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EUCALC

Explore sustainable European futures

EUCalc scenario impacts on air pollution and human health

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Short Description
This report describes how different pathways in EUCalc can lead to impacts in air pollution and human health. The methodology used to design the Air Pollution and Human Health module, and calculate the quantified and monetized impacts of air pollution on health is outlined. The report describes historical trends in air pollution in the EU, the overall calculation logic and scope, the sources and types of input data and validation data.

Quality check	
Name of reviewer	**Date**
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Statement of originality:

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation or both.

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List of abbreviations

BAU – Business as Usual

EEA – European Environment Agency

EU – European Union

EU-28 – The 28 EU Member States as of 1 July 2013

WP – Work Package

CBA – Cost-Benefit Analysis

IPA – Impact Pathway Approach

CRF – Concentration Response Function

RR – Relative Risk

YLL – Years of Life Lost

VSL – Value of a Statistical Life

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1 Introduction

Justification for change of title, scope and delivery date

As indicated in WP6, we used Stakeholder and expert engagement to identify the social impacts the model should calculate, based on a.o. conceptual and operational coherence, utility and reliable data availability. Health impacts were chosen as best option to include in the model (see Pashaei Kamali et.al. "How to find quantitative indicators for social impacts of climate change mitigation pathways in Europe: a two tier stakeholders' participation" Energy Research & Social Science (in revision)).

The resulting follow-up work included the securing of reliable data sets and designing an interface with the EUCalc model. For this we (TU Delft and Imperial College London) collaborated with IIASA. The final health impact assessments calculation takes as inputs the scenario outputs of the EUCalc model, hence the delivery date was dependent on a working core model. This is the reason for a slight delay in delivery (October instead of July 2019).

Air pollution can lead to a range of serious adverse outcomes. Epidemiologic studies have shown that there are a large number of adverse health effects associated with air pollution, particularly with particulate matter with a diameter less than 2.5 microns, called $PM_{2.5}$. Exposure to air pollution has both long-term and short-term effects. The long-term effect on health relates to premature mortality due to cardiopulmonary (heart and lung) effects. In the short-term, high pollution episodes can trigger increased admissions to hospital and contribute to the premature death of people who are more vulnerable to daily changes in levels of air pollutants.

The choice to include health impacts as a social impact to be shown in the decarbonisation transition pathways explorer was made during the first stakeholder workshop as requested by the stakeholder participants. This report describes how health risks of outdoor air pollution and its sources are estimated and how the module was constructed, which was reviewed in an expert meeting.

This human health assessment module aims to:

- Provide an objective and comparable estimate of the impacts of projected $PM_{2.5}$ air pollution between 2015 and 2050 across 28+1 EU countries in EUCalc;
- Provide input to the development and implementation of measures to improve air quality;
- Raise awareness of the harmful effects of pollution;

- Be an important tool for informing public policy decisions on linkages between options to decarbonise Europe and human health.

This document summaries the results of population exposure and mortality attributable to air pollution across 28+1 EU countries in 2015-2050 calculated by the EUCalc Air Pollution module. The main air pollutant considered in this module is $PM_{2.5}$, which includes primary $PM_{2.5}$ directly emitted from activities and the secondary $PM_{2.5}$ resulting from gaseous precursors: SO_2, NO_x, and NH_3. Sectoral contributions to population exposure are estimated in each model year, in each country, including buildings, agriculture, electricity, industry, transport, district heating and other sectors.

The IIASA GAINS model provided population-averaged $PM_{2.5}$ exposure factors, as described in the module methodology document. The population in each member state is modelled within EUCalc.

2 Trends and evolution of air pollution in Europe

This section gives an overview of the current trend of air pollution in Europe, mainly focusing on the emissions of main air pollutants (Section 2.1) and the attainment situation of regulations for $PM_{2.5}$ (Section 2.2). The main air pollutants reviewed in Section 2.1 include sulphur oxides (SO_x), nitrogen oxides (NO_x), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs) and primary fine particulate matter ($PM_{2.5}$). SO_2, NO_x, NH_3 and VOCs are key precursors for secondary PM.

2.1 Emissions of the main air pollutants

Total emissions of all main air pollutants (SO_x, NO_x, NH_3, NMVOCs and primary $PM_{2.5}$) have decreased since 1990. Compared with the baseline year ($PM_{2.5}$: 2000; others: 1990) in 2016 emissions in the EU-28 (European Environment Agency, 2018b) of:

- NO_x decreased by 58%;
- SO_x decreased by 91%;
- NMVOCs decreased by 62%;

- NH_3 decreased by 23%;
- and $PM_{2.5}$ decreased by 28%

While SO_x has the largest reduction, NH_3 has the smallest decrease with an approximately 3% increase in the agriculture sector in 2013-2016 (European Environment Agency, 2018a).

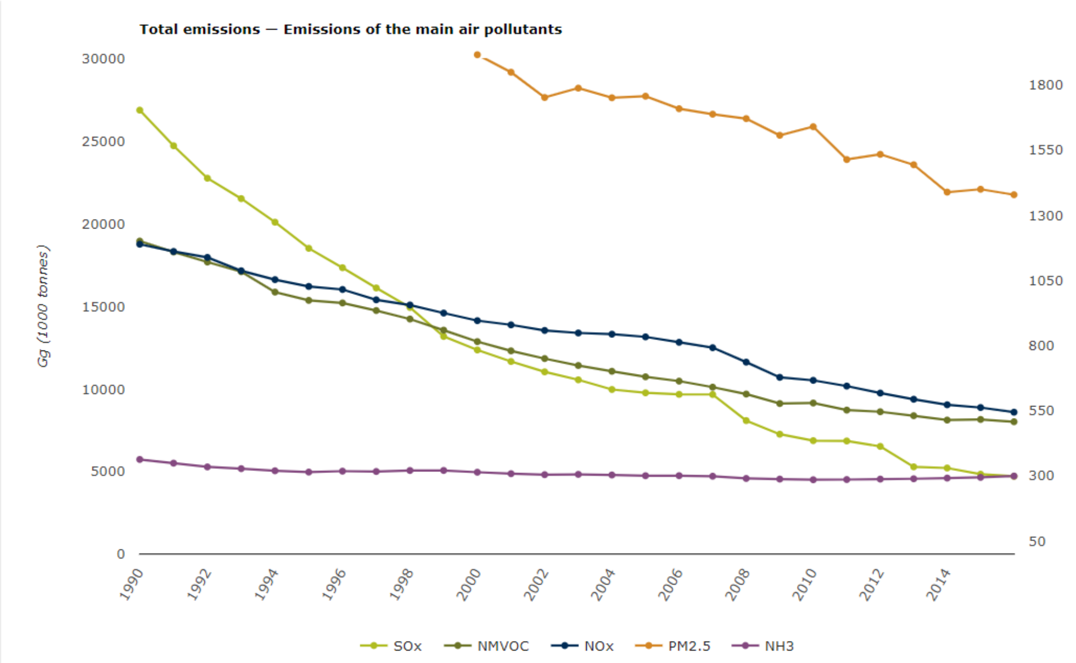


Figure 1: Emission trends of the air pollutants (sulphur oxides, nitrogen oxides, ammonia, non-methane volatile organic compounds and primary fine particulate matter) over the 1990 to 2016 period (2000 to 2016 for PM). PM2.5 emissions are shown on the secondary y-axis. (European Environment Agency, 2018b)

According to the EEA (2018a), air pollutant emissions in most of the main sectors have significantly decreased since 2000. Emissions from agriculture and waste were relatively steady. Emissions of PM_{10}, $PM_{2.5}$ and CO from the commercial, industrial and household sectors have increased.

A significant reduction in transport-related air pollutant emissions is evident in recent years, although there is an increase in transport activities. This is particularly due to the implementation of stricter regulations in vehicle emission standards and requirements in fuel quality. A similar trend has been seen in the industrial sectors. Relevant factors involve emission limits for combustion plants, regulations on stationary emission sources in the industry and energy sectors, and principles in permits and the control of installations (European Environment Agency, 2018a).

