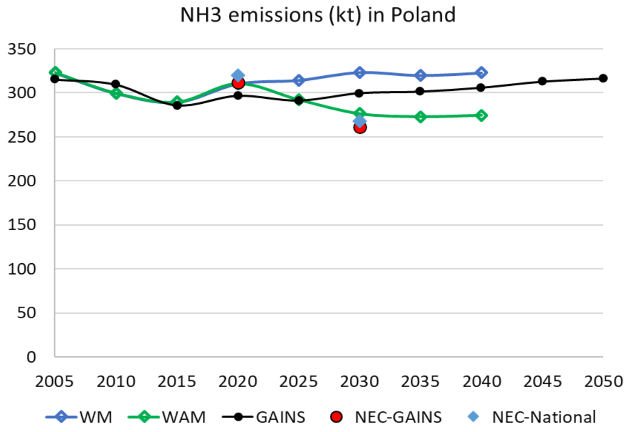

PM2.5 emissions (kt) in the Netherlands

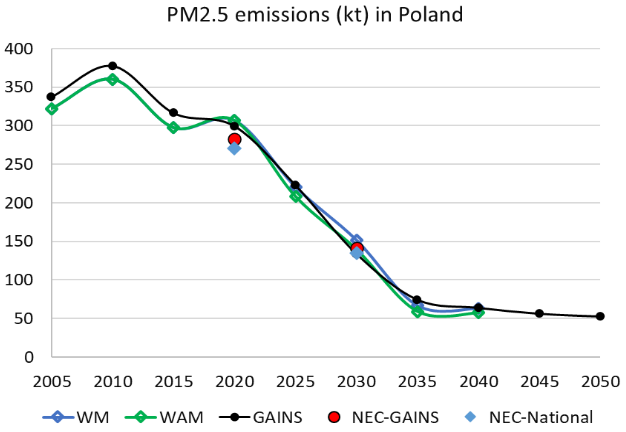

VOC emissions (kt) in the Netherlands

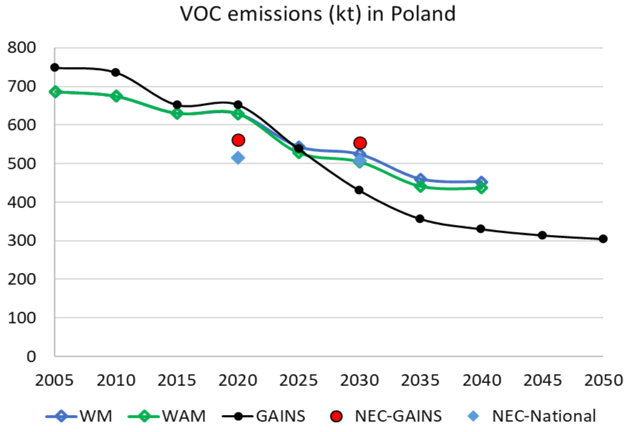
POLAND


SO2 emissions (kt) in Poland

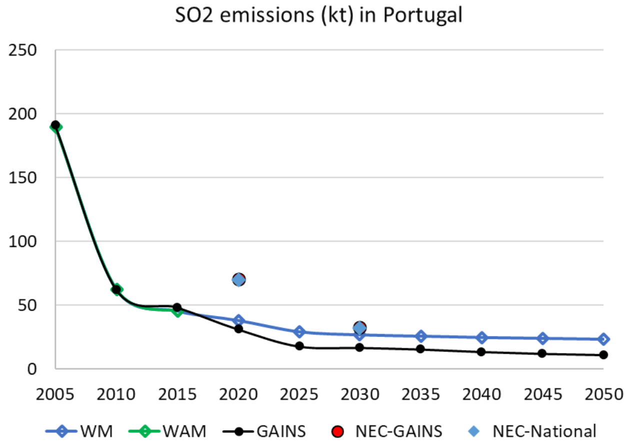

NOx emissions (kt) in Poland

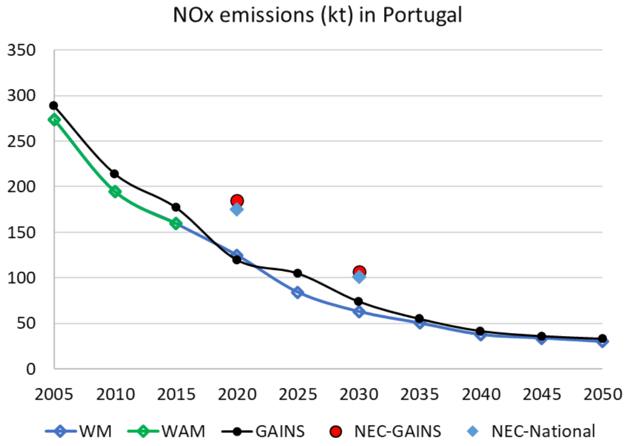

NH3 emissions (kt) in Poland

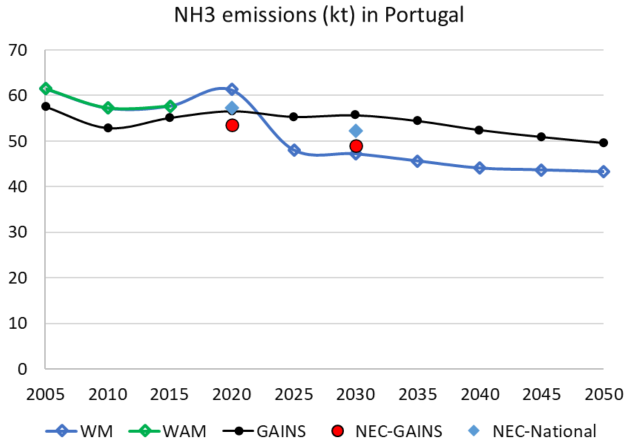

PM2.5 emissions (kt) in Poland

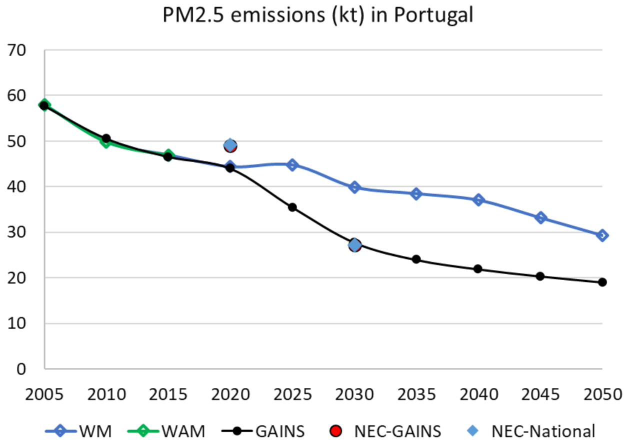

VOC emissions (kt) in Poland

PORTUGAL


SO2 emissions (kt) in Portugal
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National


NOx emissions (kt) in Portugal
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National


NH3 emissions (kt) in Portugal
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National


PM2.5 emissions (kt) in Portugal
70
60
50
40
30
20
10
0
2005
2010
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2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
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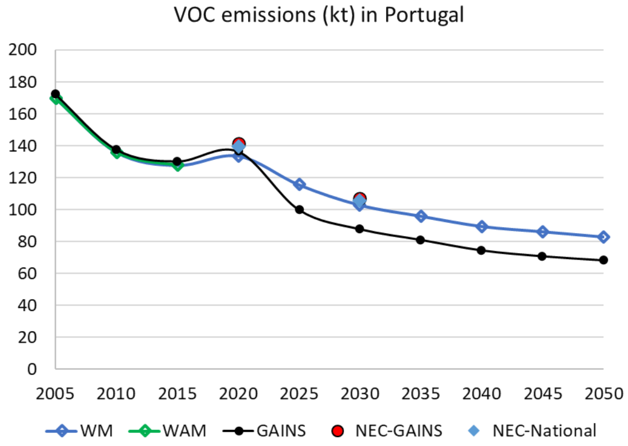
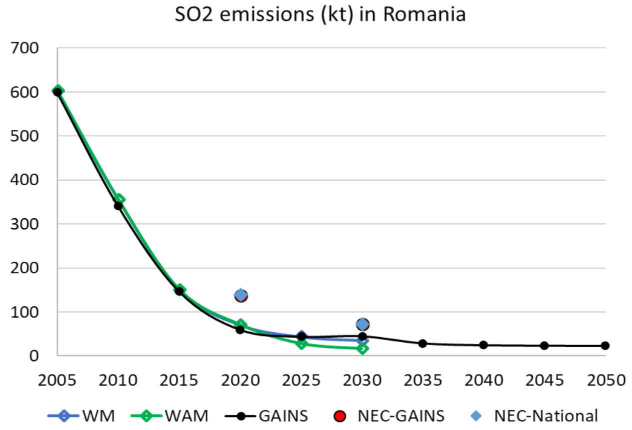
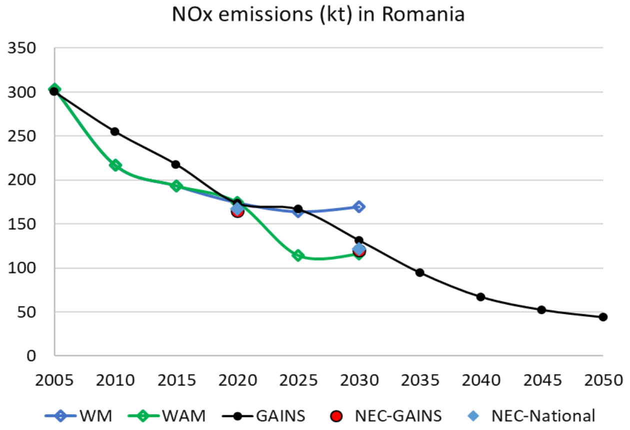
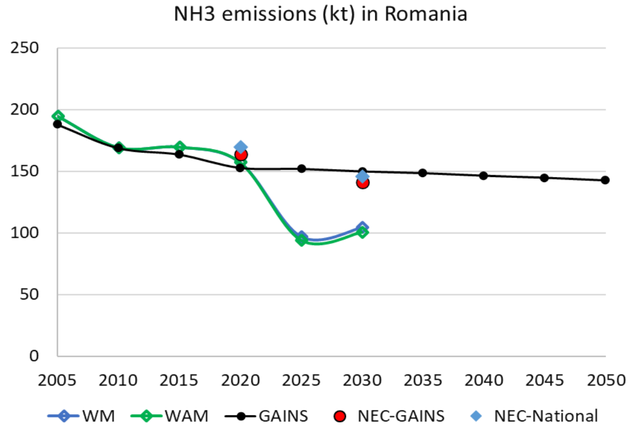
NEC-National

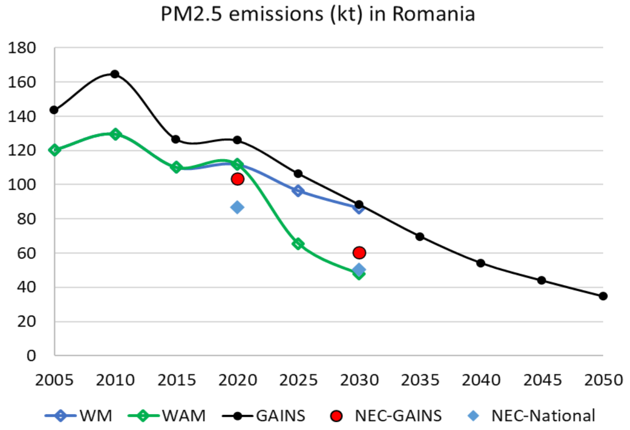

VOC emissions (kt) in Portugal
200
180
160
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

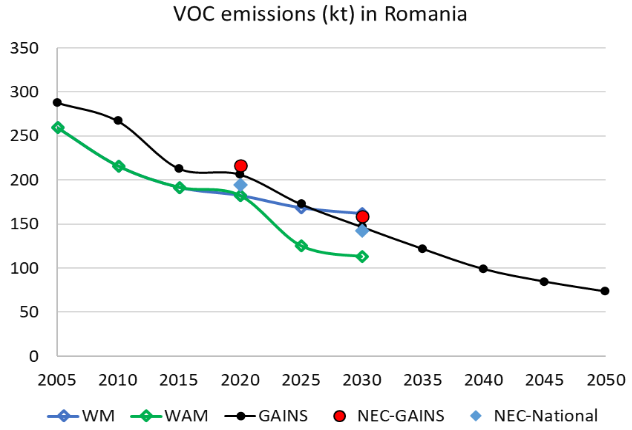
ROMANIA


SO2 emissions (kt) in Romania
700
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

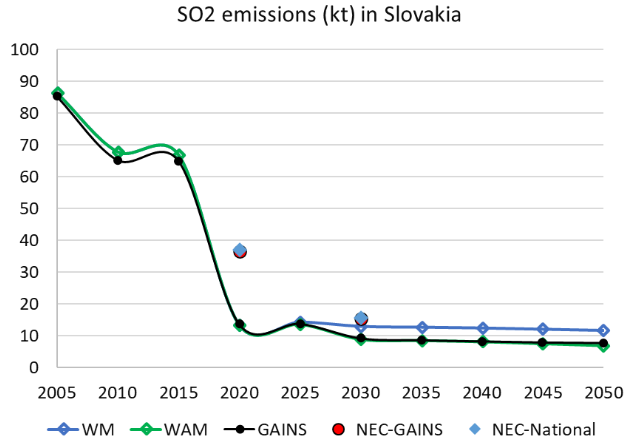

NOx emissions (kt) in Romania
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

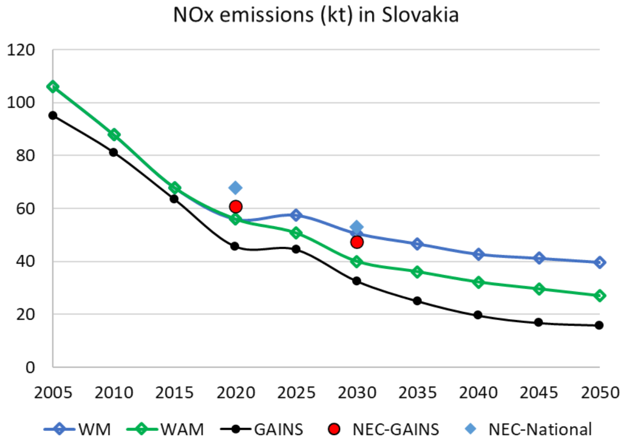

NH3 emissions (kt) in Romania
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

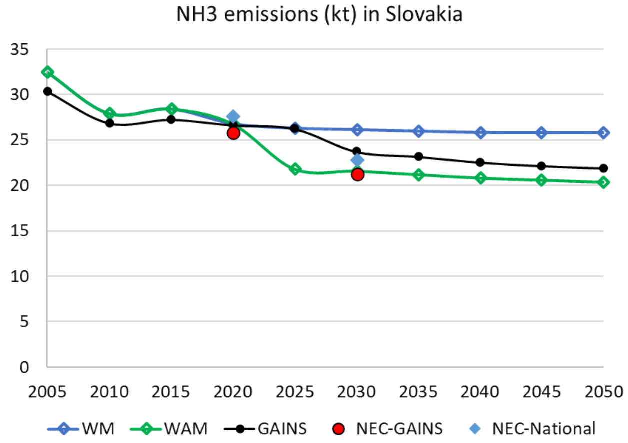

PM2.5 emissions (kt) in Romania
180
160
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

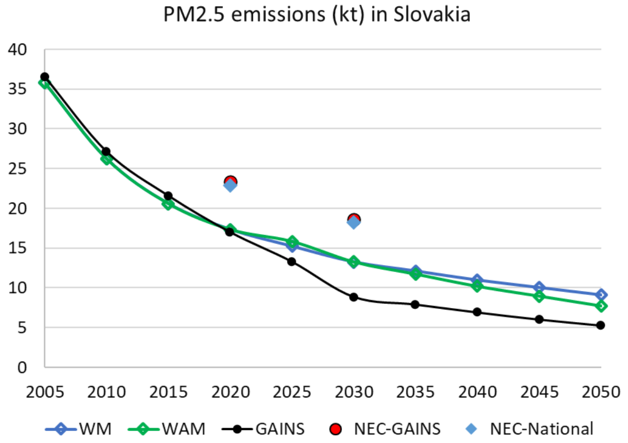

VOC emissions (kt) in Romania
350
300
250
200
150
100
50
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

