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ACCREU

Assessing Climate Change Risk in EUrope

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Changes with respect to the DoA

Due to the delay in the finalization of the Grant Agreement Amendment to include The Cyprus Institute (CYI) as a new partner in the consortium, the delivery date of the present deliverable was delayed by five months in agreement with the Project Officer.

1. Dissemination and uptake

Insights from the deliverable can inform policymakers and authorities at national and regional levels regarding the health impacts of climate change and air pollution in the near and long-term future, to account for both environmental risk factors at future policy design. Relevant stakeholders (e.g., European authorities, government agencies, environmental and climate agencies, healthcare systems, urban planners, etc.) can exploit the methodologies and results of this deliverable to design long-term emission reduction measures and protective actions in a coordinated framework.

2. Short summary of results

Fine particulate matter (PM2.5) remains a major health risk despite declining air pollution in Europe. This study assesses future impacts by combining three socio-economic pathways (SSP1-2.6, SSP2-4.5, SSP5-8.5) with climate scenarios. While PM2.5 levels are projected to decrease, attributable mortality varies by region and is strongly influenced by demographic changes, especially population aging and urbanization. Attributable mortality stabilizes after mid-century under lower-emission scenarios but rises under SSP5-8.5. By 2100, excess deaths could reach up to 808,000 annually in the worst case. The findings highlight that effective air pollution policies can mitigate health impacts, but only under sustainable development and moderate climate pathways.

3. Evidence of accomplishment

Manuscripts in preparation:

- Paisi N., Pozzer A., Steffens B., Bacer S., Lelieveld J., Excess mortality from PM2.5 exposure in Europe under future climate and sociodemographic pathways.

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Executive summary

This report, developed under the ACCREU project, evaluates the future health risks associated with fine particulate matter (PM2.5) pollution across Europe under various climate and socio-economic scenarios. PM2.5 remains one of the leading environmental health risks, significantly contributing to chronic diseases and excess mortality despite notable improvements in European air quality in recent decades.

Objectives and approach

The study aims to quantify how future climate change, air pollution, and demographic developments interact to influence health outcomes in Europe. It combines three Shared Socioeconomic Pathways (SSPs)—SSP1-2.6 (sustainability), SSP2-4.5 (middle-of-the-road), and SSP5-8.5 (fossil-fuel intensive)—with climate projections from CMIP6 models. These scenarios represent a wide range of potential futures, from strong mitigation and sustainability to high emissions and limited climate action.

Future PM2.5 concentrations were projected using multiple global climate models, while associated health impacts were estimated with the FUSION relative risk model. The analysis includes demographic projections such as population growth, aging, and urbanization, which are key factors in exposure and vulnerability.

Key findings: PM2.5 exposure

Across all scenarios, PM2.5 levels in Europe are expected to drop significantly in the near term (up to 2040–2050), mainly because of ongoing and planned air pollution control policies. The largest reductions occur under the sustainability pathway (SSP1), where emissions mitigation is most persistent.

However, long-term trends diverge across scenarios. Under SSP1 and SSP2, PM2.5 levels continue to decline throughout the century, reaching low average concentrations by 2100. In contrast, under SSP5, PM2.5 concentrations level off after mid-century due to counteracting effects of climate change, such as higher temperatures, reduced precipitation, and increased natural emissions like biogenic aerosols and wildfire-related pollution.

Importantly, population-weighted exposure trends differ from average concentrations. Urbanization and population growth, especially under SSP5, lead to increased exposure in densely populated areas, even when overall pollution levels decline.

Key findings: health impacts

The health burden from PM2.5 exposure, measured as excess mortality, is projected to decrease in the near future across all scenarios due to improved air quality. By 2050, mortality reductions compared to 2010 are estimated at about 55% under SSP1, 43% under SSP2, and 27% under SSP5.

Beyond mid-century, trends diverge significantly. Under SSP1, excess mortality continues to decline and stabilizes at relatively low levels by 2100. Under SSP2, mortality stabilizes or slightly increases. Under SSP5, however, excess mortality rises sharply after 2050, potentially reaching up to 808,000 annual deaths by 2100, roughly doubling current levels.

These differences highlight the strong influence of policy and development pathways on future health outcomes, with up to a fourfold variation in mortality between best- and worst-case scenarios by the end of the century.

Role of demographics

Demographic changes, particularly population aging and urbanization, play a central role in shaping future health risks. Even as air quality improves, the vulnerability to pollution-related diseases increases in an aging population. By 2100, the majority of excess mortality is projected to occur in older age groups, especially those over 80 or 90 years old.

Population growth and spatial distribution also affect exposure. Urban populations are expected to expand significantly, increasing the number of people exposed to pollution in high-density areas. These trends are most pronounced under SSP5, amplifying health risks despite technological and economic development.

Policy implications

The findings underscore that improvements in air quality alone are insufficient to guarantee reduced health impacts. While emissions reductions are essential, demographic trends and climate-driven changes in pollution dynamics must also be taken into account.

Key policy implications include:

- Sustained emissions reductions are critical to achieving long-term health benefits.
- Integrated climate and air quality policies are necessary, as climate change can offset gains in pollution control.
- Urban planning and public health strategies must address increasing exposure in growing cities.
- Adaptation measures targeting vulnerable populations, particularly the elderly, are essential.

The study also highlights the importance of aligning with ambitious climate pathways such as SSP1, which combine strong mitigation with sustainable socio-economic development. These pathways, which especially target fossil-fuel-related emissions, offer the most effective means of reducing both pollution levels and associated health burdens.