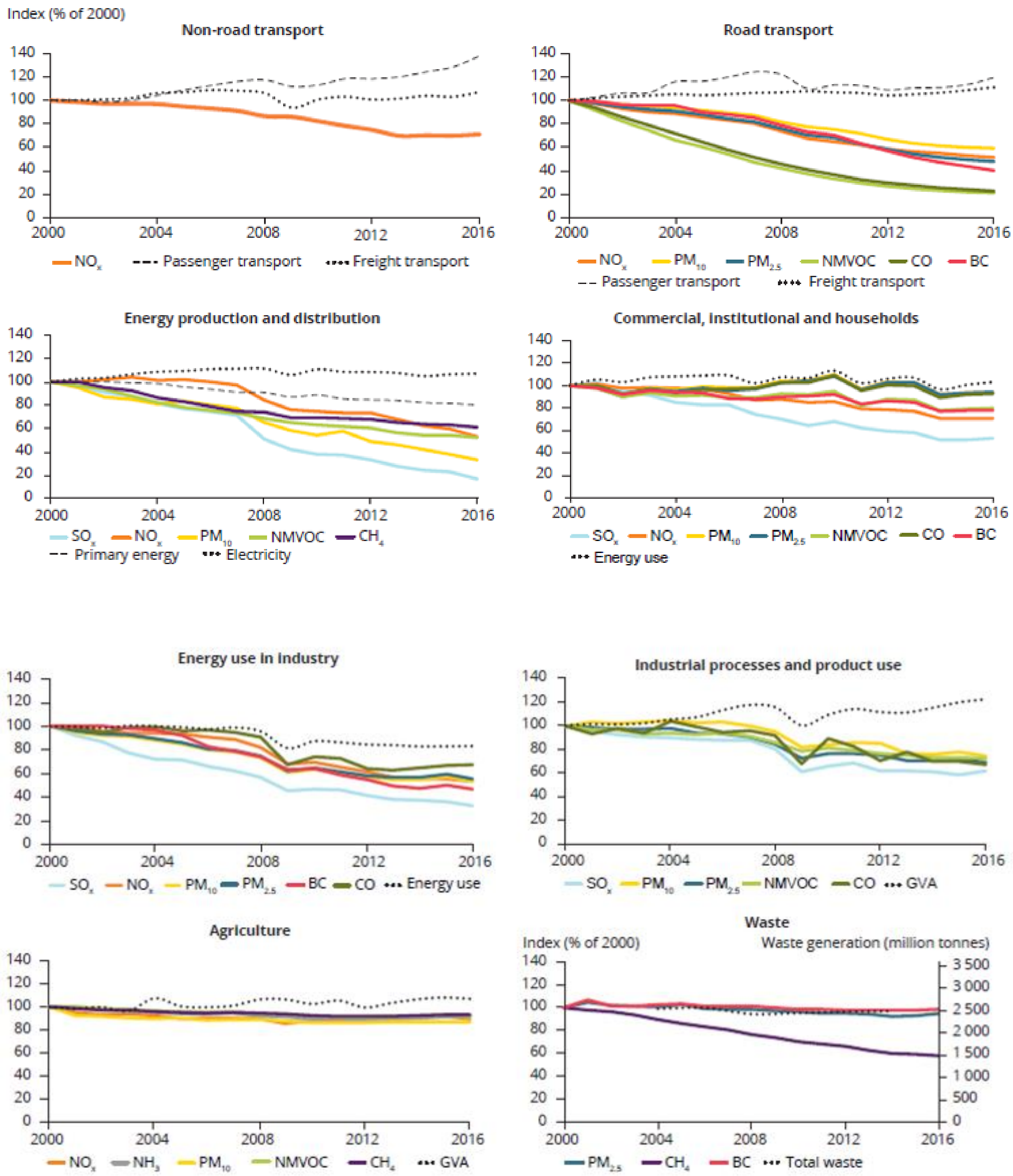


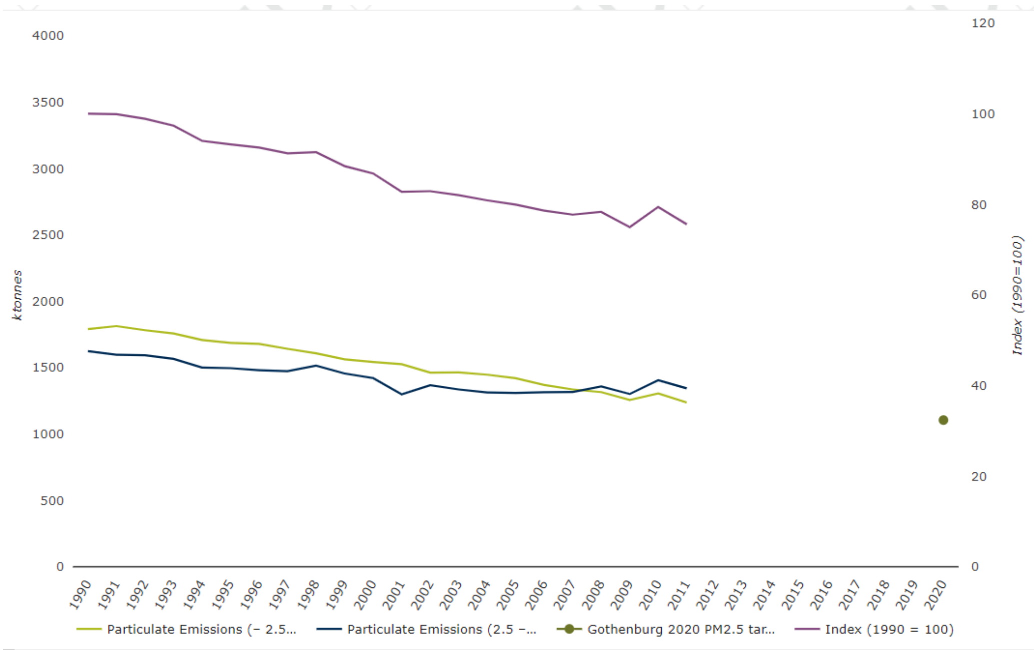
Figure 2: Development in EU-28 emissions from main source sectors of SO_X, NO_X, NH_3, PM_{10}, $PM_{2.5}$, NMVOCs, CO, BC and CH_4, 2000-2016 (% of 2000 levels). Also shown for comparison are key EU-28 sectoral activity statistics (% of 2000 levels) [1] (European Environment Agency, 2018a)

[1] Only pollutants for which the sector contributes more than 5 % to the total pollutant emissions are shown in the figures

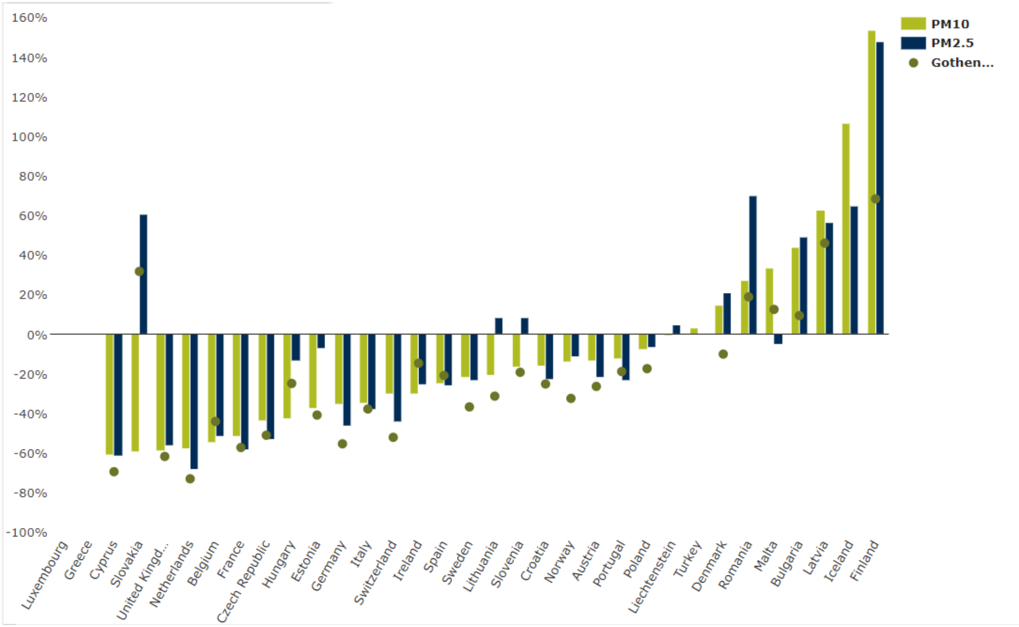
2.2 $PM_{2.5}$: Regulations and Attainment

EU air pollution legislation has followed a twin-track approach by implementing both emission controls and air-quality standards.

Under the National Emission Ceilings Directive (NECD) and the 2012 amended Gothenburg Protocol, emission ceiling and emission reduction commitments in 2020 and 2030 of primary $PM_{2.5}$ are set for European countries, together with four other main air pollutants (SO_x, NO_x, NH_3, NMVOCs) (European Environment Agency, 2018b). Based on the officially reported emissions to the EEA, the EEA-33 regions are progressively achieving the Gothenburg 2020 $PM_{2.5}$ target in general. By 2011, 25 of EEA-33 regions have already achieved their targets specified in the protocol (European Environment Agency, 2014).



(a) Emission trends of PM: 1990-2011 (EEA-33 regions overall)



(b) Percentage change in PM emissions in each EEA-33 region

Figure 3: Emissions of primary PM2.5 with Gothenburg 2020 target in EEA-33 regions: (a) trends in 1990-2011 (b) percentage change in 2011 (compared with 1990) (European Environment Agency, 2014)

Considering the harmful impacts on human health and ecosystem, air quality standards are specified for key air pollutants by regulating their ambient concentrations. Currently, ambient concentrations of SO_2, NO_2 and other nitrogen oxides, PM_{10} and $PM_{2.5}$, lead, benzene (C_6H_6), carbon monoxide (CO) and ozone are regulated under the Directive 2008/50/EC. The directive also sets two additional targets for $PM_{2.5}$, the exposure concentration obligation and the national exposure reduction target (NERT) (European Environment Agency, 2018a). Table 1 lists the air quality standards for $PM_{2.5}$ given in the EU Ambient Air Quality Directives.

Averaging period	**Legal nature and concentration Comments**	**Comments**
Calendar year	Limit value: 25 $\mu g / m^3$	
Calendar year	Exposure concentration obligation: 20 $\mu g / m^3$	Average Exposure Indicator (AEI) in 2015 (2013-2015 average)

Calendar year	National Exposure reduction target: 0-20% reduction in exposure	AEI in 2020, the percentage reduction depends on the initial AEI

Table 1: Air Quality Standards for PM2.5, given in the EU Ambient Air Quality Directives (EEA, 2018a)

In 2016, the PM2.5 concentrations of four member states and four other reporting countries exceeded the annual limit value in 2016. More than half of the 29 countries considered[2] have already attained their NERT values (EEA, 2018a).

Notes: Bars indicate the reduction of the AEI 2016 as a percentage of the AEI 2011 (AEI 2015 in the case of Croatia, see main text). Dots indicate the reduction to be obtained in the AEI 2020 as a percentage of the AEI 2011 (AEI 2015 in the case of Croatia). If the end of the bar is to the right of the dot, the NERT has already been reached in 2016.

For Croatia and Greece, where no stations have been designated for the AEI calculation, all urban and suburban background stations have been used instead.

For Hungary, which did not designate AEI stations or report $PM_{2.5}$ data from urban background stations in 2015 nor 2016, the reduction of the AEI 2014 (average 2012-2014) is presented. For Slovakia, which did not designate AEI stations in 2013 nor 2016, the reduction of the AEI 2015 (average 2014-2015) is presented.

Figure 4: Percentage of reduction of AEI 2016 in relation to AEI 2011 and distance to the national exposure reduction target (EEA, 2018a)

[2] Austria, Belgium, Cyprus, Denmark, Estonia, Finland, France, Germany, Ireland, Lithuania, Luxembourg, the Netherlands, Norway, Sweden and the United Kingdom.

3 Questions addressed by the module

Theme	Questions		Ambition[3]
What are the types of impact we want to take into account in the model?	Population exposure to $PM_{2.5}$ pollution	• What is the aggregated European population exposure to $PM_{2.5}$?	Yes
		• What is the spatial distribution of air pollution?	Yes, the module calculates air pollution impacts of $PM_{2.5}$ in each of the EU28+1 member states.
	Health impact	• What is the mortality due to exposure to $PM_{2.5}$?	Yes
	Monetary impact	• What is the cost of health impact of air pollution?	Yes
What are the solutions to reduce air pollution and health impact?		• What is the impact of implementing pollution control technologies?	Partially. The module evaluates the impact on air pollution of different technologies that can be used in different sectors, e.g. electric or hydrogen vehicles for transport, or renewable energy sources for power. However, the assumptions on emissions control technologies and regulations are implicit within the IIASA-GAINS inputs factors.
What is the impact of other sectors on health?		• What is the health impact of changes in sector dynamics in buildings, transport, industry, agriculture, power and oil refinery?	Yes
What is the impact of air pollution and health on the other sectors?	Lifestyle	• What is the impact of air pollution and health on lifestyle?	No, since this would be contrary to the EUCalc logic (it would create feedback loops)
	Agriculture and land use	• What is the impact of air pollution and health on agriculture and land use?	
	Other sectors	• What is the impact of air pollution and health on transport, industry, power generation, oil refinery?	

Table 2: Questions addressed by the health module

3 Does this module ambition to answer that question?

4 Calculation logic and scope of the module

4.1 Theoretical framework

The human health methodology aims to:

1. Provide quantitative estimates of the air pollution impacts of different 2050 calculator pathways across 28+1 EU countries in the EUCalc;
2. Enable users of EUCalc to interpret the air pollution impacts with policy relevant metrics;
3. Account for ongoing improvements in emissions control technologies that are not explicitly covered by the EUCalc methodology.

This section describes the methodology underlying the health effects calculations and:

- Defines the overall rationale for the health impact assessment, in particular by demonstrating how it builds on the impact pathway approach (IPA);

- Identifies a general framework for quantifying impacts of air pollutants on human health, including links to the other EUCalc core modules;

- Identifies the assumptions and data that will form the basis of the quantification of benefits.

The **impact pathway approach (IPA)** is a systematic method for identifying and tracing the effects of air pollution, from changes in emissions that result from changes in human activity, through to impacts on outcomes that society values (Department for Environment Food & Rural affairs, 2019). There are six component stages, as shown in Table 3. The IPA can also be represented diagrammatically, as in Figure 5.