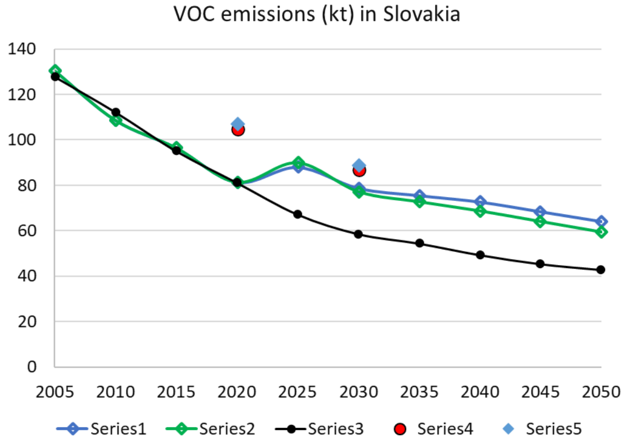
SLOVAKIA


SO2 emissions (kt) in Slovakia
100
90
80
70
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

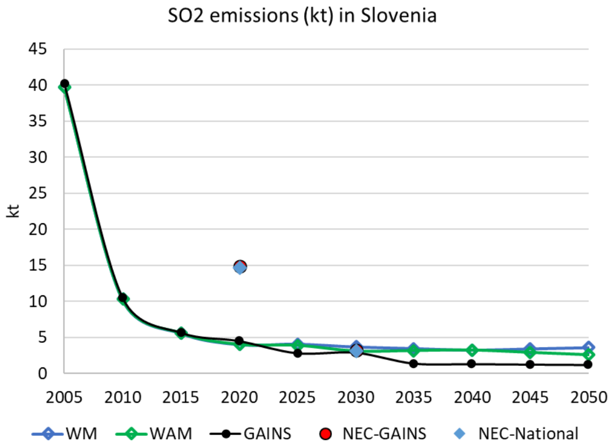

NOx emissions (kt) in Slovakia
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

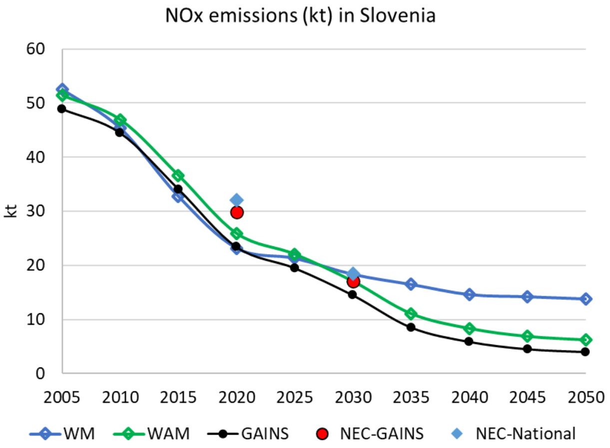

NH3 emissions (kt) in Slovakia
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

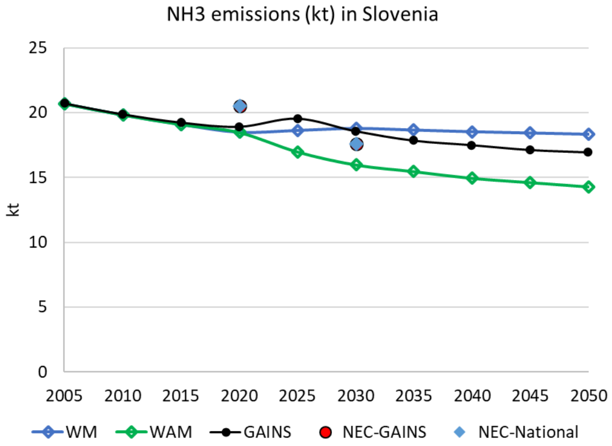

PM2.5 emissions (kt) in Slovakia
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

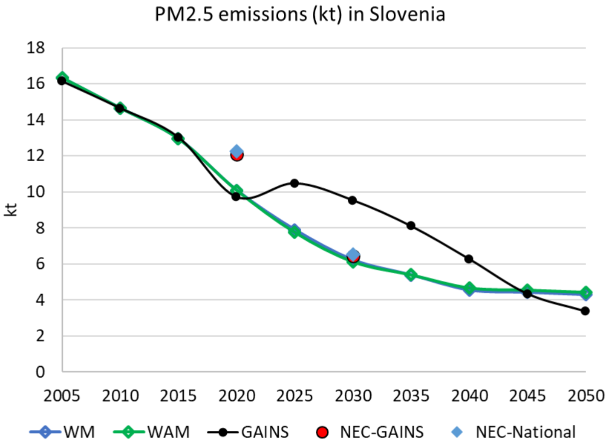

VOC emissions (kt) in Slovakia
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Series1
Series2
Series3
Series4
Series5

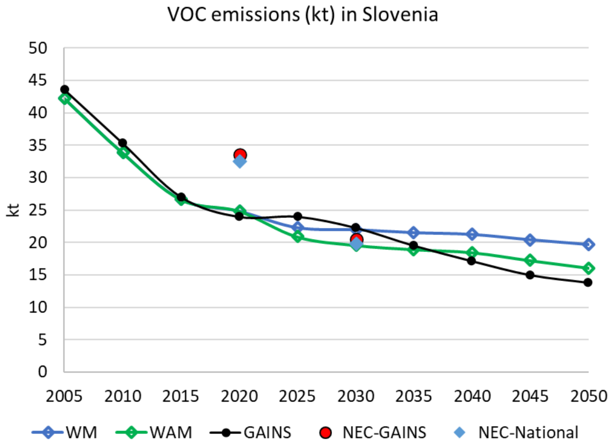
SLOVENIA


SO2 emissions (kt) in Slovenia
kt
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

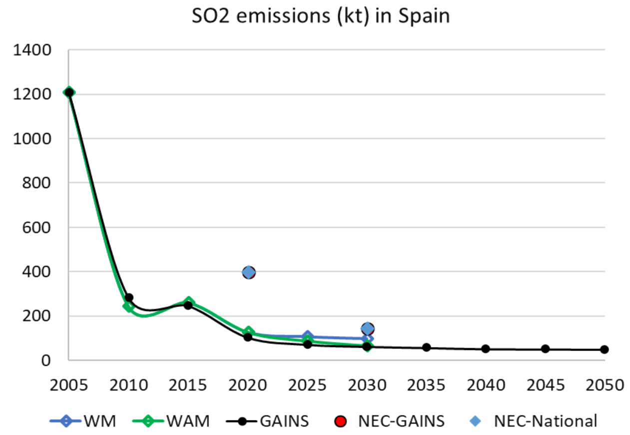

NOx emissions (kt) in Slovenia
kt
60
50
40
30
20
10
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

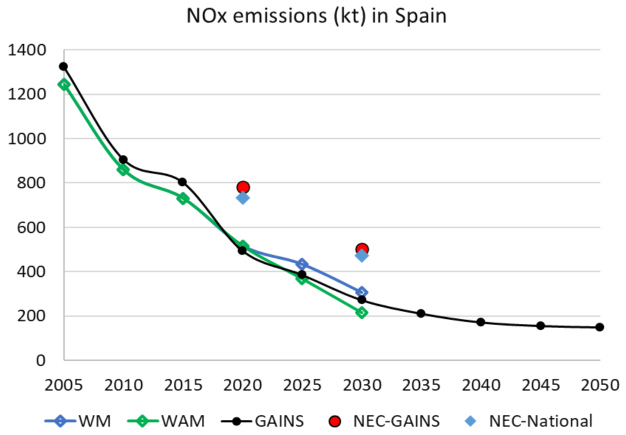

NH3 emissions (kt) in Slovenia
kt
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

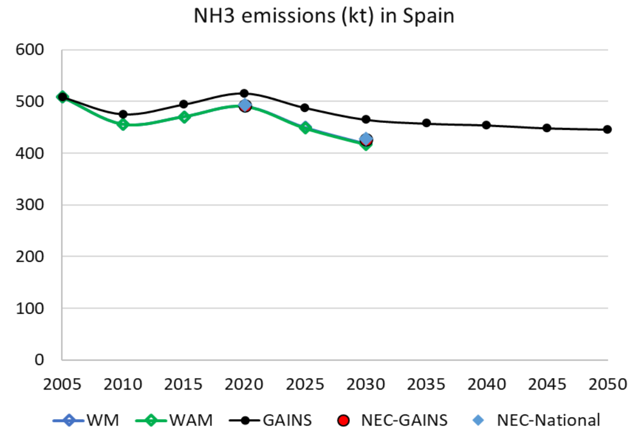

PM2.5 emissions (kt) in Slovenia
kt
18
16
14
12
10
8
6
4
2
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

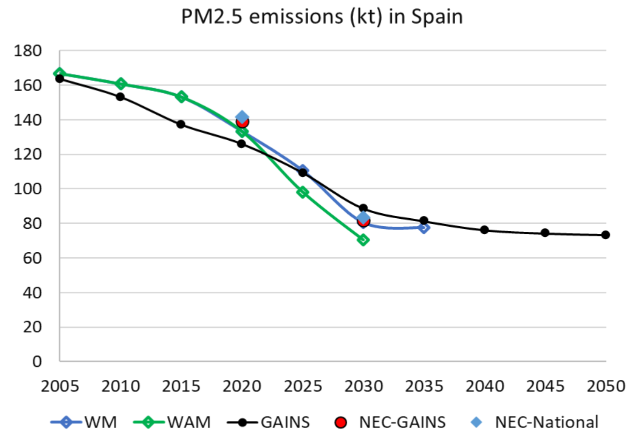

VOC emissions (kt) in Slovenia
kt
50
45
40
35
30
25
20
15
10
5
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

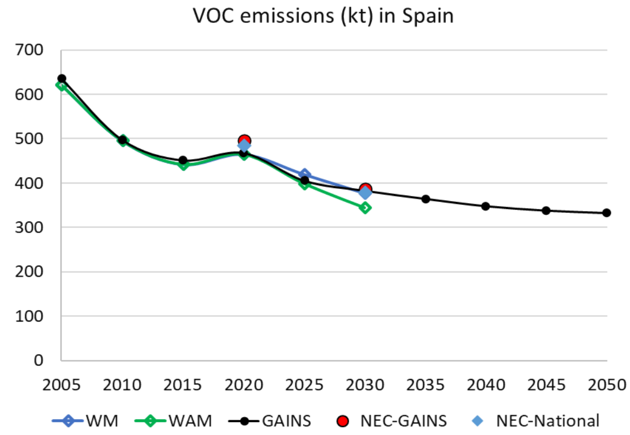
SPAIN


SO2 emissions (kt) in Spain
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

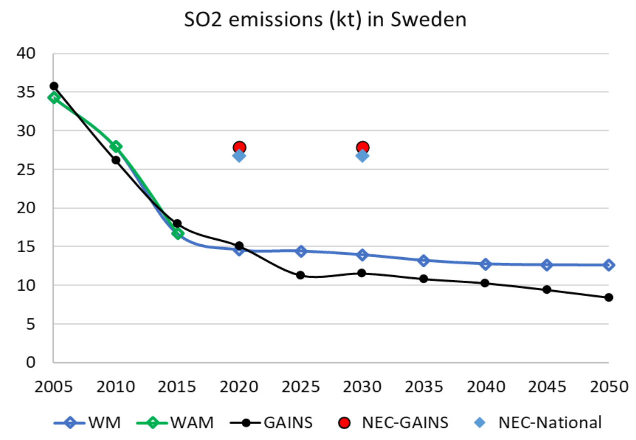

NOx emissions (kt) in Spain
1400
1200
1000
800
600
400
200
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

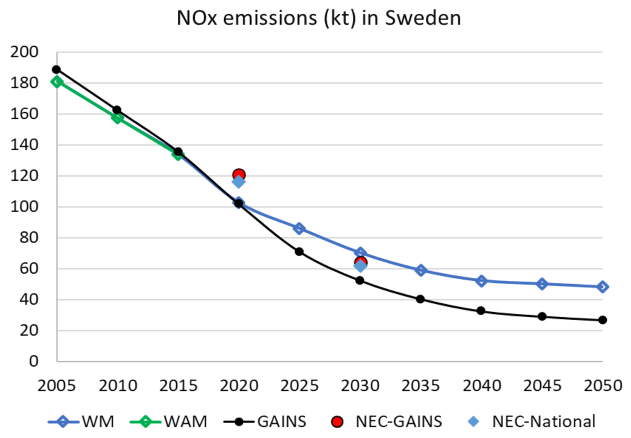

NH3 emissions (kt) in Spain
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

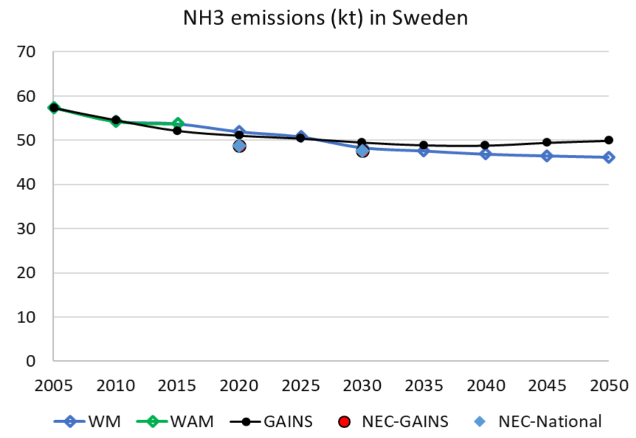

PM2.5 emissions (kt) in Spain
180
160
140
120
100
80
60
40
20
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

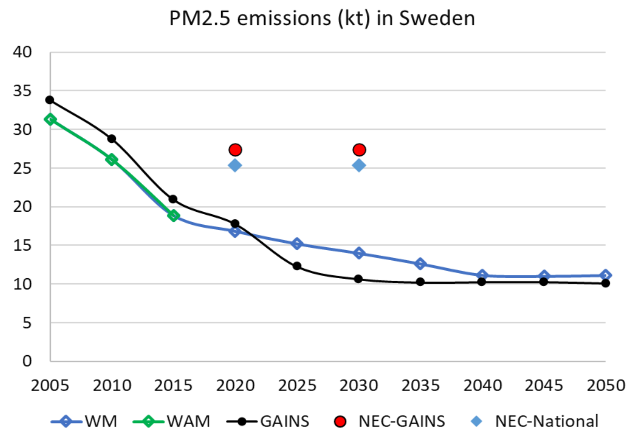

VOC emissions (kt) in Spain
700
600
500
400
300
200
100
0
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
WM
WAM
GAINS
NEC-GAINS
NEC-National

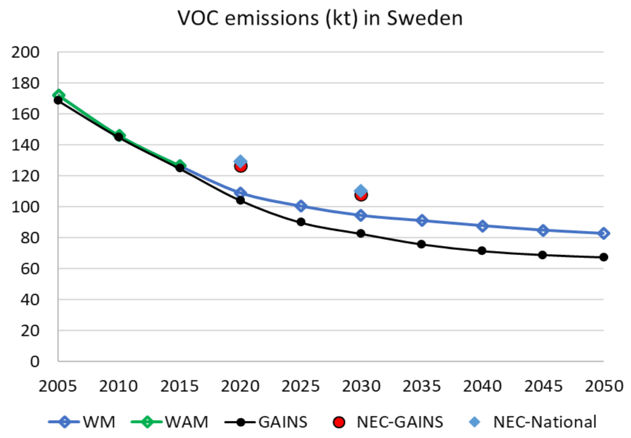
SWEDEN


SO2 emissions (kt) in Sweden


NOx emissions (kt) in Sweden


NH3 emissions (kt) in Sweden


PM2.5 emissions (kt) in Sweden


VOC emissions (kt) in Sweden

A4. Additional results for policy and sensitivity scenarios

A4.1 Health impact indicators

This section provides results for further indicators for exposure to $PM_{2.5}$ and overall results for $PM_{2.5}$, ozone, and NO_2 for scenarios analysed in the project.