Stage	Description
1	Estimating anthropogenic activity
2	Quantifying the resultant air pollutant emissions
3	Modelling the dispersion of emissions of air pollutants to understand changes in ambient pollutant concentrations in different locations
4	Quantifying the exposure of the population to changes in air pollutant concentrations
5	Estimating how those changes in exposure affect human health
6	Valuing those impacts using a single monetary metric

Table 3: Stages of the impact pathway approach

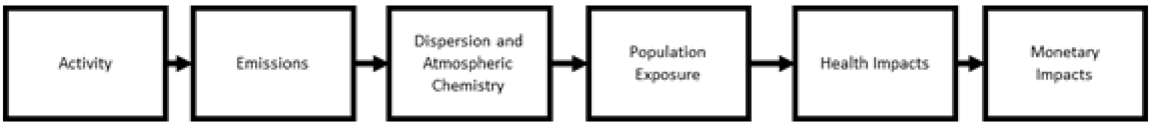


Figure 5: Impact pathway approach

4.2 Limitations of EUCalc approach for air pollution

In the process of developing the methodology to estimate air pollution impacts within EUCalc, we encountered a number of limitations that mean a full IPA would not be feasible, including:

1. **Emissions factors**. The standard method of conducting an emissions inventory is to multiply an activity value (e.g. PJ, vkm) by an appropriate emissions factor that accurately quantifies the mass of emissions per unit of activity (e.g. kg NO_x/PJ or kg NO_x/vkm). In Europe, the standard resources for emissions factors is the EMEP/EEA air pollutant emission inventory guidebook (European Environment Agency, 2016). However, it became clear that the technology definitions for each of the core energy conversion sectors within EUCalc (e.g. energy, transport, manufacturing) were not detailed enough to allow us to choose the

appropriate emissions factors. Note that this reflects the fact that the pollutant emissions factor for an energy conversion process can vary by an order of magnitude or more with negligible effect on energy efficiency (and CO_2 emissions) owing to the advancement of emissions control technologies (e.g. catalysts, filters and scrubbers). To resolve this, it would be necessary to specify emissions control technologies in each of the 28 + 1 EU countries for different sectors up to 2050.

2. **Spatial distribution of emissions.** To calculate emissions dispersion and resultant changes in concentrations due to pollutant emissions, it is necessary to know the source location of emissions. As EUCalc is a model aggregated to the country-level, there is no spatial information contained within the existing framework. Furthermore, it is therefore also not possible to represent the location of emissions with respect to population.

It was not possible to remedy the issues highlighted above and couple a full-scale IPA.

4.3 Chosen approach with IIASA-GAINS

To meet the aims of the module and to overcome the challenges posed by the aggregate country level of EUCalc, we have collaborated with Markus Amann and Fabian Wagner of the International Institute for Applied Systems Analysis (IIASA) to use their pre-existing work on integrated assessment of air pollution and climate policies and their Greenhouse Gas-Air pollution Interactions and Synergies (GAINS) model. This approach enables: (1) quantification of accurate emissions factors for each sector and country, accounting for different technological development pathways, and; (2) incorporating the spatial distribution of emissions in each country and the dispersion and transport of pollution of transport across the EU.

In the following subsections we describe GAINS, and the approach to estimate air pollution exposure resulting from emissions in EUCalc, showing an example calculation.

The approach and outstanding issues were discussed in an expert meeting in which solutions were agreed and implemented.

4.3.1 Introduction to GAINS

The GAINS model was developed by IIASA and is now employed for the international negotiations among participants under the Convention on Long-range Transboundary Air Pollution (IIASA, 2018).

The GAINS model can quantify the full pathway of the DPSIR (demand-pressure-state-impact-response) framework from the driving forces to the effects on human health and ecosystem of six air pollutants (SO_2, NO_x, NH_3, VOC, $PM_{2.5}$ and PM_{10}) and six greenhouse gases (CO_2, CH_4, N_2O the three F-gases). Examples of driving forces include economic activities, energy combustion, and agricultural production (Amann, 2012).

Source-receptor relationships have been developed to consider the atmospheric dispersion process. They quantify the impacts for the EU territory with the 50 km × 50 km grid resolution of the geographical projection of the EMEP model from changes in emissions of SO_2, NO_x, NH_3, VOC, $PM_{2.5}$ of the 25 Member States of the EU, Romania, Bulgaria, Croatia, Norway and Switzerland, and five sea areas (Amann, 2012).

Particularly for $PM_{2.5}$, the source-receptor relationships developed for GAINS describe the response in annual mean $PM_{2.5}$ levels to changes in the precursor emissions SO_2, NO_x, NH_3 and primary $PM_{2.5}$. In addition, a generalized methodology was developed to describe the urban increments in $PM_{2.5}$ concentrations in urban background air that is emitted from local sources (Amann, 2012).

The size of urban agglomerations and populations are critical to estimate the urban increment of $PM_{2.5}$ concentration and exposure in a given city. This information has been collected for 473 European cities in Europe with more than 100,000 inhabitants. Urban areas and diameters were derived from the JRC European population density data set and the www.citypopulation.de database, thereby linking population density for the individual urban agglomerations considered (Amann et al., 2011).

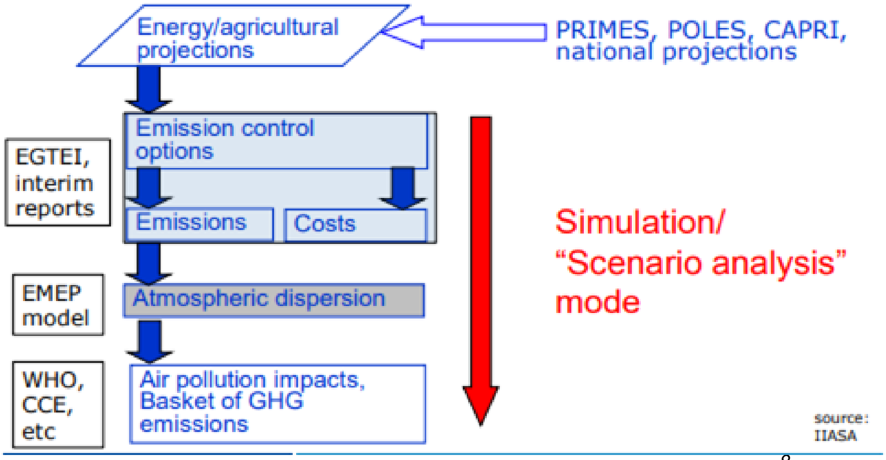


Figure 6: The GAINS model structure *(Stefan Åström, 2015)*

4.3.2 Integrating EUCalc and GAINS

The EUCalc model outputs activity for different sectors in different countries and in different years. This is stage 1 of the IPA.

The module makes use of the work that has already gone into GAINS to use derived 'population-average exposure factors' from GAINS that can be used to quantify population exposure directly by multiplying with the activity. This can be interpreted as combining steps 2-4 of the IPA.

Emissions are a function of fuel mix, energy consumption and emission control technologies. The fuel amount is factored out at the end to get to a per-PJ value. Concentration is a function of emissions in all EU member states and atmospheric transport. Exposure is a function of pollutant concentration and population in the receptor country, and by using population-averaged exposure factors, we are able to scale with the different population projections allowed as levers within EUCalc.

To reflect that emissions in one country can impact on air pollution in another, we use country to country factors; i.e. how emissions in country ***i*** affect the population weighted concentrations in country ***j***.

The units of the '**energy-based population-averaged exposure factors**' provided by IIASA are:

$$\mathbf{<(\mu g/m^3)>_{\mathit{j}}/PJ_{\mathit{i}}}\ ,$$

where ***i*** and ***j*** are the source and receptor countries, respectively. These can be multiplied with the energy consumption of each sector to obtain population-weighted pollutant concentrations from activity in different energy conversion sectors and countries.

Some sources of emissions are however not driven by combustion, and activity is best assessed by a different metric. This is the case for process emissions in industry and livestock and fertiliser application emissions in agriculture. In those cases, we chose alternative units for the denominator of the population-averaged exposure factors: tonne of material (process emissions, fertiliser application) and LSU (for livestock). The calculation logic is the same as for energy.

In cases where there is an imperfect alignment of sectors in EUCalc and GAINS, IIASA also provides '**emissions-based population-averaged exposure factors**' with units of ($\mu g/m^3$)/tonne of emissions:

$$\boldsymbol{\langle(\mu g/m^3)\rangle_j/(\text{tonne of emissions species})_i\ .}$$

This made it possible to calculate emissions for sectors that are not already included in GAINS, or for sectors that are modelled in greater detail in EUCalc than in GAINS.

Collectively, all these factors are called '**activity-based population-averaged exposure factors**'.

4.4 Model outputs

4.4.1 Estimating human health impacts

Human health impacts are calculated using the methodology developed in the ExternE studies, with updated data from the HRAPIE studies (Holland, 2014).

The method consists of calculating the relative risk (RR) of a health impact due to a change in concentration of a pollutant. The RR is derived from a concentration response function (CRF) which is based on epidemiological evidence. RR is the equivalent to the ratio of conditional probability of incidence of a health impact due the concentration to probability of incidence without the concentration. For example, several meta-analyses have shown that the RR of all-cause mortality from exposure to $PM_{2.5}$ is robust to different cohorts and studies. The RR can be characterised as a 1.06 RR per 10 $\mu g/m^3$ increase in $PM_{2.5}$ concentration (with an uncertainty range of 1.02 to 1.11) (Henschel & Chan, 2013). There is not enough scientific evidence to apply country-specific CRFs, therefore this will be treated as a constant across the EU28+1 and in time.

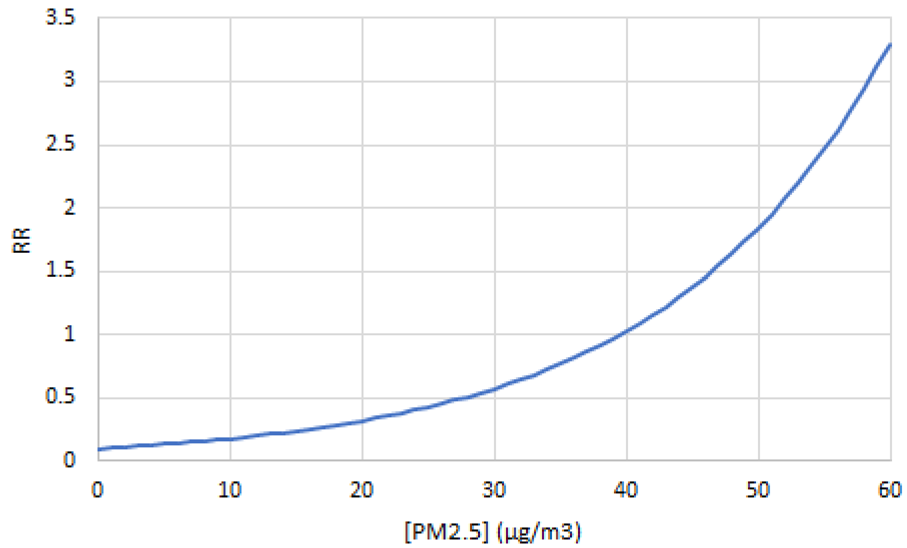


Figure 7: The relative risk of all-cause mortality associated with long term exposure to $PM_{2.5}$

The attributable fraction (AF) of an observed incident rate due to the change in concentration is defined as:

AF = (RR-1)/RR

Finally, the total incidents of a health impact due to the change in concentration can be calculated by multiplying the AF to the current baseline rate of incidence, B, and with the population exposed, P.

I = AF × B × P

The health metric that is calculated is total mortality. This is done by using data from the HRAPIE study on mortality from $PM_{2.5}$ exposure to define a CRF. The baseline mortality rates (B) is derived from existing literature, including European Environment Agency (European Environment Agency, 2018a). Detailed databases on mortality are aggregated by the WHO for Europe which are used to define the baseline rate (WHO, 2018).

The population is calculated based on inputs from the lifestyle module in EUCalc. In the GAINS model, population growth and distribution follow only one scenario into the future. EUCalc however provides the user with a lever for population, which defines four scenarios in which assumptions on population growth and urbanisation vary.

This creates a potential disconnect between the two models, which has been resolved by:

1. Exposure data from GAINS is divided by the underlying population scenario before it is used in EUCalc. This data is then multiplied by the EUCalc population, thereby adjusting for differences in population growth assumptions.
2. Since emissions that impact the most exposure tend to move with people, we estimate that different population distribution assumptions will not change the population-average exposure factors and potential changes to the spatial location of population and emissions are considered negligible.

4.4.2 Quantifying the costs of health impacts

It is common practice to estimate the costs associated with different health impacts of air pollution; most commonly premature deaths and years of life lost (YLL) (European Environment Agency, 2018a). Costs will be derived from existing literature, including from the EEA (Holland, M. et al., 2014; Holland, Mike, 2016).

$$\text{Cost} = I \times \text{Cost per incident}$$

To evaluate the cost of mortality in this module the Value of a Statistical Life (VSL) is used to quantify the cost associated with a mortality, this is a common method used throughout the European Region (WHO Regional Office for Europe, OECD, 2015). The OECD and the WHO have created an averaged VSL across the EU at $3 million US Dollars and also country specific VSL, allowing both European wide and country specific aggregated monetary impacts from mortality due to air pollution.

5 Results

This section summaries the results of population exposure and mortality attributable to air pollution across 28+1 EU countries in 2015-2050 calculated by the EUCalc Air Pollution module. As described before, the main air pollutant considered in this module is $PM_{2.5}$, which includes primary $PM_{2.5}$ directly emitted from activities and the secondary $PM_{2.5}$ resulting from gaseous precursors: SO_2, NO_x, and NH_3. Sectoral contributions to population exposure are estimated in each model year in each country, including building, agriculture, electricity, industry, transport, district heating and other sectors.

The IIASA GAINS model provided population-averaged $PM_{2.5}$ exposure factors, as described in the module methodology (chapter 2). The population in each member state is modelled within EUCalc.

5.1 Pathway definitions

The EUCalc model provides insight in scenarios that lead to decarbonisation in Europe. There are many routes to achieve lower carbon emissions, with different combinations of technologies and life style options that can be implemented, however, these have different outputs in air pollution and hence different results in human health impacts. The overall objective of EUCalc is to enable the identification of the best strategies to guide the transition so that it happens in the optimal manner, maximising economic and social benefits, wealth creation and inclusion of all stakeholders. Providing the health impacts in the model will enable policy makers to consider those social impacts as well in their choices.

The EUCalc model consists of different sectors (e.g. life style; buildings; industry; land; transport; energy) for which four ambition levels can be chosen:

- **LEVEL 1: Business as usual**
  This level contains projections that are aligned and coherent with the observed trends of the last 15 years (No TRL below 9).
- **LEVEL 2: Ambitious but achievable**
  This level is an intermediate scenario, more ambitious than business as usual but not reaching the full potential of available solutions (No TRL below 9).
- **LEVEL 3: Very ambitious but achievable**
  This level is considered very ambitious but realistic, given the current technology evolutions and the best practices observed in some geographical areas (No TRL below 7).
- **LEVEL 4: Transformational breakthrough**
  This level is considered transformational and requires additional breakthrough and efforts such as a very fast market uptake of deep measures, an extended deployment of infrastructures, major technological advances, or strong societal changes, etc.
  (No TRL below 5).

These ambition levels can be combined in pathways. There are many choices possible. In this report we will present the human health impacts for the predefined pathways, e.g. the EU Reference Scenario (EU-Ref), and the most ambitious setting (all levers on position 4).

EU-Reference scenario (EU-Ref)

The combination of lever positions under this pathway reproduces, as far as possible, the main sectoral assumptions and outputs of the EU-Reference scenario as detailed in [Capros et al 2016].

As an example, the following figure shows the graph of the greenhouse gas emissions under the EU-Reference scenario pathway until 2050 in the Transition Pathway Explorer (TPE).

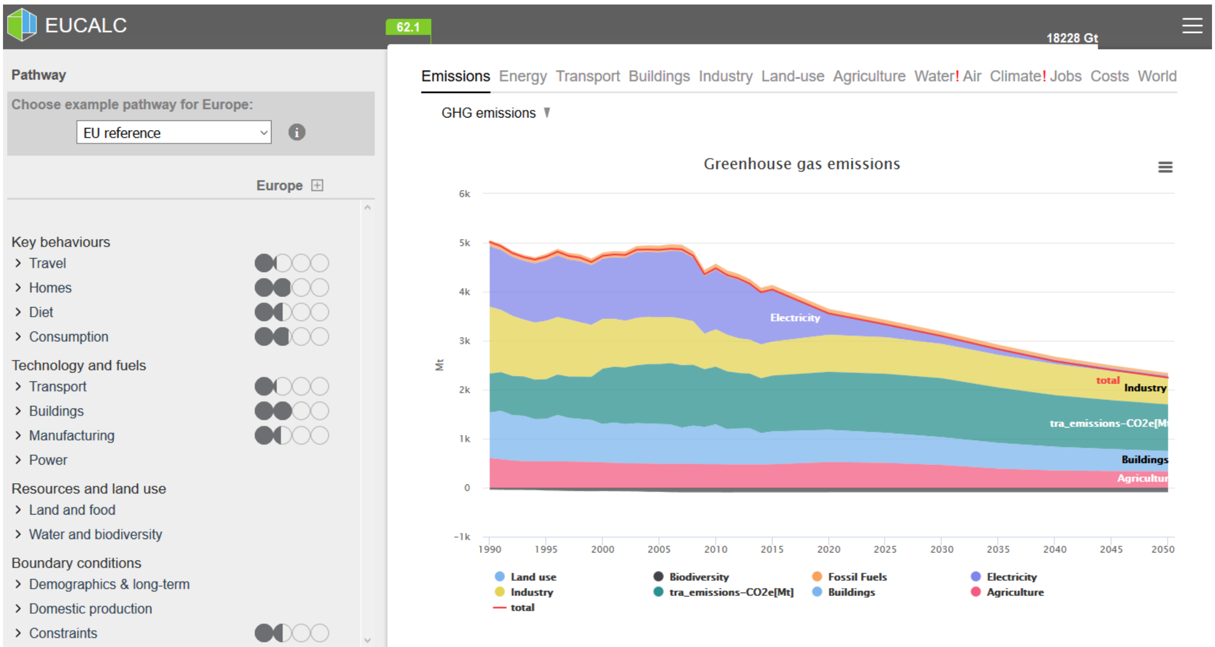


Figure 8: Greenhouse gas emissions of different sectors under the EU-Reference scenario (from D1.5)

The EU-Ref will be used to show the results for 2015 and the trends towards 2050. These results will be compared with results from all lever settings at 4, the highest ambition level for all sectoral developments.

5.2 Impacts on human health

5.2.1 Results in 2015

Exposure

The mean exposure in the EU Ref scenario in 2015 across all countries is estimated as 7.06 μg/m³. Of the 28+1 EU countries, Switzerland has the highest exposure level of 16.0 μg/m³, and for five other countries (Italy, Poland, Belgium and Hungary), the exposure is estimated to be in the range of 10 to15 μg/m³, as shown in Figure .

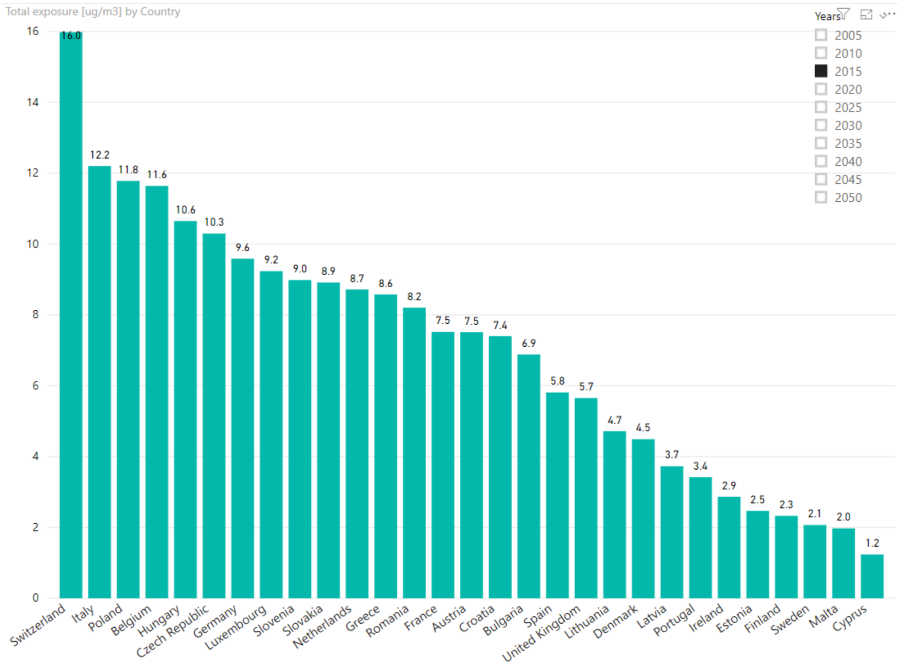


Figure 9: Population-weighted $PM_{2.5}$ exposure in each EU 28+1 country in 2015.

Mortality

Mortality attributable to $PM_{2.5}$ exposure is estimated based on the exposure estimation mentioned above and an appropriate concentration response function, as described in the methodology. In the EU Ref scenario in 2015, we estimate that there are 252,000 deaths in the EU28+1 countries attributable to $PM_{2.5}$ exposure, with an average of 9,000 deaths in each country. Germany and Italy had the highest number of mortalities (above 40,000 deaths), followed by Poland, France and the UK (figure 10). These results are a function of the population-weighted exposure, the total population and the underlying all-cause mortality rates. For example, cross-referencing to figure 9, population-weighted exposure in France, the UK, Spain and Romania is estimated to be near or below the average exposure (7.06 $\mu g/m^3$) yet the mortality estimated for these countries are relatively high. In the case of France, the UK and Spain, the relatively high number of mortalities result from the higher populations in these countries compared to the average. Whereas in the case of Romania, the underlying all-cause mortality rate (868 deaths per 100,000 per year) is higher than average, c.f. Germany (557 deaths per 100,000 per year).

Comparing the mortality estimates in the EU Ref scenario (252,000) to the latest estimate of $PM_{2.5}$-attributable premature mortalities from the European Environment Agency for 2016[4] of 378,000 for the EU28+1, we see that our model captures 2/3 of the total. However, our estimate is within the 95% confidence interval of 248,000 - 489,000, which reflect uncertainty in the concentration response function. Comparing the top five countries with the higher mortalities, our EUCalc estimates agree with the EEA in determining that the largest health impacts, and their ranking, are in the countries with the highest populations, namely Germany, Italy, Poland, France and the UK.

Our underestimation of mortality attributable to $PM_{2.5}$ compared to the EEA is likely due to: (i) the resolution of our model, which is at the country level, compared to the higher resolution pollution and population maps used by the EEA; and (ii) our approach appears to underestimate population-weighted exposure in most countries, which are then propagated through to a non-linear concentration-response function.