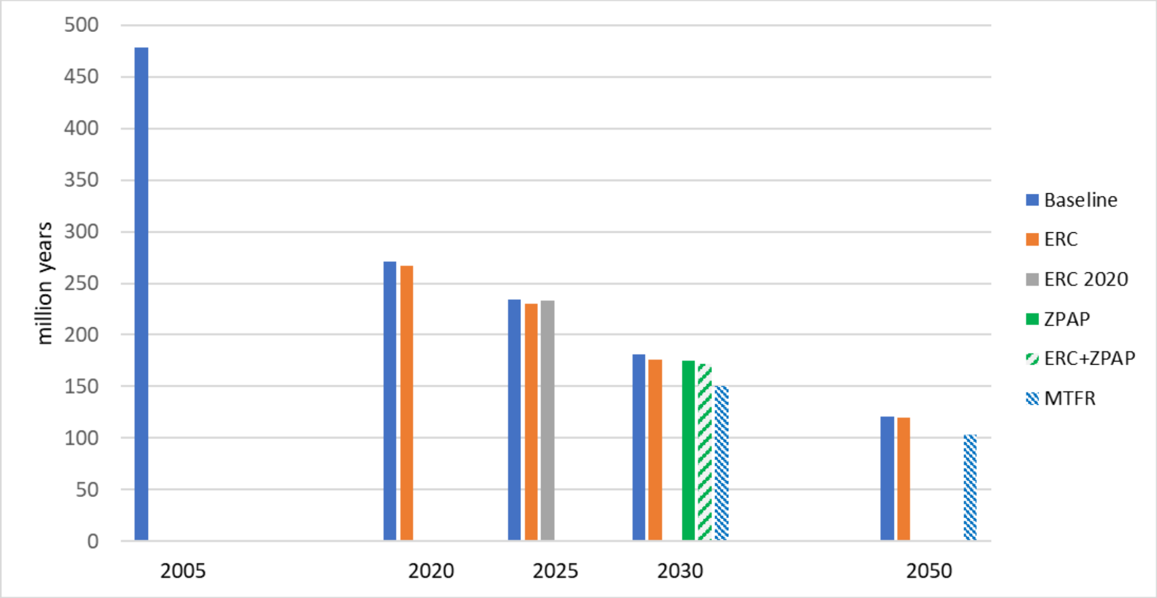
Section A4.1.1 presents other indicators related to mortality from $PM_{2.5}$ which were presented in earlier CAOs but not included in the main text of CAO4, like loss of life expectancy and years of life lost. Section A4.1.2 presents results for premature mortality from $PM_{2.5}$ concentrations above the WHO Air Quality Guideline of 5 μgm^{-3} (WHO 2021). This indicator has been used in the Impact Assessment to the AAQD, and also in CAO3 as a sensitivity case. Section A4.1.3 presents results for mortality related to NO_2 exposure above the WHO AQG of 10 μgm^{-3}.

A4.1.1 Other indicators for $PM_{2.5}$ related impacts

The main report provides mean population exposure and premature mortality. Further indicators of exposure to $PM_{2.5}$ shown here include loss of life expectancy, YOLLs and YLLs.

Years of Life Lost (YOLLs) attributable to the exposure to a given level of $PM_{2.5}$, in terms of the cumulative number of life years lost that occur over the remaining lifetime of the population living in 2010, assuming constant $PM_{2.5}$ concentrations – see Amann et al. (2011). This excludes population dynamics and is notably different from the annual YLL[52] estimates (in a particular year), which are most relevant for an economic assessment of the (annual) benefits of pollution control measures. YLLs are calculated as the sum of remaining life expectancy at age of death for all $PM_{2.5}$ attributable deaths in a given scenario year. Estimates of the annual YLLs that take into account the population dynamics in the various Member States are provided in the benefits assessment sections of the report.

Figure 8-92: Years of life lost (YOLLs) attributable to the exposure to anthropogenic $PM_{2.5}$ in the EU.



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[52] Years of life lost (YLL) due to premature deaths in one particular year

Table 8-28: Years of life lost (YOLLs) attributable to the total exposure to PM$_{2.5}$ in the EU; million years lost using constant 2010 population data, for all analysed scenarios.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	478.6		339.4	271.0	234.2	181.5		134.2		121.0
ERC				266.6	230.0	175.8				119.4
ERC 2020					233.4					
ZPAP						174.5				
ERC+ZPAP						172.0				
MTFR						150.5		110.2		102.9

Figure 8-93: Years of life lost (YLL), attributable to the exposure to total PM$_{2.5}$, in a specific year in the EU.

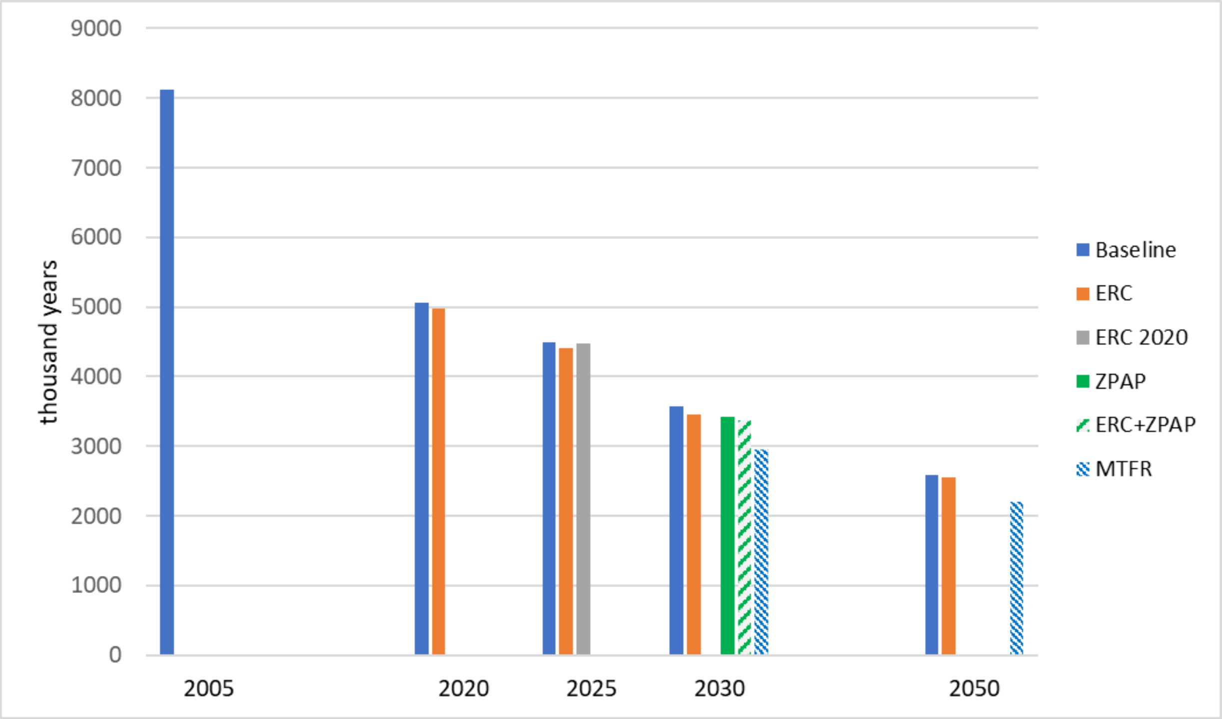


Table 8-29: Years of life lost (YLLs), attributable to the total exposure to PM$_{2.5}$, in a specific year in the EU for all analysed scenarios; [thousand years/year].

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	8117		6160	5055	4486	3568		2759		2593
ERC				4972	4406	3452				2560
ERC 2020					4471					
ZPAP						3429				
ERC+ZPAP						3377				
MTFR						2957		2264		2204

Figure 8-94: Loss in statistical life expectancy, attributable to the exposure to total $PM_{2.5}$ in the EU.

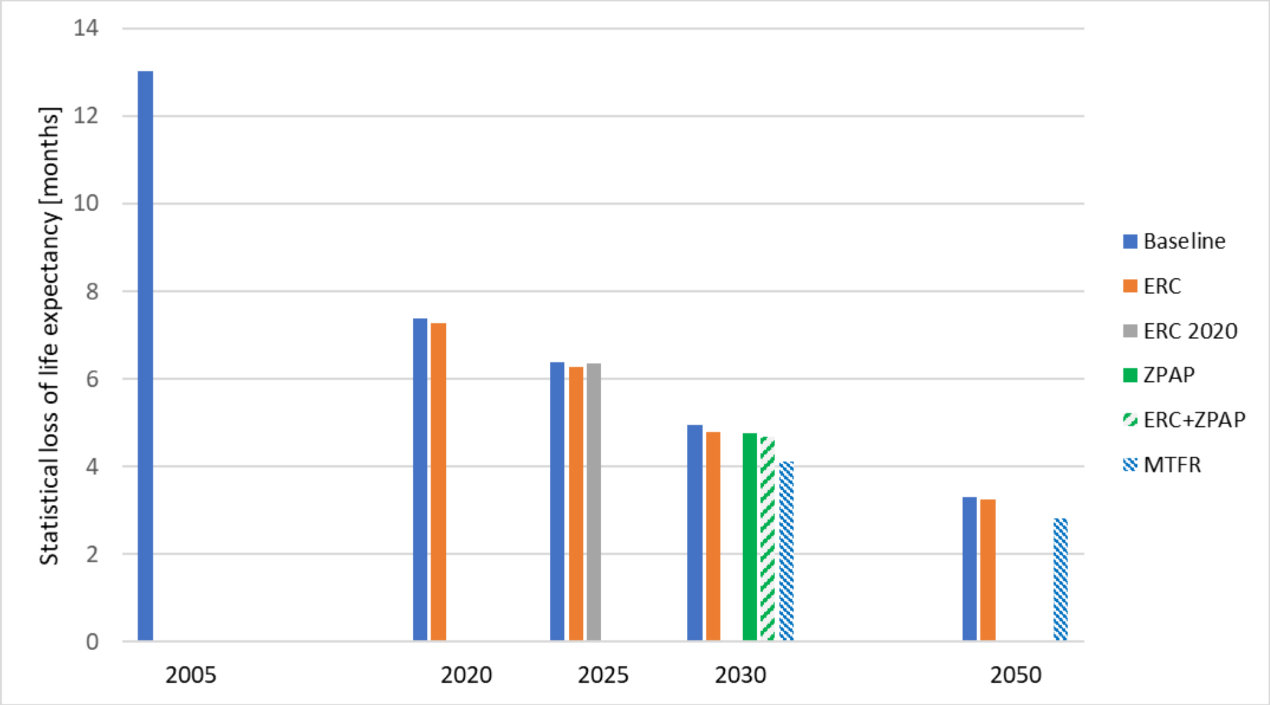


Table 8-30: Loss in statistical life expectancy, attributable to the exposure to total $PM_{2.5}$ in the EU [months].

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	13.0		9.2	7.4	6.4	4.9		3.7		3.3
ERC				7.3	6.3	4.8				3.3
ERC 2020					6.4					
ZPAP						4.8				
ERC+ZPAP						4.7				
MTFR						4.1		3.0		2.8

A4.1.2 Health impacts from PM$_{2.5}$ above WHO Air Quality Guidelines

The WHO Air Quality Guideline value for exposure to PM$_{2.5}$ is 5 µgm^{-3} (WHO 2021). Figure 8-95 and Table 8-31 summarize the estimates of premature mortality from PM$_{2.5}$ concentrations (including natural sources) above the WHO Guideline value, using static population assumptions (constant population in 2010). The comparison shows a decline in premature deaths of about 82 and 94%, related to 2005, across the scenarios (excluding MTFR) in 2030 and 2050. Not surprisingly, these reductions are larger than in case when no cut-off at PM$_{2.5}$ concentrations of 5 µgm^{-3} is considered (as shown in Section 4.4.3 in the main report).

Figure 8-95: Comparison of the cases of premature deaths attributable to the exposure to total PM$_{2.5}$ concentrations above 5 µg/m^{3} in the EU, for the analysed scenarios.

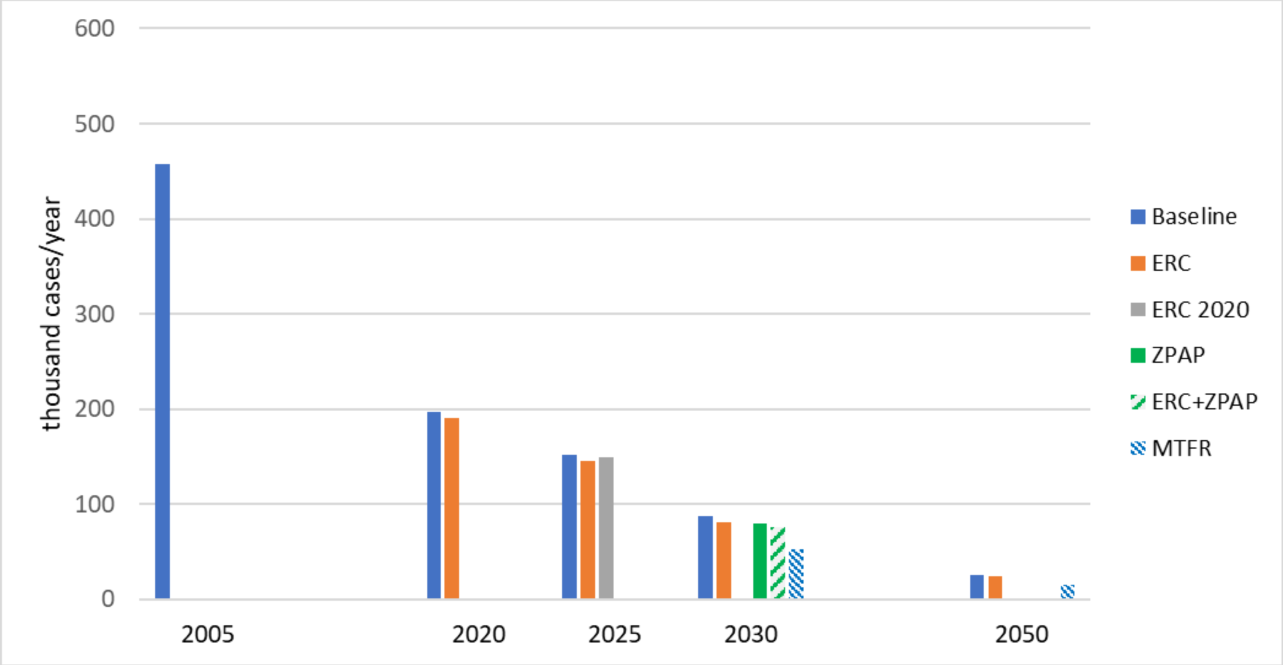


Table 8-31: Cases of premature death attributable to the exposure to total PM$_{2.5}$ above 5 µg/m^{3} in the EU; thousand cases per year, using constant 2010 population data.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	457		282	197	152	88		37		26
ERC				191	146	81		35		25
ERC 2020					150					
ZPAP						80				
ERC+ZPAP						77				
MTFR						52		19		16

Taking into account all sources of PM$_{2.5}$ (including natural sources), population-weighted exposure in the EU, considering a cut-off of 5 µgm^{-3}, is expected to decline in the *Baseline* and policy scenarios to levels below 1 µgm^{-3} in the long term, i.e., by 2050 (Table 8-32). For several EU Member States (nearly half of them) such exposure declines to levels below 0.2 µgm^{-3} or is at 0 µgm^{-3}.

Table 8-32: Population-weighted $PM_{2.5}$ concentrations in the EU; µg/m^3, including all sources but considering a cut-off of 5 µg/m^3.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	13.63		8.32	5.71	4.38	2.61		1.07		0.78
ERC				5.55	4.22	2.32		1.01		0.74
ERC 2020					4.33					
ZPAP						2.28				
ERC+ZPAP						2.20				
MTFR						1.50		0.56		0.48

A4.1.3 Health impacts from NO_2 above WHO Air Quality Guidelines

The WHO Guideline value for long-term exposure to NO_2 is 10 µgm^{-3}. This is the lower limit at which current evidence exists for health impacts of NO_2. As discussed in the main report, the expected trends in NOx emissions will strongly decrease ambient NO_2 concentrations and bring large shares of the EU population below this threshold. In the main report, calculated impacts consider the full range of NO_2 concentrations without a cut-off. As an alternative approach and consistent with calculations in CAO3, this section presents results for premature mortality considering a cut-off at 10 µgm^{-3}.

Population-weighted mean concentrations above 10 µgm^{-3} are shown in Table 8-33. In 2040 and 2050, these drop to very low values already in the Baseline and even more in the MTFR. Correspondingly, premature deaths attributable to NO_2 above this cut-off decrease to 1500 cases in 2050 in the Baseline, and 1100 cases in the MTFR (Table 8-34, Figure 8-96).

Table 8-33: Population-weighted NO_2 concentrations in the EU; µg/m^3, including all sources but considering a cut-off of 10 µg/m^3.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	15.6		10.6	6.3	4.5	2.2		0.3		0.2
ERC				6.1	4.4	2.1				0.2
ERC 2020					4.5					
ZPAP						1.8				
ERC+ZPAP						1.8				
MTFR						1.4		0.2		0.1

Figure 8-96: Comparison of the cases of premature deaths attributable to the exposure to NO$_2$ concentrations above 10 µg/m^3 (including all sources) in the EU, for the analysed scenarios.