[4] https://www.eea.europa.eu/publications/air-quality-in-europe-2019

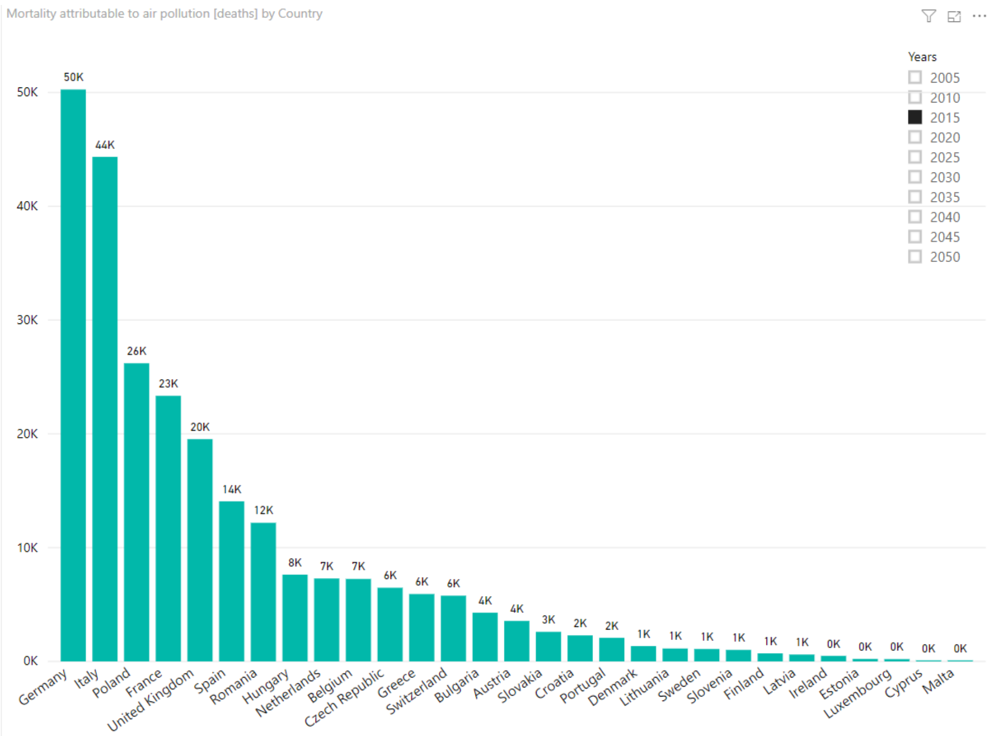


Figure 10: $PM_{2.5}$-attributable premature mortalities in each EU28+1 country in 2015.

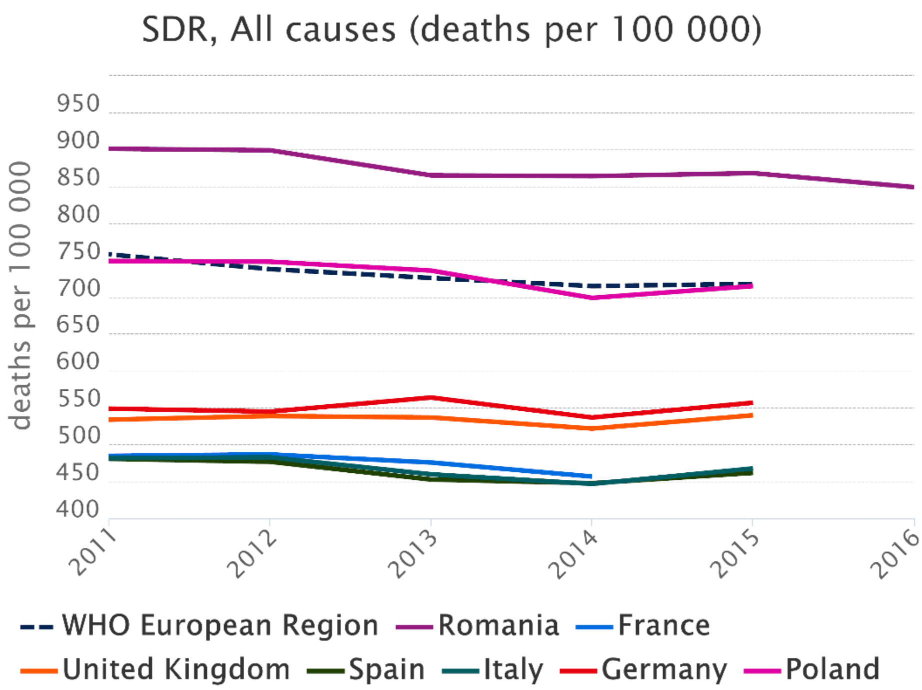


Figure 11: All-cause mortality rates in selected member states. Source: WHO European mortality database (https://gateway.euro.who.int/en/datasets/european-mortality-database/).

Sectoral contributions in 2015

The average sectoral contribution proportion to population exposure in the EU Ref scenario in 2015 across all contries are shown in figure 12. The building sector (including domestic heating) contributed about 25.7% of total exposure on average, followed by the agriculture sector (25.6%), the electricity sector (12.2%) the transport sector (10.5%), the industry sector (6.3%), and district heating (0.3%). Based on the average proportion across countries, around 75% of the building sector contributions were from energy consumption with solid biomass (figure 13(a)). The emissions from the nitrogen fertilizer and those from the livestock for dairy made up of 49% and 19% of the agriculture sector contributions respectively (Figure 13(b)). Agriculture is a key emissions sources of ammonia, which is an important precursor of $PM_{2.5}$. The control of ammonia emissions is regarded as one of the most effective control strategies in mitigating the $PM_{2.5}$ concentrations (Pozzer et al., 2017; Schiferl et al., 2014).

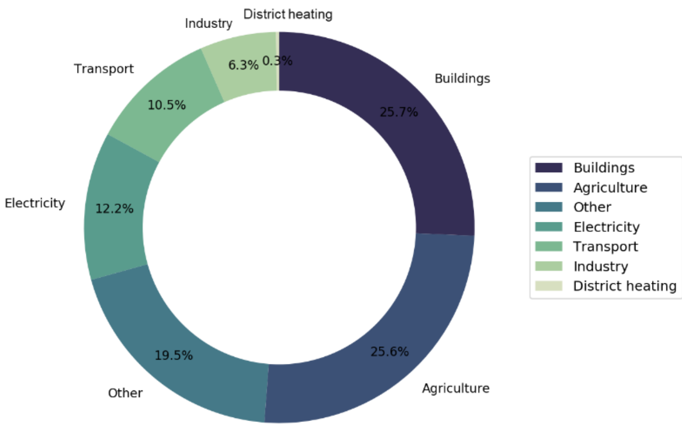
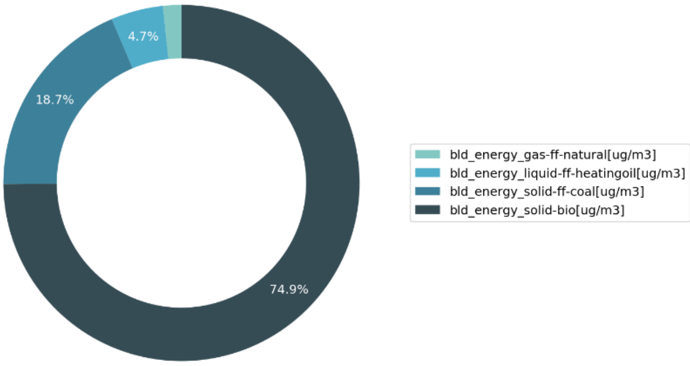
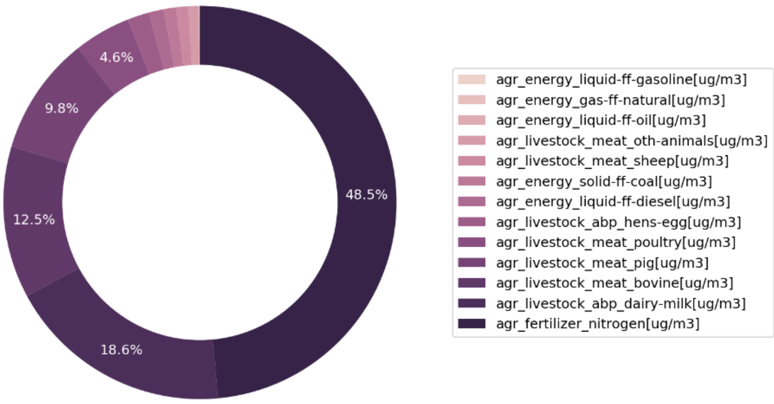


Figure 12: Sectoral contribution to total population exposure in the EU 28+1 countries in 2015.



(a) building



(b) agriculture

Figure 13: Contribution of subsectors within (a) the building sector and (b) the agriculture sector in the EU 28+1 countries in 2015.

In both Switzerland and Romania, emissions from the building sector contributed to more than 40% of the population exposure. Particularly, the contribution from solid biomass burning in the building sector accounted for 62% of the total population exposure in Switzerland. In Slovakia, Greece, and Germany, the contributions of the agriculture sector exceeded 35%. In contrast to the average distribution within the agriculture sector, shown in Figure 13(b), emissions from the livestock for dairy was the largest contributor (27% of total exposure) in the agriculture sector (37% of total exposure) in Greece.

The main sources of $PM_{2.5}$ exposure in the top 3 countries with the highest number of mortalities level are nitrogen fertilizer (agriculture sector, 17.6%) in Germany, solid biomass (building sector, 32.0%) in Italy, and coal burning (building sector, 21.7%) in Poland. In addition, the coal-burning in the electricity sector (17.4%) also contributed to a high proportion of total population exposure in Poland. The sectoral contributions in each evaluated country are indicated in Figure .

5.2.2 Forecasts 2050

In the EU Ref scenario, the mean exposure across all countries will decrease from 7.06 $\mu g/m^3$ in 2015 to 4.08 $\mu g/m^3$ in 2050, and the air pollution attributable mortality will decrease from 252,000 deaths in 2015 to 152,000 deaths in 2050, as shown in Figure . In 2050, Switzerland, Belgium, and Italy are estimated to be the countries with the highest population exposure. The exposure level in Germany and Poland are estimated to be near the 75% quartile of results from all countries (5.5 $\mu g/m^3$).

Germany and Italy will remain the top 2 countries with the highest number of mortalities in the EU Ref scenario in 2050. The mortality trend from 2005 to 2050 in each country is given in Appendix VI.

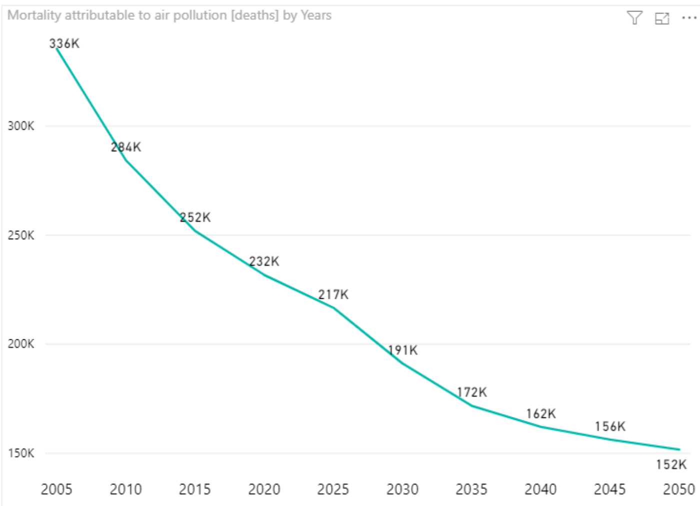


Figure 14: Estimated total mortalities attributable to $PM_{2.5}$: EU 28+1 countries (2005-2050), EU Ref scenario

In the Level 4 scenario, the air pollution attributable mortality will have a further reduction, compared with the EU Ref scenario: from 253,000 deaths in

2015 to 84,000 deaths in 2050 (Figure 15). This implies that there are air pollution benefits associated with deeper GHG emissions reductions.

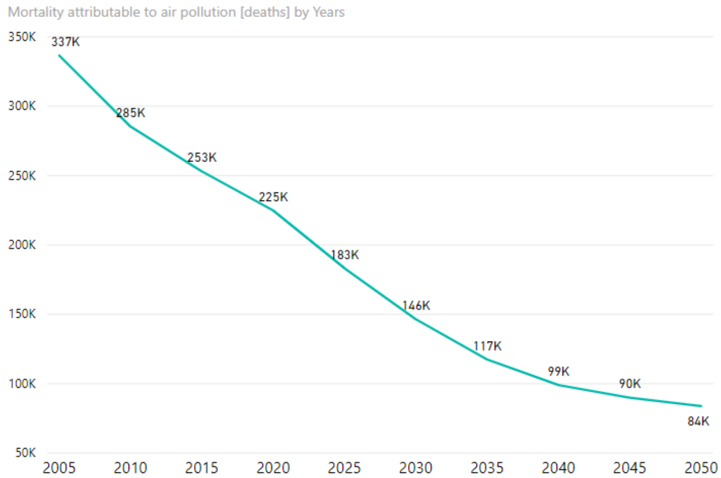
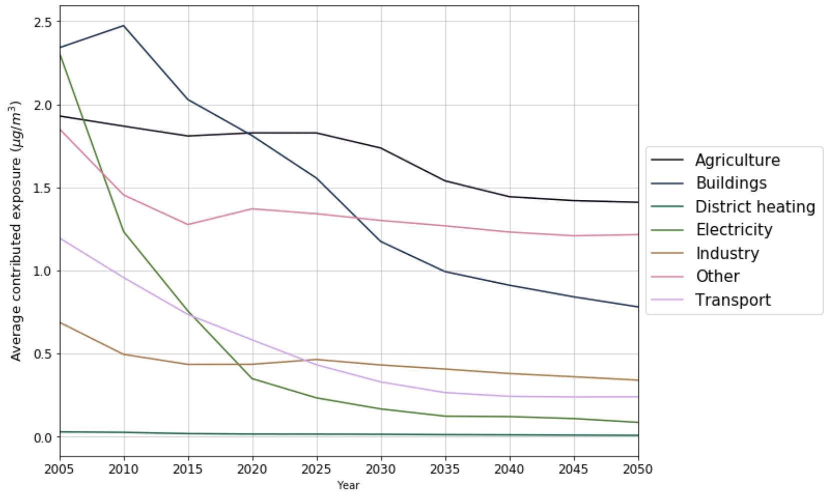


Figure 15: Estimated total mortalities attributable to $PM_{2.5}$: EU 28+1 countries (2005-2050), Level 4 scenario

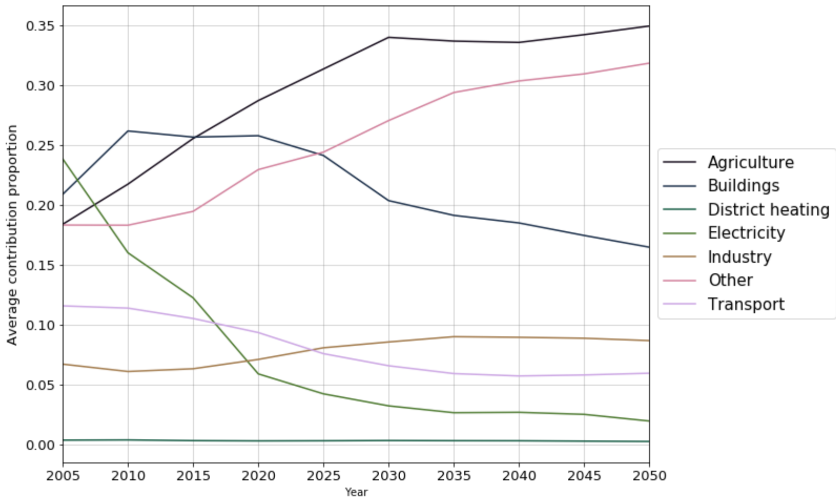
Sectoral contributions in 2050

The evolution of average sectoral contribution proportions to the total population exposure across countries is shown in Figure 16. While the contribution from the building, electricity, and transport sectors have been continuously decreasing since 2005, the exposure contributed by the agriculture and industry sectors are estimated to increase from 2015-2025 (Figure 16 (a)). As shown in Figure 16 (b), the contribution proportion of these two sectors will increase from 2015. After 2020, the agriculture sector is estimated to be the sector with the highest contribution to $PM_{2.5}$ exposure in general in Europe. Results indicate that the contribution rate of the agriculture sector will increase to 35% in 2050, and that of the transport sector will fall under 10% after 2020.

In 2050, the largest contributing sectors in Germany and that in Italy are estimated to be the same as those in 2015. The electricity sector, especially the emissions from coal-burning in Germany, and the transport sector tend to have a lower contribution in 2050 in these two countries, compared with 2015. The sectoral contribution in Poland has a significant change in 2050: nitrogen fertilizer in the agriculture sector becomes the largest contributor (14.1%), and the total contribution from coal-burning in the electricity sector and the building sector decrease from 39.1% in 2015 to 14.1% in 2050. The sectoral contributions in each country in 2050 is given in Figure VI.



(a) average contributed exposure



(b) average contributed proportion

Figure 16: Sectoral contribution estimation: EU 28+1 countries (2005-2050)

5.3 Discussion

Comparing the mortality estimates in the EU Ref scenario (252,000) to the latest estimate of $PM_{2.5}$-attributable premature mortalities from the European Environment Agency for 2016[5] of 378,000 for the EU28+1, we see that our

[5] https://www.eea.europa.eu/publications/air-quality-in-europe-2019

model captures 2/3 of the total. However, our estimate is within the 95% confidence interval of 248,000 - 489,000, which reflect uncertainty in the concentration response function. Comparing the top five countries with the higher mortalities, our EUCalc estimates agree with the EEA in determining that the largest health impacts, and their ranking, are in the countries with the highest populations, namely Germany, Italy, Poland, France and the UK.

Our underestimation of mortality attributable to $PM_{2.5}$ compared to the EEA is likely due to: (i) the resolution of our model, which is at the country level, compared to the higher resolution pollution and population maps used by the EEA; and (ii) our approach appears to underestimate population-weighted exposure in most countries, which are then propagated through to a non-linear concentration-response function.

6. Overall conclusions and policy recommendations

Overall conclusions

Social impacts are increasingly important considerations in policy strategies and for Euro- and national parliamentarians as can be observed from the recent frequent media coverages in various EU member states. Health effects are considered to be one of the most relevant social impacts. From literature and experts we know that PM2.5 is one of the most important contributors to air pollution with direct and indirect, long-term and short-term effects on exposed populations. Such effects can be reliably calculated in the number of '*life years lost'* and *costs* related to the average value of a human life as established by the World Health Organisation. It has proven possible with the aid of input of important collaborators (IIASA) to quantify health impacts related to air and incorporate these in the European Pathway Explorer.

Different technologies, use of resources and life styles have different levels of PM2.5 emissions, with relative large contributions from the building sector and from fertilisers for agriculture. Political choices for climate mitigation strategies do create either increases or decreases in population health related to air pollution. However, we also observe that these impacts differ greatly in different member states, due to a.o. population densities. This requires national decision makers to carefully analyse possible effects for their country and (because of the emissions spreading to other countries) adhering areas/countries. This EUCalc model allows policy makers and politicians to see such health effects resulting from increase or decrease of PM2.5 emissions related to different climate change mitigation strategies in different sectors. This provide insights on tensions between solutions for climate change mitigation (decarbonisation) which are counterproductive for health impacts and vice versa.

Policy recommendations

There are limitations to the social impacts which can meaningfully be shown in scenario models as it is difficult to define social impacts which can reliably be quantified and for which datasets are available which can be used in model configurations. To allow consideration of such effects and tensions policy makers need also insight into and access to information on the quality of those and other (non-quantifiable) social impacts. As these issues of tension relate to implicit values about what are good and what are bad impacts – the debate on desired solutions should pay attention to moral choices in policy making.

More research into the identification of social issues related to different sectors and lifestyles would significantly enhance our insights in political tensions. This should be followed by identifying and building reliable datasets which can be used in pathway explorers and by research on the causal relations with sector and lifestyle paths so that verifiable calculations to quantify social impacts can be made.

Only with reliable data and scientifically proven relations/calculations social impacts can become trustworthy components of pathway explorers. Considering social impacts would enhance the political choices for decarbonisation pathways. This would necessitate other methods to allow consideration of qualitative social impacts.

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EUCALC

Annexes

I Scope definition

The scope of the health module is described below. It defines the granularity of the model in terms of time, countries, pollutants and technologies.

Pollutants

The health module calculates annual mean $PM_{2.5}$ levels, which include changes in the precursor emissions SO_2, NO_x, NH_3 and primary $PM_{2.5}$.

Countries

Similar to the rest of EUCalc, the EU28 and Switzerland are modelled.

Technologies

Technologies have been chosen to allow for a mapping between EUCalc and GAINS, which imply aggregating some of the underlying granularity on both sides.

In the health module, a technology is represented by its activity, modelled in the corresponding sector, and its exposure factor.

The exposure factors for different technologies in different countries change in time with 5-year timesteps from 2005 reflecting the evolution of emissions control technologies and regulations.

Transport

- Combustion
  - Vehicle types
    - Light-duty vehicles (LDV, corresponding to GAINS' category "LDV4C")
    - Heavy-duty vehicles (HDV, which includes the light-duty trucks that are classified in GAINS as "LDV4T")
    - Bus
    - 2-wheels (2W)
    - Aviation (only take-off and landing emissions)
    - Sea-going ships (small and large)
    - Inland waterways
  - Engine types
    - Internal combustion engines (ICE)

- Plug-in hybrid electric vehicles (split by fuel use) for LDV, HDV, bus and 2W
    - Fuel type
        - Diesel
        - Gasoline
        - Natural gas
        - Jet fuel
        - Marine fuel oil
- Abrasion
    - Vehicle types
        - LDV (corresponding to GAINS' category "LDV4C")
        - HDV (which includes the light-duty trucks that are classified in GAINS as "LDV4T")
        - Bus
        - 2-wheels
    - Emission source
        - Tyres
        - Brakes

Buildings

- Heating
    - Heating system type
        - Decentralised
        - District
    - Energy vector
        - Natural gas
        - Heating oil
        - Solid biomass
        - Coal

Industry

- Type of material produced:
    - Steel
    - Cement
    - Ammonia
    - Chemicals (excluding ammonia)
    - Pulp and paper
    - Aluminium
    - Glass
    - Lime
    - Copper
- The type of material is further broken down by type of energy carrier used for production (for production emissions):
    - Biogas
    - Natural gas
    - Liquid biofuel
    - Oil
    - Solid biofuel

- Coal
- Waste

- Specifically, for process emissions, some technology are broken down into their main production process technologies:
    - Aluminium
        - Primary
        - Secondary
    - Cement
        - Dry kilns
        - Wet kilns
        - Geopolymer
    - Paper
        - Recycled
        - Wood pulp
    - Steel
        - Blast furnace – basic oxygen furnace (BF-BOF)
        - Scrap – electric arc furnace (Scrap-EAF)
        - Hydrogen – Direct reduced iron (Hydrogen-DRI)
        - Hisarna
- The following materials are modelled by the industry sector, but were not included separately in this module, since they were added after having received the GAINS data. In the model, they are therefore account for in the "other sectors".
    - Transport equipment
    - Food, beverage and tobacco
    - Textiles and leather
    - Machinery equipment
    - Wood and wood products
    - Other industries

Electricity production

- Natural gas
- Oil
- Coal

Agriculture

- Direct energy use
    - Diesel
    - Gasoline
    - Coal
    - Oil
    - Natural gas
- Fertilizer application (nitrogen)
- Livestock population
    - Dairy milk cows
    - Egg hens
    - Bovine
    - Pigs
    - Poultry

- Sheep
- Other animals

Non-modelled sectors

A number of sources of air pollution are modelled in GAINS but not in EUCalc, for instance industrial sectors having no impact on CO2 emissions, or background air pollution in the different countries.

To account for this, a "contribution from other sectors" has been extracted from GAINS, and is added to the total exposure.

II Interactions with other modules

II.1 Inputs from other modules

Lifestyle

The Lifestyle module of EUCalc provides the user with a lever for population, which defines four scenarios for population growth for each country and each year. This data varies with the scenario selected by the user.

Buildings

The buildings module provides energy demand data in TWh for each heating system type and each vector, as mentioned in the section Scope definition.