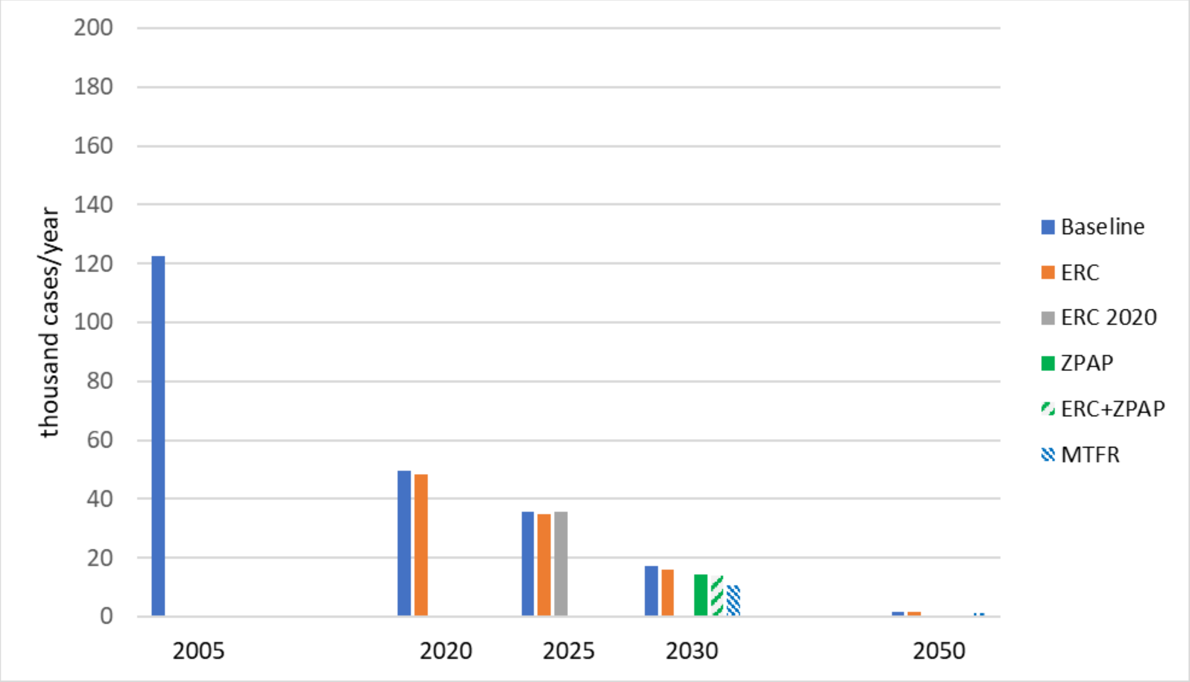


Table 8-34: Cases of premature death attributable to the exposure to NO$_2$ (all sources) above 10 µg/m^3 in the EU; thousand cases per year, using constant 2010 population data.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Baseline	122.5		83.3	49.5	35.7	17.2		2.7		1.5
ERC				48.5	34.7	16.0				1.5
ERC 2020					35.6					
ZPAP						14.2				
ERC+ZPAP						14.1				
MTFR						10.8		1.4		1.1

A4.2 Ecosystem impact indicators

Further indicators, not shown in the main report, are included in this section.

Figure 8-97: Nature2000 nature protection area in the EU with nitrogen exceeding critical loads for eutrophication. The marked 25% reduction of 2005 area with N deposition exceeding CLs refers to the ZPAP target for all ecosystems – for comparison only.

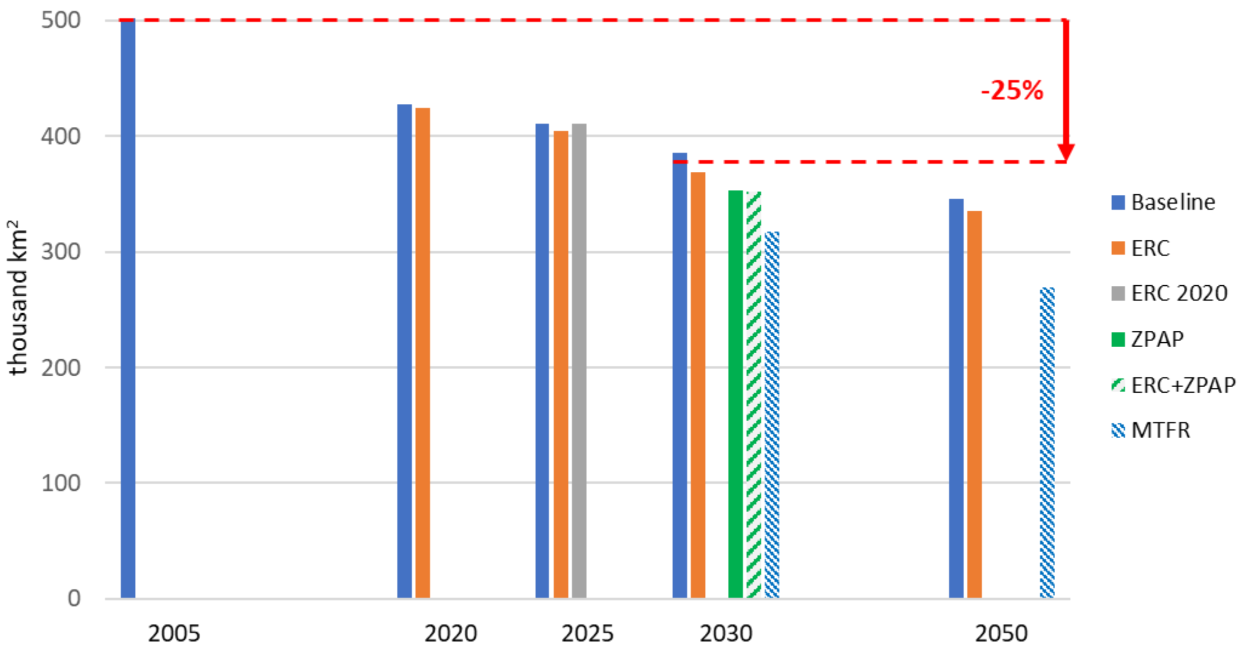


Table 8-35: Nature2000 nature protection areas with nitrogen deposition exceeding CLs for eutrophication.

	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Nature2000 nature protection area with nitrogen deposition exceeding critical loads for eutrophication (1000 km²)										
Baseline	502		468	428	411	386		357		346
ERC				425	405	369				335
ERC 2020					411					
ZPAP						353				
ERC+ZPAP						352				
MTFR						318		278		269
Nature2000 nature protection area with nitrogen deposition exceeding CLs for eutrophication (% of total Nature2000 areas)										
Baseline	78.0		72.6	66.4	63.8	59.9		55.4		53.7
ERC				65.9	62.8	57.3				52.0
ERC 2020					63.7					
ZPAP						54.8				
ERC+ZPAP						54.7				
MTFR						49.3		43.1		41.7

A4.3 Analysis of measures to achieve ERCs

While the estimated non-compliance with ERCs appears most severe for ammonia, several Member States are estimated to be in non-compliance for a number of other NECD air pollutant species in the 2030 Baseline scenario. That was illustrated in the analysis of compliance in the main report.

The analysis and discussion of measures to achieve the ZPAP objectives for ecosystems, necessitating mostly further reduction of emissions of ammonia, was shown in Section 5 of the main report. Here we illustrate the measures, shown as key sector-measure categories, for other pollutants.

Since the health ZPAP target is met, there is no need for additional mitigation of PM precursors in the ZPAP case. However, we observe emission reduction in the ZPAP also for $PM_{2.5}$, NMVOC, NOx; these are co-benefits of mitigation needed for NH_3 or NOx to achieve the ZPAP objectives for ecosystems. However, in case of the ERC scenario, there are several countries where additional mitigation would be required to achieve the ERCs by 2030. This is mostly the case for $PM_{2.5}$, NOx, and in few cases also NMVOC, not for SO_2. The results of the analysis, where the compliance with the ERCs for all pollutants is required simultaneously, shows that even for SO_2 there is some (very small) additional mitigation, however, this is a co benefit of measures needed to reduce $PM_{2.5}$, i.e., curbing emissions from open burning of agricultural residue – in fact forbidden by law, but according to remote sensing data it still takes place in many Member States.

A dedicated set of measures to reduce emissions from residential combustion (driven by need of bringing down $PM_{2.5}$ emissions) causes also reductions of NMVOC, which is helping to achieve the needed reductions for that pollutant and taking pressure off more typical NMVOC source sectors like solvent use.

Figure 8-98: Distribution of further SO_2 reductions in the ERCs compliant and ZPAP scenario, compared to Baseline, in 2030.

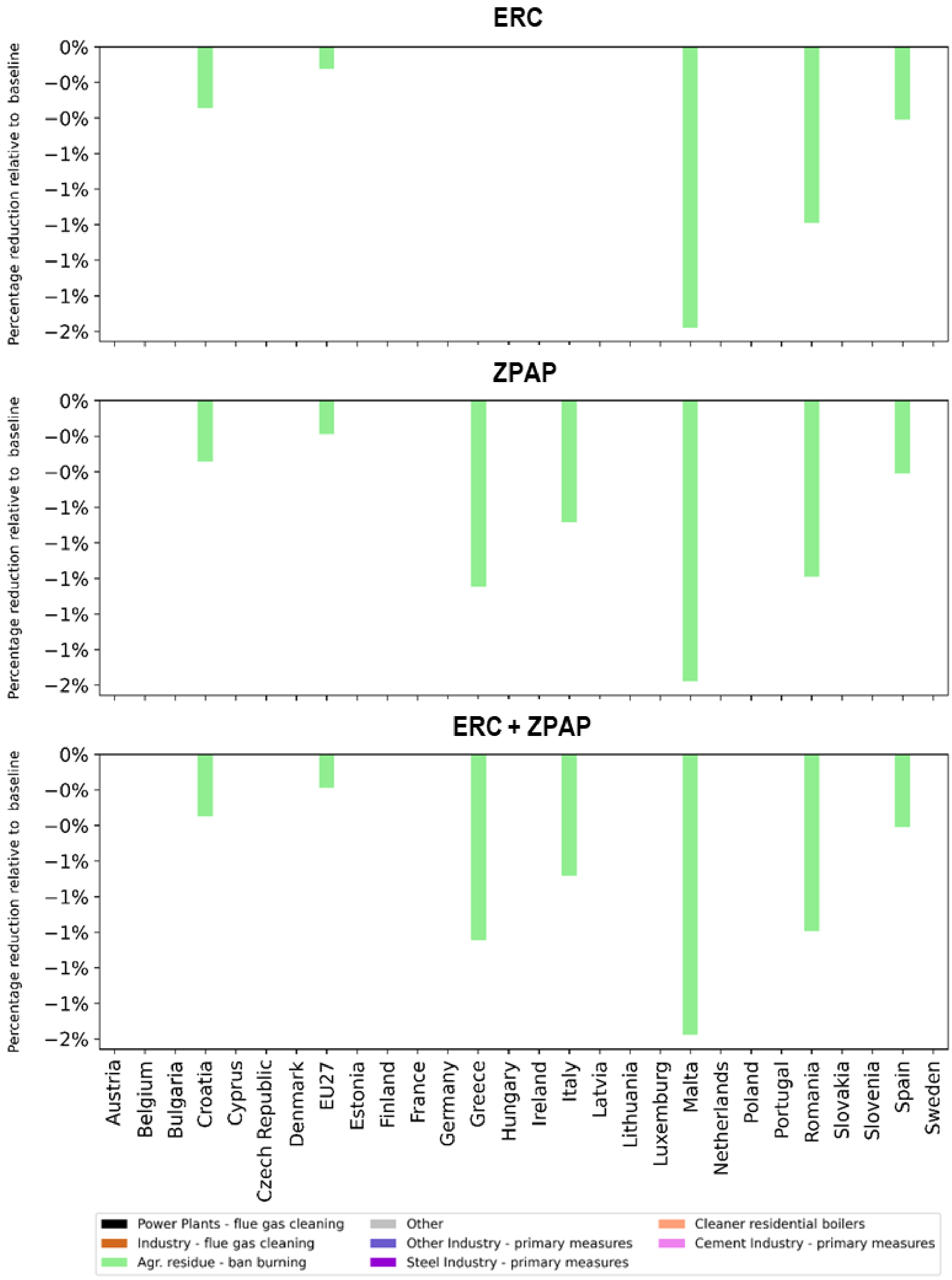


Figure 8-99: Distribution of further NOx reductions in the ERCs compliant and ZPAP scenario, compared to Baseline, in 2030.

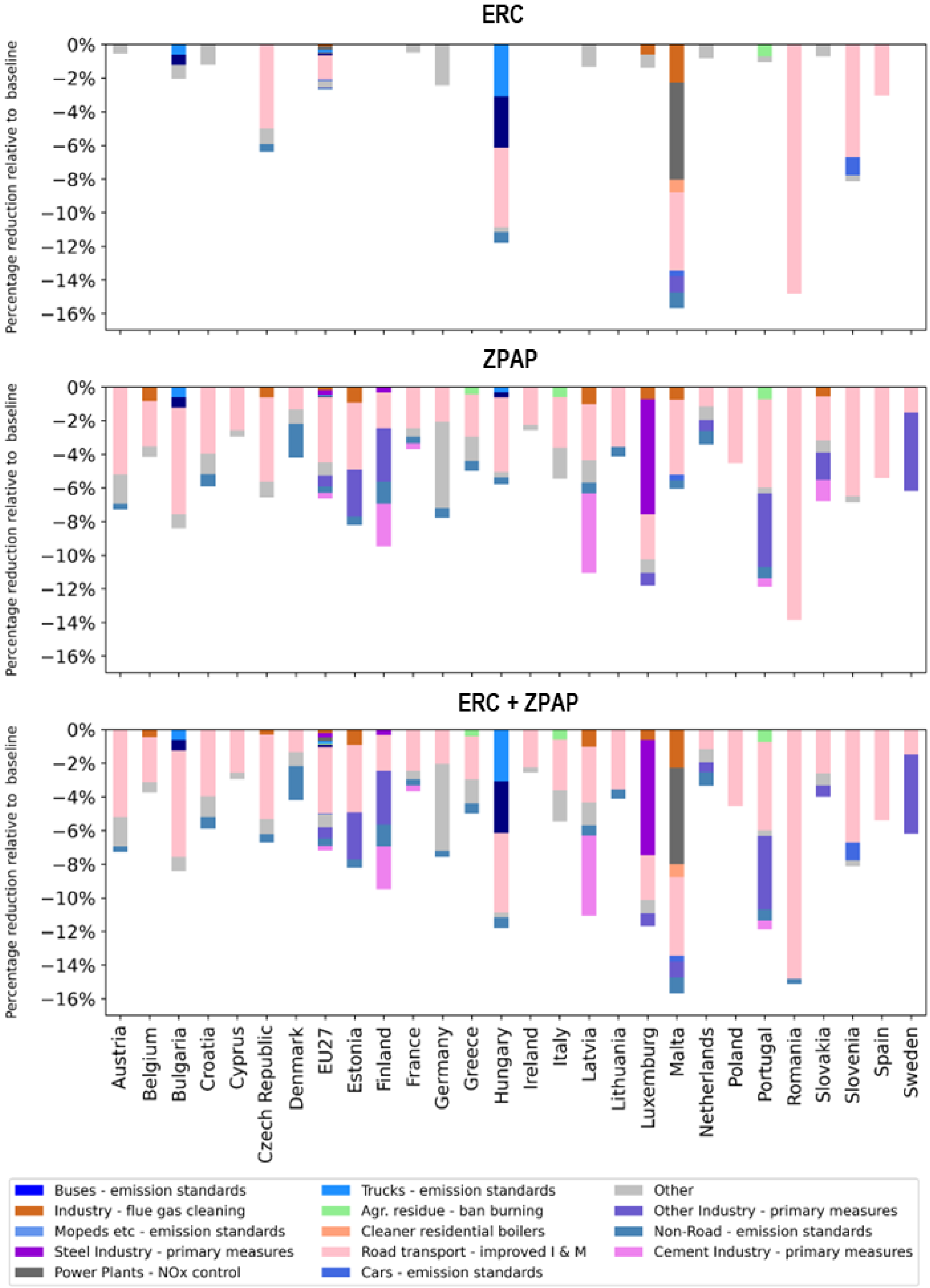
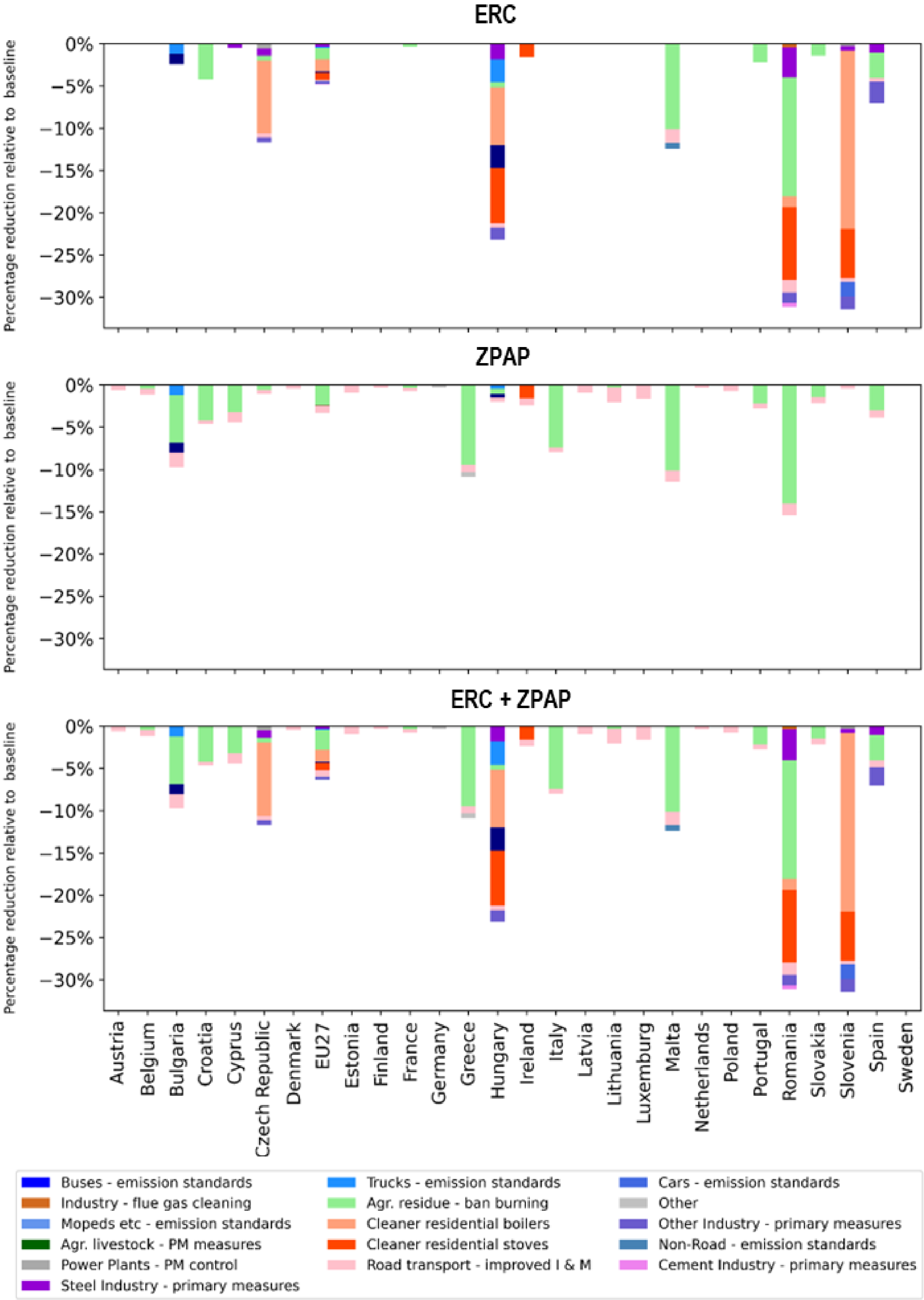