Transport

The transport module provides the following data:

- Energy demand in TWh for each vehicle type, engine type and fuel type according to the modelled technologies as specified in Scope definition, with the following exceptions:
    - Heavy-duty vehicles are split into three sub-categories: light, medium, heavy
    - Energy demand for PHEV vehicles include only the non-electric component
- Distance travelled expressed in vehicle-km for LDV, bus, 2W, HDVL, HDVM, HDVL.

Matching a common level with GAINS requires to sum the three HDV categories for both types of variables.

In addition, each fuel is split into 3 variants: regular fossil fuels, e-fuels and biofuels. This granularity is not modelled in GAINS, so e-fuels and biofuels have been aggregated with the corresponding fossil fuel for calculations.

Fuel consumption in the aviation sector is handled differently in EUCalc and in GAINS. In EUCalc, energy consumption represents the total consumption of the flight, while GAINS models only take-offs and landings. GAINS exposure factors have therefore been adapted by IIASA so that they can be multiplied by total flight consumption.

Industry

The industry module provides energy demand data in TWh for each subsector and each vector, as mentioned in the section Scope definition.

In addition, the module provides the quantity of material produced for each subsector and production technology when available.

Since GAINS doesn't differentiate ammonia from other chemicals, it has been aggregated with the chemical subsector for both energy and material production variables.

As a rule, combustion emissions are calculated based on the energy demand from the industry sector, and process emissions are calculated based on the quantity of material. However, GAINS models cement, lime and glass differently: all emissions are calculated based on material production. For these three subsectors, direct energy consumption from the industry module is therefore ignored.

Note that the industry sector models a few additional sectors that represent a small fraction of the total. These sectors have not been explicitly modelled, but are accounted for in the "other industries":

- Transport Equipment
- Food, beverages and tobacco
- Textiles and leather
- Machinery Equipment
- Wood and wood products

- Other Industrial Sectors

Agriculture

The agriculture module provides the direct energy consumption of the agricultural sector by energy vector in TWh. In addition, it provides activity metrics for livestock and nitrogen fertiliser application respectively in LSU and in tons.

Note that fertiliser production is included in the industry sector.

Electricity

The electricity module provides energy demand data in TWh for each energy vector used for production of electricity, as mentioned in the section Scope definition.

II.2 Outputs to other modules

Transition pathway explorer

The only output of the health module to the pathway explorer consists of:

- Mortality attributable to pollution exposure per year for each EU28+1 country
- Cost of air pollution attributable mortalities

III Detailed calculation trees

Pre-processing steps

Data from the GAINS model has been pre-processed at IIASA before being used as input in the health module. The steps performed in this pre-processing are:

- Extraction of exposure factors by dividing the population exposure by the activity metrics, to have exposure factors per activity unit.
- Division by the GAINS population variable to obtain population-averaged exposure factors.

As mentioned earlier, the activity metrics can be either energy (in PJ), production- or usage-related metrics (tons or LSU) or emissions (in tons).

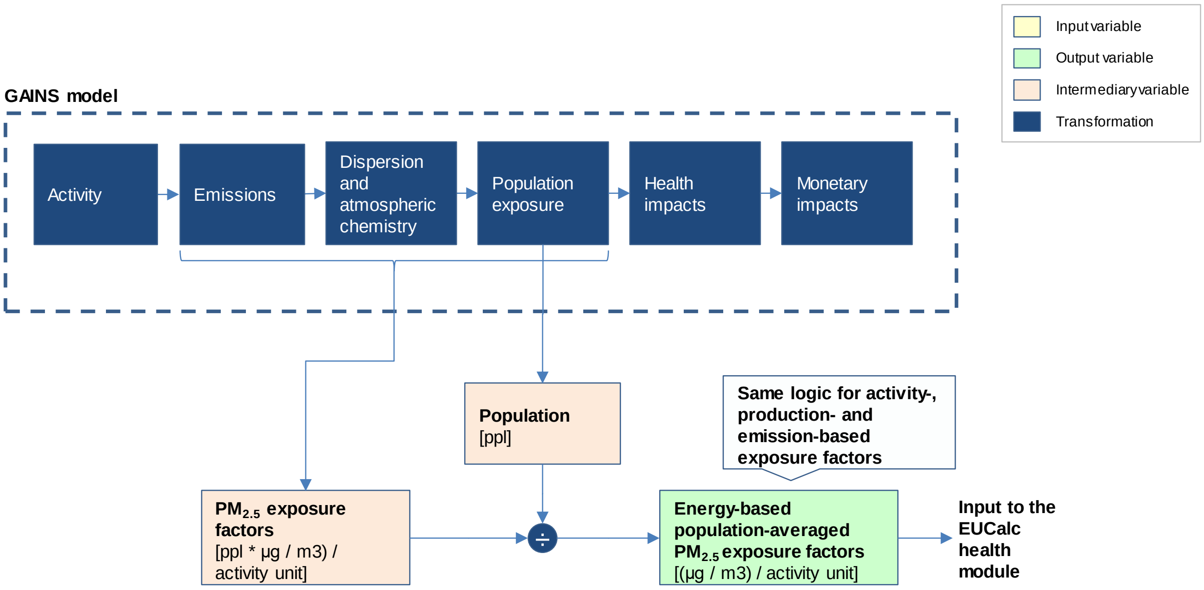


Figure A.1: Pre-processing steps executed by IIASA on GAINS data

Mapping between GAINS and EUCalc

The mapping step has the following objectives:

- Prepare the exposure factors from GAINS to be mapped to EUCalc data by aligning the variable names and converting the units
- Prepare the EUCalc activity data to be mapped to the exposure factors by summing variables across dimensions that are too granular (e.g. HDV subdivision)
- Convert activity-based data to emissions-based data to align granularity with GAINS (for vehicle emissions from brakes and tyres).

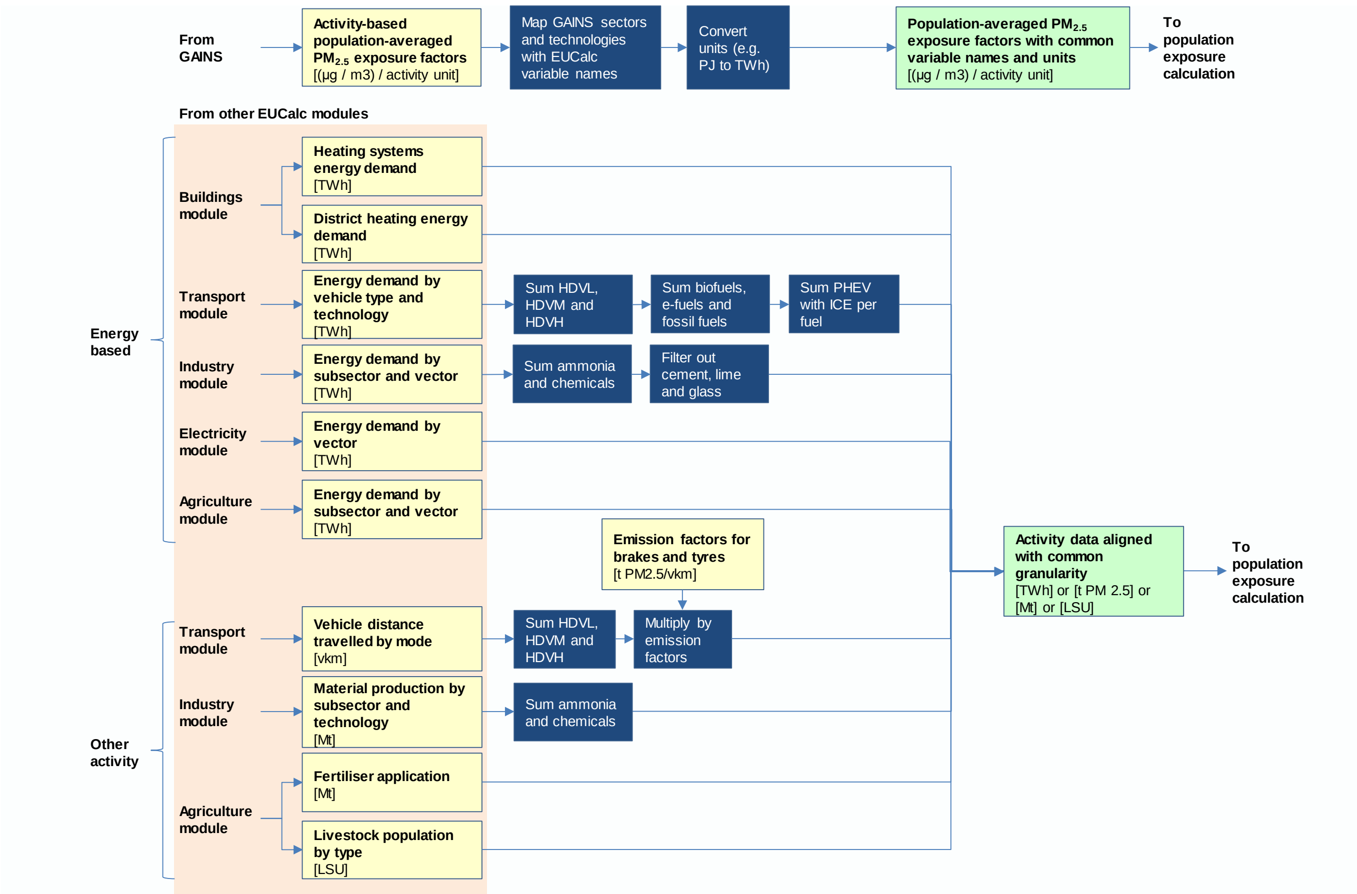


Figure A.2: Mapping data from GAINS with EUCalc data

Population exposure

The population exposure tree uses input from the pre-processing step and the contribution from other sectors (from GAINS) to calculate the average $PM_{2.5}$ exposure for each EU28+1 country and the aggregated European population.

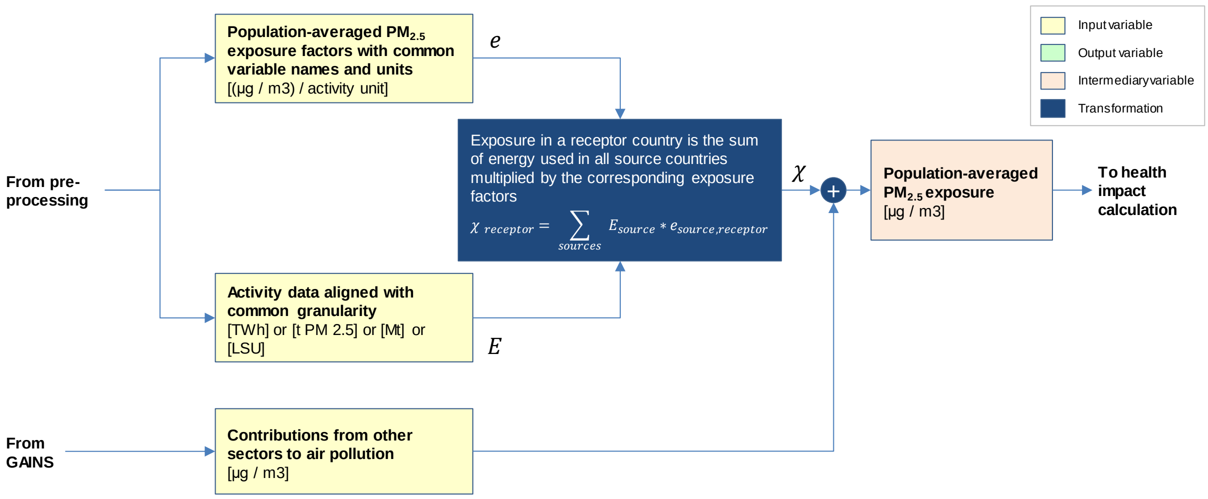


Figure A.3: Calculation tree for population exposure to $PM_{2.5}$

Health and monetary impacts

This step uses the result of the previous step together with additional inputs (European Mortality Database (WHO, 2018) and Value of a Statistical Life data (WHO Regional Office for Europe, OECD, 2015) and the population data from the lifestyle module to calculate the health and monetary impacts.