Figure 8-100: Distribution of further $PM_{2.5}$ reductions in the ERCs compliant and ZPAP scenario, compared to Baseline, in 2030.

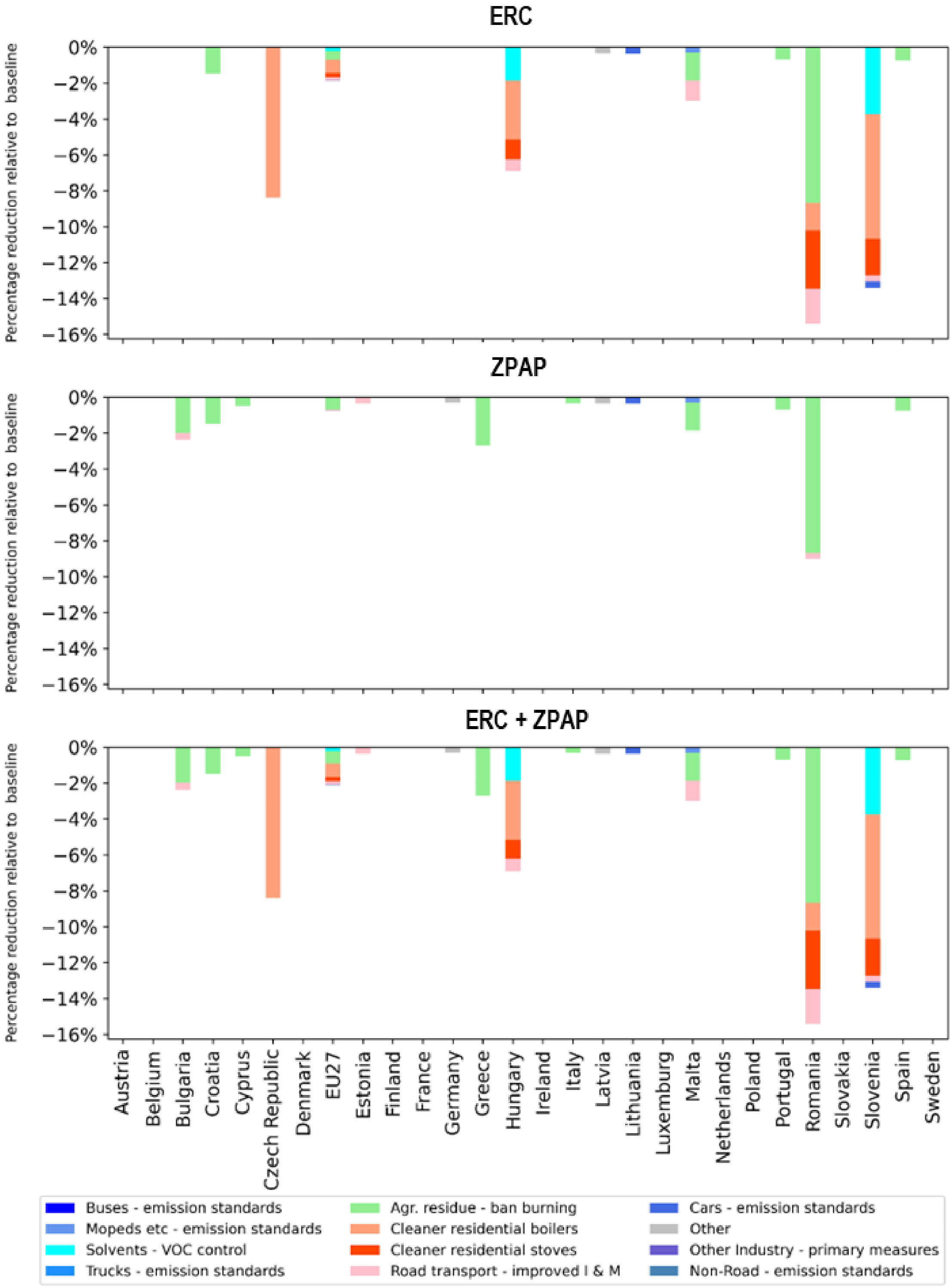


ERC

ZPAP

ERC + ZPAP

Figure 8-101: Distribution of further NMVOC reductions in the ERCs compliant and ZPAP scenario, compared to Baseline, in 2030.



A4.4 Sensitivity to condensable PM

This section presents more detailed information about the model setup and analysis performed to analyse the sensitivity of calculated PM concentrations on various assumptions about emission factors and volatility of condensable PM.

The physics and chemistry of organic aerosols are complex and cannot be described in detail here. Briefly, primary organic aerosol (POA) emissions are classified in broad classes as either non-volatile (NV – these are simply treated as inert compounds in the model), semi-volatile (SV, in which a fraction of the emissions are allowed to evaporate to form VOC, though these may be oxidised back to the aerosol in downwind chemical reactions), and with both semi- and intermediate-volatility compounds (SIV, where as well as allowing evaporation of organic PM emissions, we also assume an additional source of organic aerosol caused by associated intermediate-volatility VOC compounds. For further explanation, see Denier van der Gon (2015) and Simpson et al. (2020; 2022).

While the GAINS model with its linear approximation of the EMEP model can analyse the effect of different total amounts of emissions, analysis of different assumptions on volatility can only be done using a full chemistry-transport model with a detailed formulation of condensation and re-evaporation processes. The impact of the different assumptions on ambient concentrations was therefore assessed with the EMEP model at a 0.3° × 0.2° resolution using the techniques and datasets discussed in Simpson et al. (2022).

A4.4.1 Model setup

The model setup, emission scenarios, and some acronyms are summarized in Table 8-36: Model setup, acronyms and emission scenarios. Table 8-36. Briefly, the setup used here follows closely that use in the NMR report of Simpson et al., 2022. In general, the model treatment of emissions follows the standard EMEP procedures for all sources, except for primary organic aerosol (POA) from residential combustion sector. Following Simpson et al. (2022), POA emissions are assumed to consist of two fractions: FPOA is the so-called filterable fraction, and CPOA is the condensable fraction.

$$\mathrm{POA} = \mathrm{FPOA} + \mathrm{CPOA}$$

Emissions of both FPOA and CPOA were provided by IIASA/TNO. FPOA emissions are always treated as non-volatile and inert. CPOA emissions (here only from residential combustion sector) are treated as either non-volatile (NV), semi-volatile (SV) or in the most complex ‘SIV’ case as semi-volatile but with additional emissions of intermediate volatility VOC (IVOC). IIASA/TNO also provided emission factors for both a central (C) emission factor estimate and a high (H) emission factor estimate. Thus, the emission scenarios presented in Table 8-36 combine these different CPOA modelling approaches with the central or high emission factor estimates. For example, scenario SV-C uses the SV semi-volatile assumption for CPOA, and the central emission factor estimates.

All runs use a 0.3° x 0.2° degree longitude/latitude resolution, and simulations are for the year 2019, using (unless otherwise stated) emissions from the year 2020. In comparison with measurements, we use the standard OC emissions from the EMEP network, using sites with altitudes less than 500 m.

Table 8-36: Model setup, acronyms and emission scenarios.

EMEP model	rv5.4, with MARS thermodynamics
Emissions	Provided by IIASA, Sep 2024, for inorganics and PM components. Fine fraction OC and OM provided for filterable, central estimate, and high estimate emission factors (EFs). Last updated for Swiss OC emissions 13/9/2024.
Evaluation software	AeroTools (MET Norway)
POA	Primary organic aerosol
FPOA	Primary filterable (non-volatile) organic aerosol
CPOA	condensable fraction of POA
Emission scenarios	
NV-F	Only includes filterable POA (FPOA)
NV-C	All CPOA emissions as nonvolatile, C=Central (typical) emissions.
NC-H	As NVC, but with high CPOA emissions
SV-C	As NVC, but with semivolatile fine-mode OA from GNFR C, which are allowed to evaporate (using 1.5D VBS).
SIV-C	As SVC, but with added intermediate volatility compounds from GNFR C

A4.4.2 Time-series comparison

We first present time-series comparisons as it is easier to visualize the overall impact of the various scenarios. Figure 4-22 shows the model agreement with OC (in $PM_{2.5}$) measurements, averaged across all sites, for the three non-volatile runs, NV-F, NV-C and NV-H. Of these three runs, only the central estimate, NV-C, shows a satisfactory agreement with the observations. This is expected since the NV-F cases omits the known CPOA contributions, and the NV-H case assumes both high emission factors and that CPOA are involatile.

Note that in the main report the NV-F is referred to as '*Ref2_Filter*', NV-C as '*GAINS_EF*', and NV-H as '*High_C*' to keep the consistency with the definitions of emission factors sets and sensitivity scenarios analyzed (see Table 4.1 in section 4.3 in the main report).

Figure 8-102: All-site comparison of modelled OC (in $PM_{2.5}$) versus observations, 2019, non-volatile tests (see above for model scenarios; the '32' refers to the model resolution used, 0.3×0.2 degrees).

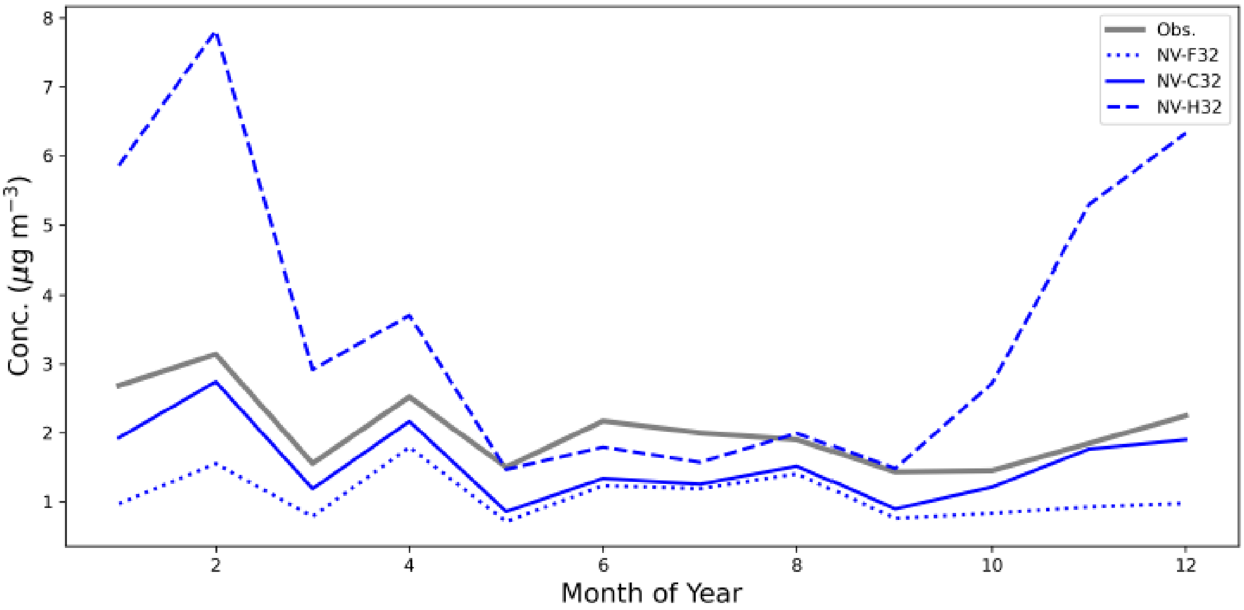


Figure 8-103 presents results from most of the model runs compared with observed OC (in $PM_{2.5}$). Here we see that both the SV-C and SV-H runs, which assume semi-volatile CPOA, still underestimate the observed OC. The central SIV-C case is also underpredicting OC in all months. However, the SIV-H case matches the observed OC at least as well as the NV-C case.

Figure 8-103: All-site comparison of modelled OC (in $PM_{2.5}$) versus observations, 2019, NV, SV and SIV tests.