Since baseline mortality is only available for years up to 2015, baseline mortality for future years have been assumed constant in percentage of the population, as provided by the lifestyle module

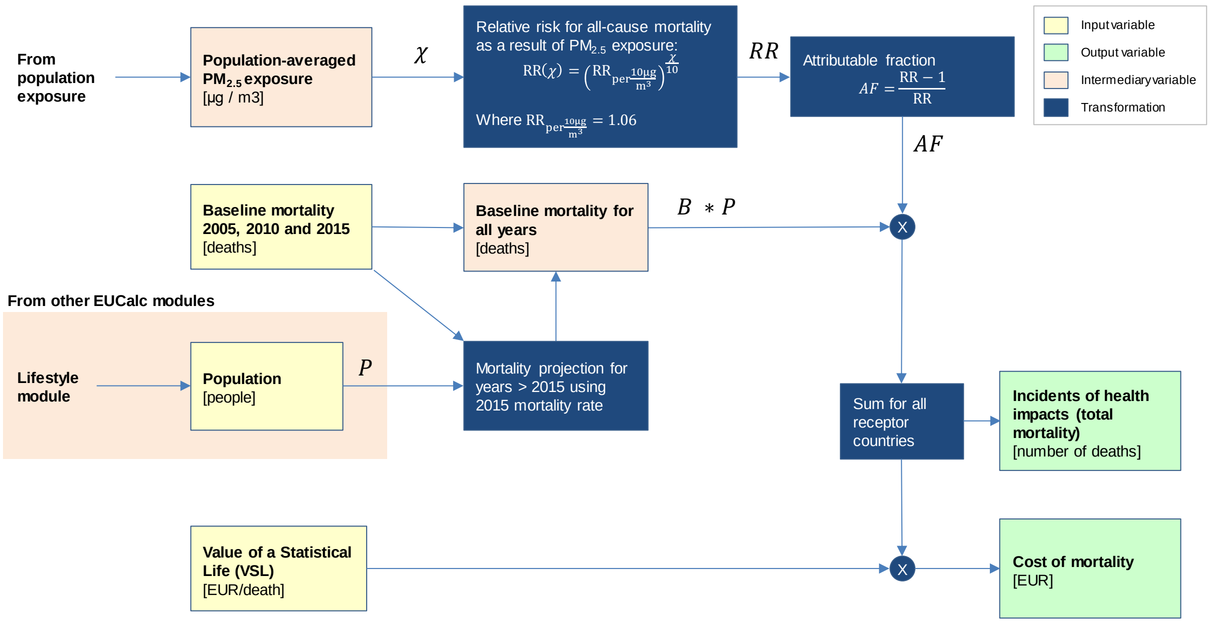


Figure A.4: Calculation tree for health and monetary impact of exposure to $PM_{2.5}$

IV Validation and calibration

The calculated health impacts and monetary costs are compared to other estimates of the health impacts and costs of air pollution across Europe (European Environment Agency, 2018a). However, since EUCalc does not include all sectors of the economy and all sources of pollution including biogenic sources, the estimates from this module are lower than estimates that do include the full range of sources.

Description of constant or static parameters

Constants

- Concentration Response Function (CRF), defined by the Relative Risk for concentrations of PM2.5, is constant.

Static parameters

- Exposure Factors (derived from the GAINS model)
- Emission Factors (from the GAINS model)

- Contribution of other sectors and background air pollution (from the GAINS model)
- Baseline mortality rates (European Morbidity Database – WHO)
- Value of Statistical Life (Economic cost of the health impact of air pollution in Europe - WHO and OECD)

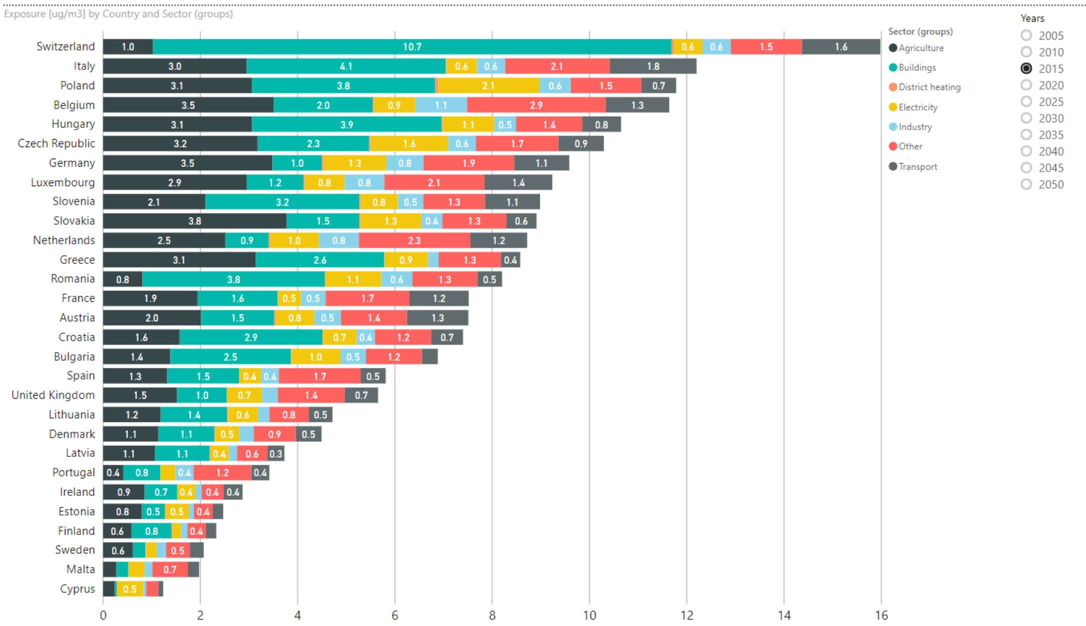
V Historical Database

This section describes each historical dataset that is used in the model. When the base year (2015) data is not available in the required granularity (e.g. all countries, all technologies), we apply some hypothesis to fill the gaps.

Dataset	**Description**	**Source**
Exposure Factors	Factors derived from the GAINS model.	IIASA DOI: 10.22022/AIR/08-2019.51 http://dare.iiasa.ac.at/51/
Emission factors for brakes and tyres	Factors used in the GAINS model.	
Contribution of other sectors and background air pollution	Exposure from sectors modelled in GAINS but not in EUCalc and from background air pollution	
Baseline Mortality Rate (European Mortality Database)	Data of mortality rates in the EU. Contains European average and country specific values.	WHO
Value of a Statistical Life	Economic cost of a human life in Europe. Contains European average and country specific values.	WHO and OECD

Table A.1: Historical Databases used in WP6.

VI Detailed model results per sector



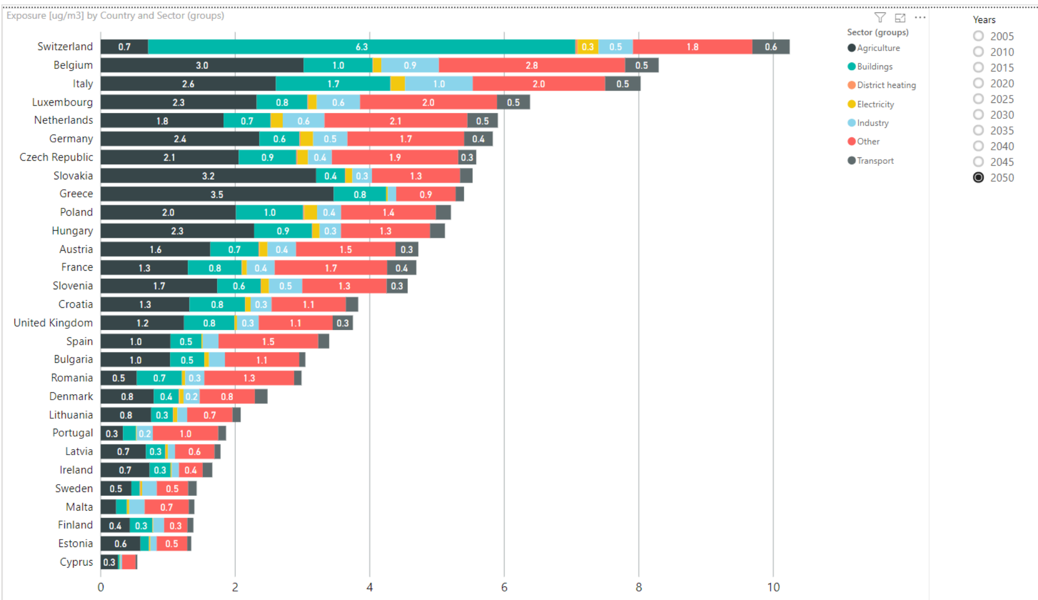


Figure A.5: Sectoral contributions of $PM_{2.5}$ exposure by country: EU 28+1 countries, (a) 2015 and (b) 2050 in the EURef scenario.

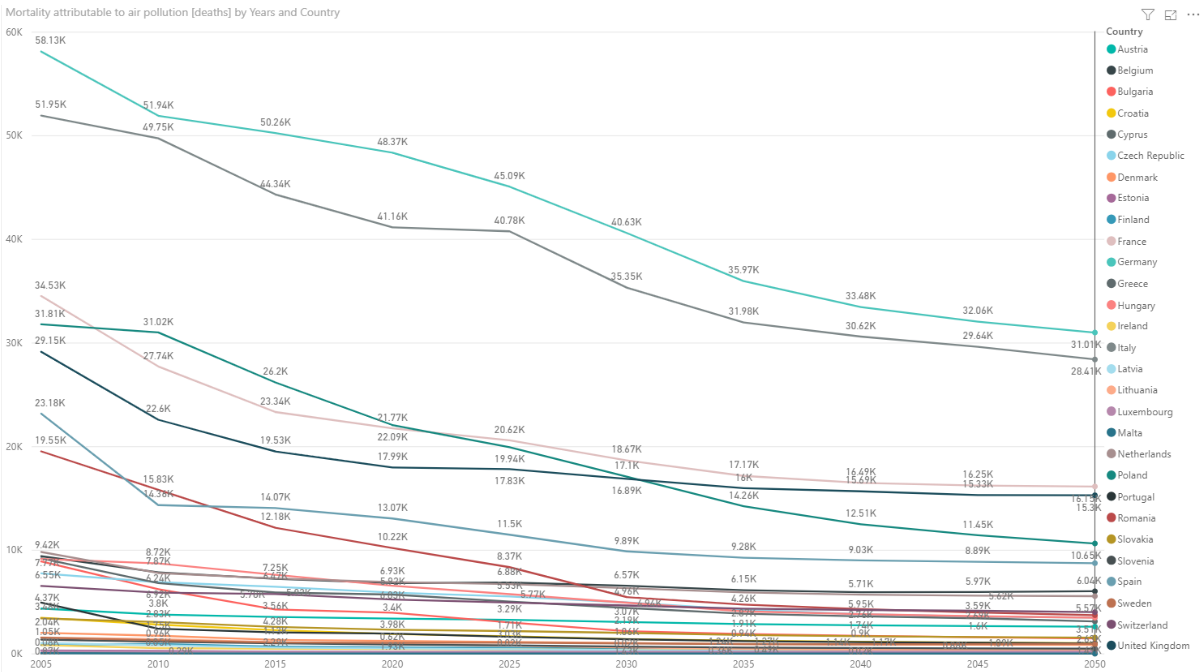


Figure A.6: Mortality per country per year in scenario with high ambition levels (all at level 4).