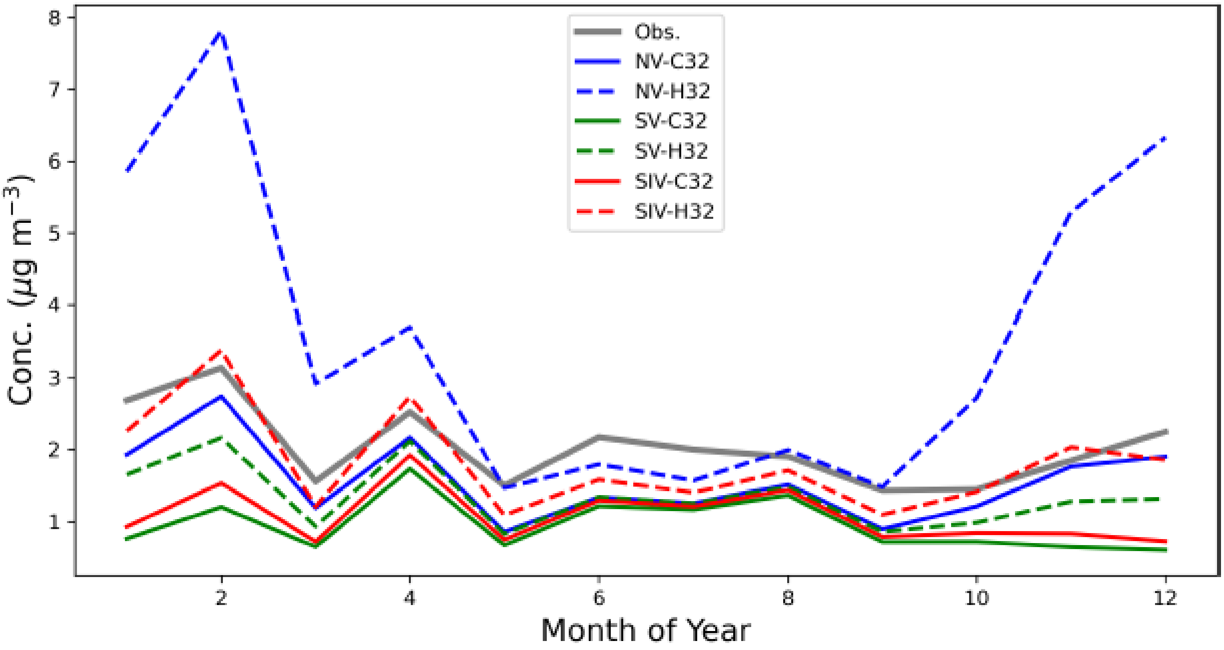
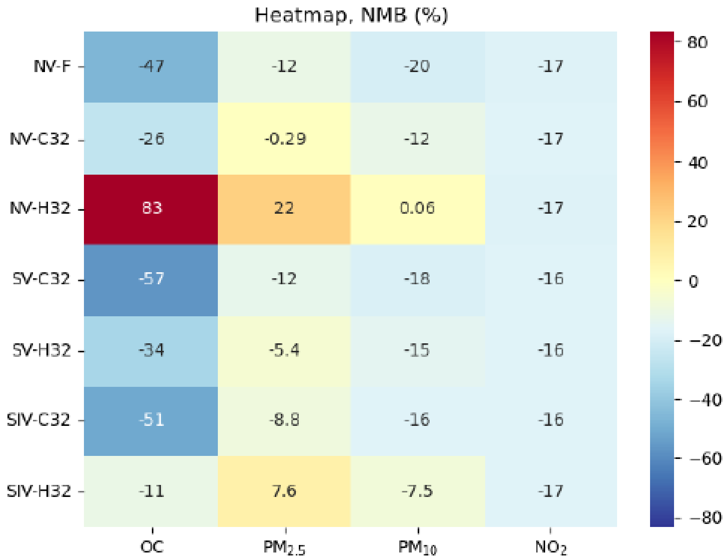


Figure 8-104 to Figure 8-106 present some statistics from these comparisons (note that although $PM_{2.5}$ and PM_{10} ae shown, we only discuss OC here). In terms of normalised mean bias (Figure 8-104) the SIV-H run has lowest NMB (-11%) for OC. The NV-C case shows next best agreement for OC, with -26%. In terms of spatial correlation (Figure 8-105), the SIV-H case is again best (Rspace=0.88), though the NV-H and SV-H cases also show high correlations (0.84, 0.86, respestively). The NV-C case has a lower Rspace, 0.75, though this is still rather good for such a complex pollutant. Finally, Figure 8-106 shows the median temporal correlations. Again, SIV-H provides the best result for OC (Rtemp=0.78), but NV-C has very similar value, 0.75.

For comparison we can mention that NO_2 shows an NMB of -16%, Rspace = 0.80, and Rtemp=0.63. Thus, even though OC modelling is far more uncertain in terms of emissions estimation and chemical processing, the results shown here for OC are comparable in many respects.

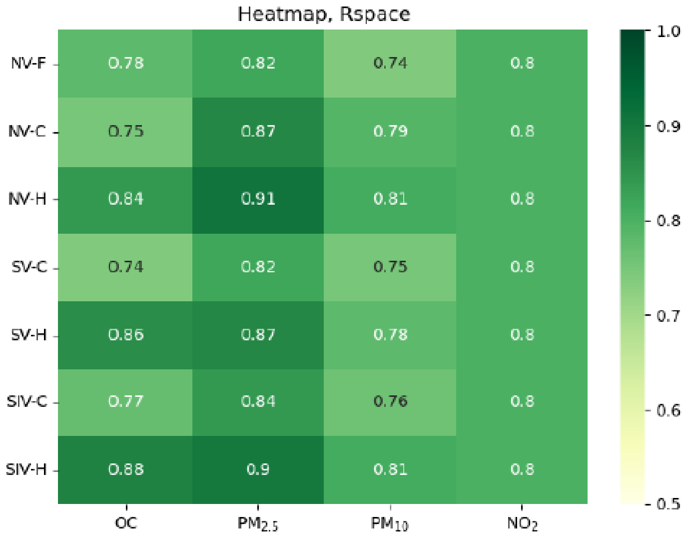
Figure 8-104: Normalized mean bias (NMB, %), all sites, 2019 (from monthly data).



	OC	$PM_{2.5}$	PM_{10}	NO_2
NV-F	-47	-12	-20	-17
NV-C32	-26	-0.29	-12	-17
NV-H32	83	22	0.06	-17
SV-C32	-57	-12	-18	-16
SV-H32	-34	-5.4	-15	-16
SIV-C32	-51	-8.8	-16	-16
SIV-H32	-11	7.6	-7.5	-17

C

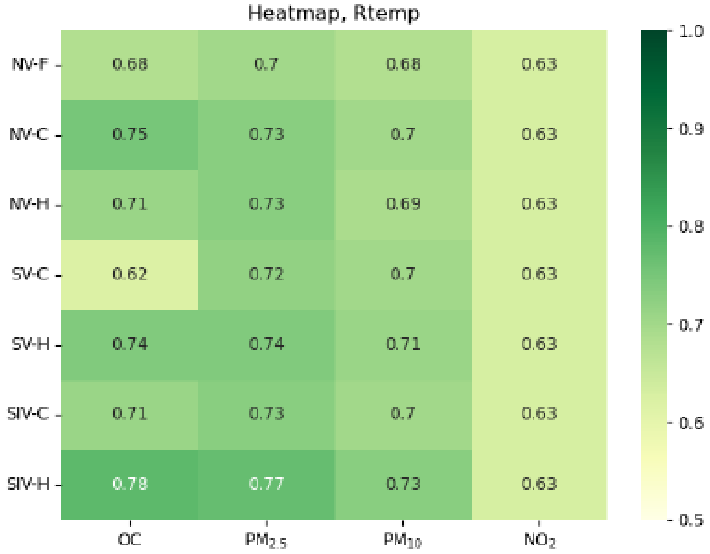
Figure 8-105: Mean spatial correlation (Rspace), all sites, 2019 (from monthly data). (Note: R-values from 0.5 to 1.0.)



	OC	$PM_{2.5}$	PM_{10}	NO_2
NV-F	0.78	0.82	0.74	0.8
NV-C	0.75	0.87	0.79	0.8
NV-H	0.84	0.91	0.81	0.8
SV-C	0.74	0.82	0.75	0.8
SV-H	0.86	0.87	0.78	0.8
SIV-C	0.77	0.84	0.76	0.8
SIV-H	0.88	0.9	0.81	0.8

C

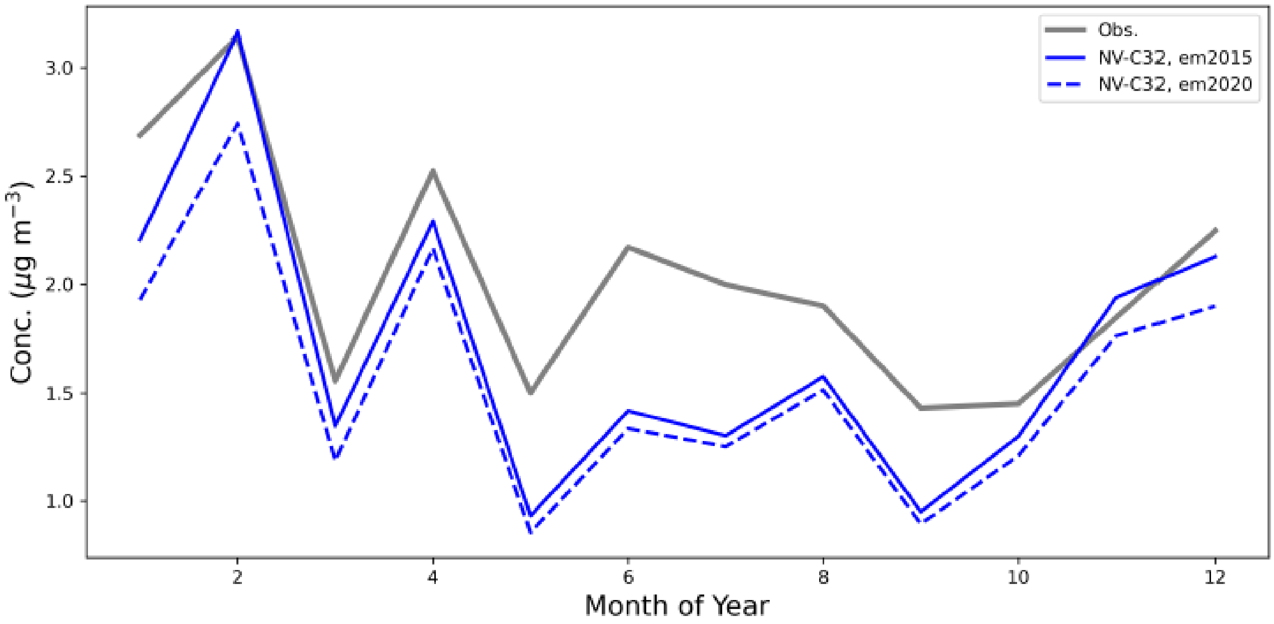
Figure 8-106: Median temporal correlation (Rtemp), all sites, 2019 (from daily data). (Note: R-values from 0.5 to 1.0.)



	OC	$PM_{2.5}$	PM_{10}	NO_2
NV-F	0.68	0.7	0.68	0.63
NV-C	0.75	0.73	0.7	0.63
NV-H	0.71	0.73	0.69	0.63
SV-C	0.62	0.72	0.7	0.63
SV-H	0.74	0.74	0.71	0.63
SIV-C	0.71	0.73	0.7	0.63
SIV-H	0.78	0.77	0.73	0.63

C

Figure 8-107: All-site comparison of NV-C modelled OC (in PM2.5) versus observations, 2019, 2015 emissions vs 2020 emissions



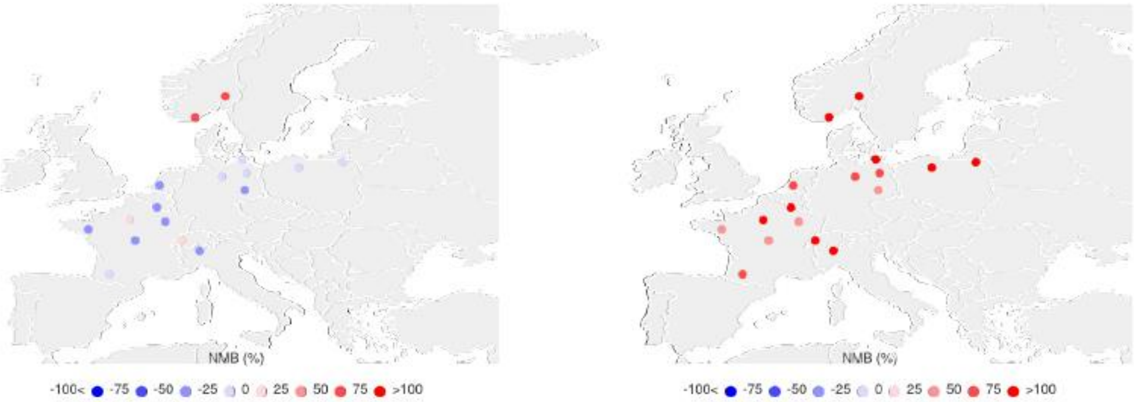
Finally with regard to these time-series, we can mention that the year 2019 was chosen as a focus of the modelling since the number of OC measurements was satisfactory, and we wished to avoid the COVID year 2020. The emissions provided were for either 2015 or 2020, and in general we have used the 2020 emissions (we assume COVID impact on residential sector was minor) as the best estimate for the 2019 case. However, the model runs have proven rather insensitive to this choice. As illustrated in Figure 8-107 the modelled OC is rather similar whether we use the 2015 or 2019 emissions. Further model runs were also made for 2018 and

2020, but again these did not change the basic conclusions from this work, so we have restricted this note to the 2019 simulations.

A4.4.3 Comparison across sites

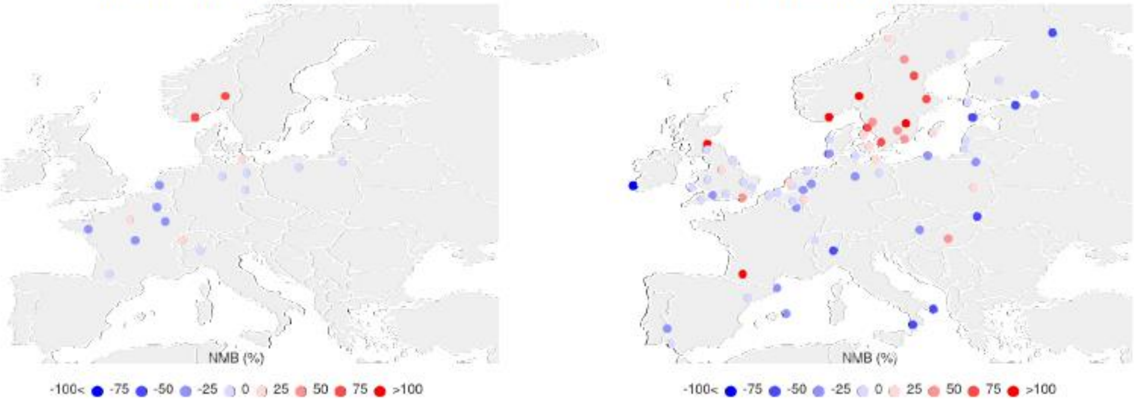
The time-series plots and statistics shown above offer a concise summary of the model results, but it is also important to be aware of the large site-to-site differences. Figure 8-108 shows the normalised mean bias (NMB) for OC in $PM_{2.5}$ at the available OC sites using the NV-C, NV-H and SIV-H runs. NO_2 is also shown for comparison. By default, the EMEP model uses the NV-C treatment of POA emissions, and Figure 8-108(a) shows that this leads to some underestimation of OC in continental Europe, but substantial overestimates at two sites in Norway. The NV-H scenario generates too much OC at all sites (Figure 8-108(b)), and the SIV-H scenario gives results which look rather similar to those of NV-C. The NO_2 (Figure 8-108(d)) is provided to show that there can be issues with particular regions (e.g. Norway) even for other pollutants whose emissions and chemistry are far better known than that of POA, so we should not try to over-interpret differences in POA emission factors and/or POA chemical schemes.

Figure 8-108: EMEP results for OC in $PM_{2.5}$ with NV-C, NV-H and SIV-H runs, and NO_2, meteorological data for 2019 was used in simulations.



(a) OC, NVC

(b) OC, NVH



(c) OC, SIVH

(d) NO_2

A4.4.4 Discussion

The above results show that OC modelling is very sensitive to the emission factors used, and to the assumptions concerning volatility used in the modelling. Of the schemes tested, the SIV-H combination (semi- and intermediate volatility scheme) seemed to give the best results, but this scheme has some highly uncertain assumptions concerning the volatility of SVOC, the amount and character of the IVOC, and the atmospheric processing (e.g. aging) assumed for the CPOA and IVOC compounds. (We can also note that the CPOA schemes used were designed for residential wood burning. In areas where GNFR C is dominated by, e.g. coal burning, it is very unclear which CPOA scheme should be used.)

Although the default NV-C scheme was not quite as good as the SIV-H setup, the results were rather similar to those of SIV-H and to observations in any case (sometimes matching observed OC better than for NO_2). Although we know that the assumption that CPOA is non-volatile is incorrect, it is also the simplest assumption we can make, and both the model results presented here, and other studies (see Simpson et al, 2022, for refs) confirm that such an approach generates OC levels consistent with much more complex approaches.

Thus, for EMEP regional scale modelling the non-volatile approach with central emission factors still seems to represent the best approach. For finer-scale modelling (e.g. uEMEP) the impacts of volatility (initial evaporation) would be stronger, so these issues would need further consideration.

A5. Additional results for the costs of air pollution and the benefits of air pollution reduction

Results presented below include additional information, including results by Member States, that are not included in the CAO4 main report.

A5.1 Health damage

The value of health impacts under the CAO4 *Baseline* for each country from 2005 to 2050 are shown in Table 8-37 to, Table 8-40 accounting for sensitivities in mortality valuation (VLY and VSL) and the inclusion of NO_2 effects where there is potential for double counting. Tier 3 morbidity effects (mostly dementia, but also diabetes) are included only in the last row of the table. Table 8-41 and Table 8-42 then provide a breakdown of impact numbers and monetised value respectively for each effect at the EU27 level for the CAO4 *Baseline*.

Table 8-37: Health impacts (mortality and morbidity) under the CAO4 Baseline by Member State, 2005-2050, €million (2015) per year. Mortality valued using the VOLY and all NO_2 functions included. Tier 3 morbidity only included in last row.

	2005	2020	2025	2030	2040	2050
Austria	17,182	10,453	7,891	5,814	4,171	3,628
Belgium	28,640	14,859	12,077	9,656	7,028	6,293
Bulgaria	25,099	13,893	10,317	7,411	4,517	3,478
Croatia	12,225	6,860	4,846	3,232	2,012	1,566
Cyprus	998	875	830	791	762	745
Czech Republic	25,647	17,155	12,954	9,339	5,791	4,538
Denmark	8,095	4,361	3,724	3,197	2,447	2,154
Estonia	1,812	1,053	861	671	454	387
Finland	4,275	2,495	2,111	1,814	1,475	1,314
France	122,396	67,396	56,800	45,568	32,536	29,288
Germany	162,922	92,695	74,745	58,155	41,417	36,022
Greece	37,673	18,735	13,665	10,786	7,797	6,888
Hungary	27,155	17,292	12,926	9,954	6,124	4,739
Ireland	3,991	2,490	2,260	1,916	1,583	1,542
Italy	158,535	91,150	73,357	54,588	40,362	34,982
Latvia	5,139	2,313	1,551	1,134	702	550
Lithuania	5,706	3,104	2,307	1,724	1,083	872
Luxembourg	965	546	485	407	320	310
Malta	692	622	596	622	695	736
Netherlands	41,196	21,975	18,604	15,355	11,685	10,355
Poland	99,228	73,528	50,796	33,921	18,655	15,219
Portugal	16,547	9,574	8,297	6,758	5,360	4,825
Romania	64,380	38,550	28,766	22,331	13,769	9,916
Slovakia	12,684	7,275	5,478	3,957	2,619	2,092
Slovenia	5,343	3,176	2,712	2,167	1,385	978
Spain	81,363	51,617	41,390	33,287	27,706	26,844
Sweden	7,974	5,282	4,308	3,729	3,289	3,214
Totals	**977,862**	**579,322**	**454,652**	**348,284**	**245,746**	**213,476**
Total with Tier 3 morbidity	**1,268,005**	**790,303**	**656,072**	**531,220**	**410,631**	**373,530**

Table 8-38: Health impacts (mortality and morbidity) under the CAO4 Baseline by Member State, 2005-2050, €million (2015) per year. Mortality valued using the VSL and all NO_2 functions included. Tier 3 morbidity only included in last row.

	2005	2020	2025	2030	2040	2050
Austria	46,587	33,223	23,973	18,325	14,084	13,710
Belgium	81,433	50,581	37,061	30,231	23,767	23,060
Bulgaria	76,946	53,939	38,442	28,488	18,140	14,214
Croatia	34,729	24,570	17,413	12,196	8,392	6,916
Cyprus	2,184	2,001	1,854	1,896	2,120	2,308
Czech Republic	69,021	55,205	39,441	30,506	20,834	16,633
Denmark	23,937	13,218	11,458	10,500	8,755	8,055
Estonia	5,956	3,715	3,204	2,547	1,758	1,570
Finland	12,121	8,274	7,249	6,583	5,986	5,469
France	329,223	221,817	180,582	150,296	117,933	114,933
Germany	477,713	333,716	265,159	208,428	149,651	142,590
Greece	100,604	70,298	50,985	41,615	32,357	31,980
Hungary	82,714	60,423	45,644	35,819	23,006	18,073
Ireland	8,709	5,686	5,351	4,864	4,597	5,103
Italy	468,247	351,815	257,911	202,494	162,554	157,369
Latvia	15,912	8,555	6,171	4,639	3,024	2,542
Lithuania	16,320	11,706	8,694	6,651	4,518	4,075
Luxembourg	2,290	1,334	1,094	943	817	917
Malta	1,672	1,607	1,504	1,654	2,041	2,248
Netherlands	104,097	68,185	54,351	47,823	41,214	39,449
Poland	230,889	228,394	156,823	112,583	71,536	63,030
Portugal	50,171	35,414	29,444	25,080	22,055	21,998
Romania	165,792	132,890	97,735	79,149	53,150	40,195
Slovakia	29,970	20,317	15,772	12,359	9,444	8,202
Slovenia	13,895	10,828	8,744	7,430	5,310	4,099
Spain	232,924	176,795	129,460	108,172	99,514	111,094
Sweden	25,690	16,527	12,638	11,366	10,570	10,397
Totals	**2,709,746**	**2,001,029**	**1,508,157**	**1,202,636**	**917,127**	**870,226**
Total with Tier 3 morbidity	**2,999,889**	**2,212,010**	**1,709,577**	**1,385,572**	**1,082,012**	**1,030,280**

Table 8-39: Health impacts (mortality and morbidity) under the CAO4 Baseline by country, 2005-2050, €million (2015) per year. Mortality valued using the VOLY with NO_2 functions excluded where there is potential for double counting. Tier 3 morbidity only included in last row.

	2005	2020	2025	2030	2040	2050
Austria	13,254	8,296	6,461	4,921	3,690	3,281
Belgium	22,064	11,314	9,418	7,769	6,009	5,506
Bulgaria	22,397	12,085	8,908	6,387	4,085	3,275
Croatia	11,191	6,296	4,455	2,954	1,851	1,447
Cyprus	947	838	798	760	733	715
Czech Republic	21,960	14,984	11,360	8,215	5,203	4,113
Denmark	6,396	3,570	3,108	2,683	2,137	1,918
Estonia	1,273	746	588	479	388	347
Finland	3,095	1,869	1,650	1,483	1,284	1,173
France	93,653	50,398	42,710	35,331	28,320	26,124
Germany	127,464	71,725	60,217	48,360	36,428	32,146
Greece	29,720	13,740	9,931	8,195	6,694	6,113
Hungary	23,287	15,015	11,289	8,737	5,512	4,296
Ireland	3,033	1,928	1,753	1,520	1,337	1,312
Italy	126,717	74,755	61,015	46,219	35,439	31,249
Latvia	4,540	1,981	1,330	973	629	501
Lithuania	4,909	2,592	1,951	1,488	979	801
Luxembourg	771	456	413	354	289	282
Malta	594	547	519	540	594	630
Netherlands	30,687	16,255	14,307	12,219	9,800	8,902
Poland	88,572	65,698	45,331	29,963	16,783	13,847
Portugal	12,553	7,647	6,700	5,665	4,752	4,308
Romania	58,510	34,514	25,452	19,859	12,520	9,131
Slovakia	11,211	6,511	4,860	3,531	2,397	1,927
Slovenia	4,435	2,551	2,208	1,811	1,248	896
Spain	58,616	38,158	31,665	26,703	23,876	23,571
Sweden	6,373	4,305	3,584	3,204	2,961	2,941
Totals	**788,221**	**468,774**	**371,981**	**290,323**	**215,939**	**190,751**
Total with Tier 3 morbidity	**1,078,364**	**679,755**	**573,401**	**473,259**	**380,824**	**350,805**

Table 8-40: Health impacts (mortality and morbidity) under the CAO4 Baseline by country, 2005-2050, €million (2015) per year. Mortality valued using the VSL with NO_2 functions excluded where there is potential for double counting. Tier 3 morbidity only included in last row.

	2005	2020	2025	2030	2040	2050
Austria	33,688	24,814	18,544	14,753	11,958	11,941
Belgium	58,753	36,142	27,146	22,964	19,389	19,310
Bulgaria	66,084	45,012	31,621	23,351	15,787	13,040
Croatia	30,844	21,930	15,545	10,806	7,485	6,188
Cyprus	2,040	1,893	1,762	1,799	2,011	2,180
Czech Republic	56,438	46,322	33,201	25,758	18,036	14,536
Denmark	17,965	10,342	9,148	8,419	7,352	6,916
Estonia	3,917	2,451	2,001	1,673	1,431	1,354
Finland	8,231	5,798	5,311	5,077	4,974	4,687
France	236,994	155,397	126,636	109,066	98,241	98,544
Germany	349,406	240,133	199,658	163,145	125,706	121,668
Greece	74,082	47,514	33,892	29,070	26,227	26,989
Hungary	67,944	50,465	38,257	30,200	19,992	15,818
Ireland	6,320	4,209	3,955	3,677	3,722	4,148
Italy	349,818	271,346	201,968	161,984	135,913	134,162
Latvia	13,607	7,050	5,062	3,804	2,613	2,233
Lithuania	13,558	9,354	6,998	5,483	3,940	3,622
Luxembourg	1,739	1,071	901	794	718	811
Malta	1,381	1,372	1,265	1,385	1,670	1,838
Netherlands	72,654	47,249	39,328	35,942	32,862	32,337
Poland	199,539	197,606	135,083	95,722	62,093	55,385
Portugal	35,708	26,656	22,364	19,911	18,740	18,807
Romania	146,332	115,249	83,176	67,762	46,728	35,844
Slovakia	25,639	17,669	13,528	10,665	8,388	7,334
Slovenia	10,929	8,193	6,701	5,872	4,609	3,630
Spain	155,833	121,445	92,135	81,335	81,492	92,813
Sweden	19,398	12,793	10,007	9,346	9,202	9,230
Totals	**2,058,841**	**1,529,474**	**1,165,193**	**949,764**	**771,278**	**745,366**
Total with Tier 3 morbidity	**2,348,984**	**1,740,455**	**1,366,613**	**1,132,699**	**936,163**	**905,421**

Table 8-41: Aggregated health impacts for the EU27 per year under the CAO4 Baseline Scenario, 2005-2050. Units: Thousand life years lost, cases, etc.

IMPACTS Note: results are in thousands	Poll.	Tier	Baseline 2005	Baseline 2020	Baseline 2025	Baseline 2030	Baseline 2040	Baseline 2050
Chronic Mortality (30yr +) deaths	O_3	1	74	83	69	68	69	72
Chronic Mortality (All ages) LYL	$PM_{2.5}$	1	6,328	3,680	2,801	2,149	1,555	1,345
Chronic Mortality (30yr +) deaths	$PM_{2.5}$	1	519	391	294	240	195	189
COPD (>30) cases	$PM_{2.5}$	1	386	254	230	191	155	144
Stroke (30+) cases	$PM_{2.5}$	1	189	123	110	90	71	65
IHD events (>30) cases	$PM_{2.5}$	1	374	241	215	175	136	124
Lung cancer (>30) cases	$PM_{2.5}$	1	69	45	40	33	26	24
Asthma (new incidence, 0-18) cases	$PM_{2.5}$	1	378	254	232	181	131	119
Chronic Mortality (All ages) LYL	NO_2	1	1,990	1,160	866	607	312	238
Chronic Mortality (30yr +) deaths	NO_2	1	180	131	95	70	40	35
Asthma in adults (19+) cases	NO_2	1	136	92	81	61	34	28
ALRI in children (0-12) cases	NO_2	1	44	28	24	17	9	7
Asthma in children (0-18) cases	NO_2	1	165	103	91	65	34	27
Respiratory hospital admissions (>64)	O_3	2	17	16	16	17	19	20
Cardiovascular hospital admissions (>64)	O_3	2	89	80	81	84	91	95
Infant Mortality (0-1yr) deaths	$PM_{2.5}$	2	1	0	0	0	0	0
Bronchitis in children aged 6 to 12 cases	$PM_{2.5}$	2	1,148	691	615	468	349	324
Respiratory Hospital Admissions (All ages)	$PM_{2.5}$	2	174	105	93	73	56	50
Cardiac Hospital Admissions All ages)	$PM_{2.5}$	2	191	114	100	78	58	52
Restricted Activity Days (all ages) days	$PM_{2.5}$	2	657,738	401,742	357,242	285,553	221,098	201,693
Lost working days (15-64 years) days	$PM_{2.5}$	2	179,075	105,432	91,944	71,627	52,598	46,290
Bronchitis in children aged 5 to 14 cases	NO_2	2	655	438	377	272	151	125
Respiratory Hospital Admissions (All ages)	NO_2	2	206	126	107	78	42	34
Type 2 diabetes (>30) cases	$PM_{2.5}$	3	199	128	115	93	73	68
Dementia (60+) cases	$PM_{2.5}$	3	584	425	406	369	333	324

Table 8-42: Value of health impacts for the EU27 per year under the CAO4 Baseline Scenario, 2005-2050. Figures in italics represent sensitivity cases. Units: €M per year.

IMPACTS	Poll.	Tier	Baseline 2005	Baseline 2020	Baseline 2025	Baseline 2030	Baseline 2040	Baseline 2050
Chronic Mortality (30yr +) VOLY	O_3	1	7,044	7,838	6,489	6,415	6,496	6,827
Chronic Mortality (All ages) VOLY	$PM_{2.5}$	1	598,976	348,374	265,182	203,438	147,194	127,280
Chronic Mortality (30yr +) VSL	$PM_{2.5}$	1	1,869,596	1,409,074	1,058,394	862,879	702,533	681,896
COPD (>30)	$PM_{2.5}$	1	24,649	16,212	14,687	12,158	9,862	9,179
Stroke (30+)	$PM_{2.5}$	1	18,547	12,074	10,823	8,847	6,953	6,360
IHD events (>30)	$PM_{2.5}$	1	12,556	8,081	7,230	5,877	4,579	4,173
Lung cancer (>30)	$PM_{2.5}$	1	2,045	1,334	1,202	987	788	729
Asthma (new incidence, 0-18)	$PM_{2.5}$	1	2,620	1,758	1,609	1,250	905	823
Chronic Mortality (All ages) VOLY	NO_2	1	188,419	109,788	82,021	57,492	29,552	22,520
Chronic Mortality (30yr +) VSL	NO_2	1	649,683	470,796	342,314	252,403	145,594	124,654
Asthma in adults (19+)	NO_2	1	940	639	562	424	238	191
ALRI in children (0-12)	NO_2	1	22	14	12	8	4	4
Asthma in children (0-18)	NO_2	1	1,144	714	628	448	232	186
Respiratory hospital admissions (>64)	O_3	2	82	76	78	82	92	98
Cardiovascular hospital admissions (>64)	O_3	2	524	471	478	495	534	562
Infant Mortality (0-1yr) VSL	$PM_{2.5}$	2	3,925	1,511	1,327	849	442	263
Bronchitis in children aged 6 to 12	$PM_{2.5}$	2	411	247	220	168	125	116
Respiratory Hospital Admissions (All ages)	$PM_{2.5}$	2	834	504	444	352	267	242
Cardiac Hospital Admissions All ages)	$PM_{2.5}$	2	1,127	672	589	463	344	307
Restricted Activity Days (all ages)	$PM_{2.5}$	2	86,164	52,628	46,799	37,407	28,964	26,422
Lost working days (15-64 years)	$PM_{2.5}$	2	27,757	16,342	14,251	11,102	8,153	7,175
Bronchitis in children aged 5 to 14	NO_2	2	234	157	135	97	54	45
Respiratory Hospital Admissions (All ages)	NO_2	2	988	603	515	372	201	161
Type 2 diabetes (>30)	$PM_{2.5}$	3	4,221	2,719	2,429	1,962	1,548	1,432
Dementia (60+)	$PM_{2.5}$	3	285,922	208,262	198,991	180,973	163,336	158,622

Note: mortality values are not additive where VOLY and VSL values are provided for the same age group for any pollutant.

Table 8-43 shows the effects of changing response functions for morbidity between CAO3 and CAO4. Without adding in the Tier 3 effects, dementia and to a lesser extent, $PM_{2.5}$ diabetes, the changes largely cancel each other out with costs for the effects listed in the region of €30 billion/year. However, adding dementia increases impacts by a factor 6. Further research will be needed to assess the reliability of these functions. Results underline the value of further research.

Table 8-43: Value of morbidity health impacts for the EU27 per year under the CAO3 and CAO4 Baseline Scenario, 2030, where response functions have changed between CAO3 and CAO4 reflecting new evidence. Units: €M per year.

Damage, MEuro/year		CAO3	CAO4
Minor Restricted Activity Days (MRADs all ages)	O_3	3,834	-
COPD (>30)	$PM_{2.5}$	9,537	12,158
Stroke (30+)	$PM_{2.5}$	10,528	8,847
IHD events (>30)	$PM_{2.5}$	2,095	5,877
Lung cancer (>30)	$PM_{2.5}$	676	987
Asthma (new incidence, 0-18)	$PM_{2.5}$	26	1,250
Asthma symptom days (children 5-19yr)	$PM_{2.5}$	284	-
Asthma in adults (19+)	NO_2	1,054	424
ALRI in children (0-12)	NO_2	-	8
Asthma in children (0-18)	NO_2	-	448
Type 2 diabetes (>30)	NO_2	1,119	-
Stroke (40-89)	NO_2	4,022	
Total for the effects above		**33,176**	**30,001**
Dementia (60+)	$PM_{2.5}$	-	180,973
Type 2 diabetes (>30)	$PM_{2.5}$	585	1,962
Total with Dementia and diabetes		**33,761**	**212,936**

Note: “-“ identifies cases where a pollutant-effect pair was not quantified.

A5.2 Economic value of non-health impacts

Damage to materials, crops, forests and ecosystems under the *Baseline* scenario is shown in Table 8-44 to Table 8-48. For forests there is a step change in damage from 2030 to 2040. This is not an indication of change in harm to forests per se but is linked to a step change in the valuation of carbon sequestration according to the DG MOVE Handbook on the External Costs of Transport (CE Delft et al. 2020).

Table 8-44: Value of the damage to materials under the CAO4 Baseline by country, 2005-2050, €million (2015) per year.

	2005	2020	2025	2030	2040	2050
Austria	60.63	30.85	22.36	15.93	11.37	9.11
Belgium	128.31	31.56	29.44	25.49	18.98	17.43
Bulgaria	286.85	31.61	31.99	21.68	11.34	9.62
Croatia	29.10	7.12	5.93	4.73	3.57	3.12
Cyprus	15.26	5.44	1.27	1.10	0.85	0.79
Czech Republic	194.31	73.00	57.03	38.30	19.46	16.09
Denmark	28.89	12.49	10.45	9.44	7.19	6.16
Estonia	11.39	2.17	1.19	0.78	0.49	0.43
Finland	22.84	12.29	9.58	7.40	5.12	4.26
France	306.29	102.91	91.25	72.62	47.93	41.26
Germany	484.18	261.90	229.57	162.01	99.92	86.59
Greece	100.01	19.02	11.36	9.22	6.37	5.41
Hungary	72.18	38.27	30.47	25.16	17.57	14.69
Ireland	15.06	5.25	4.54	3.54	2.57	2.33
Italy	176.77	57.99	50.56	38.05	26.38	21.53
Latvia	4.36	2.76	2.28	1.98	1.55	1.35
Lithuania	13.53	8.34	6.63	5.29	3.38	2.74
Luxembourg	9.59	2.29	1.86	1.42	1.02	0.89
Malta	5.33	0.37	0.39	0.29	0.21	0.11
Netherlands	87.77	33.06	27.26	20.95	17.09	15.14
Poland	916.78	364.58	275.26	183.61	82.34	72.81
Portugal	14.18	3.76	2.87	2.27	1.53	1.26
Romania	370.00	71.54	62.53	56.40	33.82	28.66
Slovakia	77.42	20.95	20.78	15.22	11.67	10.37
Slovenia	27.28	6.57	5.13	4.29	2.05	1.62
Spain	108.23	20.27	15.62	12.21	9.01	8.23
Sweden	9.11	4.41	3.30	3.02	2.48	2.06
Totals	**3,576**	**1,231**	**1,011**	**742**	**445**	**384**

Table 8-45: Value of the damage to crops under the CAO4 Baseline by country, 2005-2050, €million (2015) per year.

	2005	2020	2025	2030	2040	2050
Austria	199	178	170	161	149	146
Belgium	202	205	205	204	198	197
Bulgaria	476	422	416	401	376	369
Croatia	184	160	154	146	135	132
Cyprus	7	6	6	6	6	6
Czech Republic	317	287	276	263	243	238
Denmark	191	181	179	176	170	169
Estonia	34	31	30	29	28	27
Finland	35	32	31	30	29	29
France	2,699	2,407	2,336	2,239	2,101	2,083
Germany	1,575	1,465	1,428	1,372	1,285	1,265
Greece	521	454	440	424	401	397
Hungary	665	590	570	544	502	491
Ireland	19	17	17	16	16	16
Italy	2,563	2,238	2,177	2,076	1,967	1,946
Latvia	97	89	87	84	80	79
Lithuania	230	212	208	200	189	187
Luxembourg	4	4	4	4	3	3
Malta	5	4	4	4	4	4
Netherlands	305	321	326	328	324	325
Poland	1,422	1,305	1,267	1,212	1,123	1,104
Portugal	247	221	214	206	198	199
Romania	1,405	1,270	1,253	1,211	1,143	1,125
Slovakia	154	136	131	124	113	111
Slovenia	27	23	22	21	19	19
Spain	1,692	1,499	1,448	1,391	1,341	1,347
Sweden	89	82	80	77	74	73
Totals	15,362	13,840	13,481	12,948	12,220	12,087

Table 8-46: Value of the damage to forest production and carbon sequestration under the CAO4 Baseline by country, 2005-2050, €million (2015) per year.

	2005	2020	2025	2030	2040	2050
Austria	1,026	945	916	880	1,897	1,864
Belgium	133	131	130	128	332	330
Bulgaria	529	490	486	475	1,154	1,141
Croatia	-	-	-	-	-	-
Cyprus	-	-	-	-	-	-
Czech Republic	687	644	629	608	1,344	1,322
Denmark	136	133	133	132	347	346
Estonia	252	236	233	227	585	579
Finland	1,529	1,422	1,398	1,364	3,120	3,110
France	3,043	2,781	2,723	2,642	6,059	6,031
Germany	3,515	3,385	3,340	3,258	7,525	7,444
Greece	100	89	87	85	204	202
Hungary	250	230	224	217	505	496
Ireland	69	67	66	65	172	174
Italy	1,103	977	955	918	2,223	2,201
Latvia	535	502	494	480	1,054	1,044
Lithuania	302	285	281	273	677	670
Luxembourg	18	19	19	19	42	42
Malta	-	-	-	-	-	-
Netherlands	53	58	59	60	148	149
Poland	1,867	1,759	1,727	1,678	3,965	3,921
Portugal	-	-	-	-	-	-
Romania	1,103	1,026	1,015	990	2,371	2,342
Slovakia	375	343	335	323	728	716
Slovenia	271	241	234	224	495	485
Spain	1,150	1,051	1,024	994	2,424	2,434
Sweden	2,064	1,954	1,927	1,888	4,134	4,112
Totals	20,109	18,768	18,435	17,927	41,504	41,156

Table 8-47: Lower bound estimate of the value of the damage to ecosystems under the CAO4 Baseline by country, 2005-2050, €million (2015) per year.

	2005	2020	2025	2030	2040	2050
Austria	118	82	71	52	37	32
Belgium	42	39	38	37	33	29
Bulgaria	254	221	219	211	193	188
Croatia	146	121	119	114	111	109
Cyprus	4	4	4	4	4	4
Czech Republic	85	68	59	46	29	22
Denmark	18	18	18	18	18	18
Estonia	39	27	26	25	24	23
Finland	51	31	21	11	4	2
France	955	758	719	648	571	548
Germany	221	188	180	167	150	143
Greece	237	237	237	237	237	237
Hungary	124	101	95	89	86	85
Ireland	-	-	-	-	-	-
Italy	324	223	208	185	172	164
Latvia	52	46	45	41	36	33
Lithuania	57	56	56	55	53	52
Luxembourg	4	4	4	4	4	4
Malta	0	0	0	0	0	0
Netherlands	27	23	23	22	21	21
Poland	438	366	342	313	259	249
Portugal	80	68	66	64	64	64
Romania	350	327	325	319	305	296
Slovakia	110	98	96	92	87	84
Slovenia	54	40	36	32	28	27
Spain	911	852	835	817	807	799
Sweden	84	74	71	70	65	61
Totals	**4,784**	**4,072**	**3,914**	**3,675**	**3,396**	**3,293**

Table 8-48: Upper bound estimate of the value of the damage to ecosystems under the CAO4 Baseline by country, 2005-2050, €million (2015) per year.

	2005	2020	2025	2030	2040	2050
Austria	353	245	214	157	110	97
Belgium	126	117	115	111	98	88
Bulgaria	762	664	656	634	580	563
Croatia	439	363	358	343	332	327
Cyprus	12	12	12	12	12	12
Czech Republic	254	204	177	139	88	67
Denmark	53	53	53	53	53	53
Estonia	116	82	79	75	72	70
Finland	154	92	64	33	12	7
France	2,865	2,275	2,156	1,944	1,713	1,643
Germany	663	563	539	500	449	430
Greece	711	711	711	711	710	710
Hungary	371	302	286	266	258	255
Ireland	-	-	-	-	-	-
Italy	972	669	624	554	515	492
Latvia	155	139	135	124	107	100
Lithuania	170	168	167	165	158	156
Luxembourg	13	13	13	13	12	12
Malta	0	0	0	0	0	0
Netherlands	80	69	68	66	64	62
Poland	1,315	1,099	1,026	939	778	746
Portugal	241	203	199	193	192	192
Romania	1,049	982	975	958	915	888
Slovakia	329	295	288	276	260	251
Slovenia	162	119	108	96	84	80
Spain	2,734	2,556	2,504	2,451	2,422	2,396
Sweden	253	222	213	210	195	183
Totals	**14,351**	**12,217**	**11,741**	**11,024**	**10,188**	**9,880**

A5.3 Health impacts of $PM_{2.5}$ and NO_2 above WHO Air Quality Guidelines

The WHO Air Quality Guidelines (WHO, 2021) represent concentrations above which there is greater confidence in impact quantification than below. Health impact quantification provided in the main report has considered the full range of concentrations. An alternative to this assumption is examined in this section. Health impacts for Tiers 1 and 2 are shown in Table 5-3. Results for materials, crops, forests and ecosystems remain as given above in Table 8-44 to Table 8-48. Health damage up to 2025 under the Baseline scenario is roughly half the estimates shown in the main text with no cut-off applied. Thereafter, the gap widens as increasing areas come under the cut-off point and contribute nothing to damage estimates.

Table 8-49: Economic value of health impacts linked to $PM_{2.5}$, NO_2 and O_3 by scenario accounting for sensitivity to the approach used for mortality valuation (VOLY, VSL), to the inclusion of NO_2 impacts and to use of the WHO Air Quality Guidelines as cut-off points for analysis. Units € million/year, 2015 prices. Excludes Tier 3 impacts.

	2020	2025	2030	2040	2050
Including all NO_2 functions					
Mortality valued using VOLY					
Baseline	310,143	213,584	120,105	48,694	35,943
ERC			111,757		
ZPAP			108,419		
ERC+ZPAP			105,134		
MTFR			75,526	29,335	25,529
Mortality valued using VSL					
Baseline	1,083,157	712,113	411,357	169,053	130,319
ERC			382,161		
ZPAP			369,272		
ERC+ZPAP			357,944		
MTFR			255,531	95,698	87,818
Including NO_2 functions only for adult asthma and child ALRI morbidity					
Mortality valued using VOLY					
Baseline	261,106	182,229	105,476	46,539	34,799
ERC			98,031		
ZPAP			96,291		
ERC+ZPAP			93,026		
MTFR			66,135	28,153	24,668
Mortality valued using VSL					
Baseline	869,654	580,095	346,516	158,026	123,585
ERC			321,324		
ZPAP			315,567		
ERC+ZPAP			304,339		
MTFR			214,102	89,678	82,754

Overall benefits covering health, crops, forest, materials and ecosystems for each scenario relative to the CAO4 Baseline in the appropriate year (2030 or 2050), when applying the cut-off concentrations, are shown in Table 8-50. VOLY- and VSL-based estimates for health benefit are combined with the Low and High estimates for ecosystems, respectively, so show the range of overall estimated benefits.

Table 8-50: Benefits from reduced $PM_{2.5}$, NO_2 and O_3 damage relative to the CAO4 Baseline for the EU27. Units: € million/year, 2015 prices. Tier 3 health effects excluded. WHO Air Quality Guidelines used as cut-off points for analysis.

	2030	2040	2050
Including all NO_2 functions			
Mortality valued using VOLY			
ERC	8,685		
ZPAP	12,289		
ERC+ZPAP	15,584		
MTFR	46,214	21,459	12,373
Mortality valued using VSL			
ERC	29,870		
ZPAP	43,319		
ERC+ZPAP	54,670		
MTFR	158,763	76,963	45,927
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	7,782		
ZPAP	9,787		
ERC+ZPAP	13,062		
MTFR	40,976	20,486	12,090
Mortality valued using VSL			
ERC	25,866		
ZPAP	32,182		
ERC+ZPAP	43,433		
MTFR	135,351	71,957	44,258

Results show that benefits by scenario increase in order from ERC_2030 to ZPAP, to ERC+ZPAP to MTFR. Going forward in time, the annual benefits of MTFR are reduced, largely reflecting action accounted for in the Baseline. Net benefits (benefits – costs) are shown in Table 5-10 and benefit-cost ratios (net benefits divided by net costs, taken from Table 5-2 in the main text) in Table 5-11. In all cases except MTFR in 2040 and 2050 with mortality valued with the VOLY, results demonstrate a strong excess of benefit over further control costs. Impacts of the use of the cut-off points are modest in 2030, indicating that the most populated parts of the EU will exceed the cut-off points at that time. Proportionally, impacts on the benefit:cost ratios through the application of the cut-off points increase over time, as the area subject to their exceedance shrinks and estimated benefits fall.

It is again stressed that care is needed in interpretation of the results for the MTFR scenarios as they could be interpreted as demonstrating a net benefit for all measures included for MTFR. In reality, some of the measures included in the cost curve will be cost-efficient whilst some others are extremely expensive per unit emission abated, and on their own may not generate a net benefit either across the EU27 or in all Member States. This is suggested by the decline in benefit-cost ratios when moving down through scenarios to the MTFR. More detailed analysis, involving a series of additional scenarios would be needed to test the costs and benefits of the increasingly less cost-effective measures towards the upper end of the cost curve.

Table 8-51: Net benefits from reduced $PM_{2.5}$, NO_2 and O_3 damage relative to the CAO4 Baseline for the EU27. Units: €M/year, 2015 prices. Tier 3 health effects excluded. WHO Air Quality Guidelines used as cut-off points for analysis.

	2030	2040	2050
Including all NO_2 functions			
Mortality valued using VOLY			
ERC	8,129		
ZPAP	11,890		
ERC+ZPAP	14,786		
MTFR	23,201	847	-7,522
Mortality valued using VSL			
ERC	29,314		
ZPAP	42,920		
ERC+ZPAP	53,872		
MTFR	135,751	56,352	26,033
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	7,225		
ZPAP	9,388		
ERC+ZPAP	12,264		
MTFR	17,963	-125	-7,805
Mortality valued using VSL			
ERC	25,310		
ZPAP	31,783		
ERC+ZPAP	42,635		
MTFR	112,338	51,345	24,363

Table 8-52: Benefit-cost ratios by scenario for the EU27. Tier 3 health effects excluded.

	2030	2040	2050
Including all NO_2 functions			
Mortality valued using VOLY			
ERC	16		
ZPAP	31		
ERC+ZPAP	20		
MTFR	2.0	1.0	0.6
Mortality valued using VSL			
ERC	54		
ZPAP	109		
ERC+ZPAP	69		
MTFR	6.9	3.7	2.3
Including NO_2 functions only for adult asthma and child ALRI morbidity			
Mortality valued using VOLY			
ERC	14		
ZPAP	25		
ERC+ZPAP	16		
MTFR	1.8	1.0	0.6
Mortality valued using VSL			
ERC	46		
ZPAP	81		
ERC+ZPAP	54		
MTFR	5.9	3.5	2.2

A6. Ad-hoc support to inform the review of the NEC Directive

Within this task, the team has undertaken further analysis and comparison of the results of this Service Request with the previous Clean Air Outlooks and as well as of Member States' reported air pollutant emissions for recent years. The aim is to provide additional insight to the role of policies and measures resulting from the implementation of the NEC Directive versus other (national or EU level) control policies.

This analysis provides an additional view on the impact of policies collectively that impact on emission factors (including NEC Directive, but also others such as source-specific legislation). It cannot fully isolate the effect of the NEC Directive alone.

The work addresses evaluation, and to the extent possible, disentangling of the (i) effectiveness, (ii) efficiency, and (iii) coherence of various EU and national policies introduced and analysed since the implementation of the NEC Directive.

Analysis of *effectiveness* addresses the question to what extent EU policies or external factors affected emissions of NECD pollutants. Addressing *efficiency* answers questions about costs and respective measures to implement NEC Directive, what are the costs and respective measures of implementing it, and whether other policies or factors have affected the costs of compliance. Finally, discussion of *coherence* addresses the question to what extent has the non-inclusion of CH_4 in the NEC Directive hampered reduction of methane emissions (from agriculture, waste, energy) at the EU and international level.

The initial analysis has been performed in the context of this service request and was shared with the Commission and the contractors of another service request supporting the evaluation of the NEC Directive[53]. The work will continue including further discussion and additional assessments to support the NEC review process under the evaluation-specific service request.

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[53] Service request 090202/2024/917478/SFRA/ENV.C.3 on supporting the evaluation of Directive (EU) 2016/2284 on the reduction of national emissions of certain atmospheric pollutants (NEC Directive)

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