Conclusion

This report demonstrates that Europe’s future health burden from air pollution will depend not only on emissions reductions but also on broader socio-economic and climate trajectories. While near-term improvements are likely, long-term outcomes diverge sharply depending on policy choices. Sustainable development pathways can significantly reduce excess mortality, whereas fossil-fuel-driven economic growth may reverse progress and substantially increase health risks.

Ultimately, the results emphasize the urgency of coordinated climate, environmental, and public health policies to safeguard population health in a changing climate.

1. Introduction

Fine particulate matter pollution (PM2.5, with a diameter <2.5 µm) is recognized as a significant health hazard and is considered the leading environmental health risk factor, ranking among the top two causes of excess mortality worldwide (GBD, 2024). Over the past decades, air quality in Europe has significantly improved (Juginović et al., 2021; Turnock et al., 2020); however, the challenges posed by the aging population and urbanization (Akritidis et al., 2024), as well as climate change, call for an assessment of the potential health impacts of future pollution trends.

Climate change-driven meteorological changes can affect air pollution directly and indirectly. Temperature, precipitation, humidity, wind speed, and direction can influence boundary layer stability, cloud/fog formation, and radiation, all of which affect the transport, dispersion, and photochemistry of pollutants (Gilliam, et al., 2015). Specifically, temperature is an important parameter that directly affects the reaction rates and volatility of PM2.5 precursors (e.g., organic aerosols) and thus their partitioning between the gas and aerosol phases (Denier Van Der Gon et al., 2015, Paisi et al., 2023). Temperature is positively correlated with elemental carbon (EC), organic carbon (OC), and sulfate (SO_4^{2-}), and negatively correlated with nitrate (NO_3^-), whereas precipitation is negatively correlated with all these components (Bhattarai et al., 2024).

An important cause of air pollution exacerbated by climate change is the occurrence of wildfires (Lozano et al., 2017), which adds complexity to air pollution management. Natural aerosols, including biogenic emissions of particle precursors (e.g., isoprene, monoterpenes), are also affected by climate change. For example, higher temperatures directly affect plant photosynthetic activity (Hantson et al., 2017) and biogenic volatile organic compound (VOC) emissions, which are important precursors of organic aerosol particles (Bourtsoukidis et al., 2024). However, biogenic particles are less hazardous than combustion-related particles (e.g., from wildfires) (Aguilera et al., 2021). Air pollution and climate change strongly depend on the socioeconomic pathways that the world will follow to mitigate and adapt to climate change. Hence, the effects of climate change on PM2.5 pollution and its consequent health impacts require a comprehensive approach to evaluate and address environmental and public health challenges, link them to future scenarios, and develop adaptation strategies.

To project how the future climate may change due to atmospheric greenhouse gas (GHG) concentrations resulting from human activities, the Representative Concentration Pathways (RCPs) were developed within the framework of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014). However, these pathways include only components of radiative forcing and do not consider other factors such as socioeconomic development, emissions, or land-use changes.

To overcome this limitation, the scientific community, including climate scientists, economists, and energy systems experts, developed the Shared Socio-economic Pathways (SSPs) that explicitly account for potential changes in global societal, demographic, and economic trends over the century, considering the effects of climate warming. Within Phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al., 2016), in addition to the RCPs pathways, the multi-model climate projections are based on alternative scenarios that are directly relevant to societal concerns regarding climate change mitigation, adaptation, and impacts.

Integrated assessment models are commonly used to update emissions and land-use scenarios in light of future pathways of societal development (Gidden et al., 2019; O'Neill et al., 2016). The SSP narratives are linked with future climate radiative forcing (RF) outcomes (RCPs) in a scenario matrix architecture. The Tier-1 or top priority scenarios are updated versions of previous CMIP5-RCP scenarios (RCP2.6, RCP4.5, and RCP8.5) to allow for ease of comparison between CMIP5 and CMIP6 projections. These include SSP1-2.6 (sustainable green pathway), SSP2-4.5 (middle of the road), SSP3- 7.0 (regional rivalry), and SSP5-8.5 (fossil-fuel growth) and are designed to provide a full range of forcing targets similar in both magnitude and distribution to the RCPs (O'Neill et al., 2016) as used in CMIP5. Tier 2 scenarios include the SSP1-1.9, SSP4-6.0, SSP4-3.4, and the SSP5-3.4.

Future demographic and socio-economic trend estimates incorporate population projections based on expected changes in fertility, mortality, migration, and other drivers of population change (KC & Lutz, 2017). For instance, the level of education is a key driver not only of the population's capacity to adapt to climate change (Frankenberg et al., 2013) but also of population growth (Yang et al., 2023). It is important to note that the effects of sociodemographic changes across and among countries are likely to be highly relevant for accelerating future health progress (Murray, 2016). KC and Lutz (2017) have translated the SSP storylines to population and education pathways. For example, in SSP1, the assumption of strong investments in education and health was translated into a relatively low global population, low mortality, and a high level of education.

Migration levels and fertility assumptions were related to country categories. The low-mortality assumption was also applied in the SSP5 scenario regarding technological investments, economic growth, and higher education. Differences between the SSP5 and SSP1 pathways arise from assumptions regarding fertility rates, which are assumed to be high in high-income countries included in the Organization for Economic Co-operation and Development (OECD). Finally, the SSP2 scenario combines medium fertility for all countries, medium mortality, and medium migration with the Global Education Trend (GET) education scenario (KC & Lutz, 2017). In this study, we selected three socioeconomic and climate-warming scenarios for analysis that encompass the full range of climate change possibilities: SSP1-2.6, SSP2-4.5, and SSP5-8.5 (Table 1).

Table 1. Qualitative characteristics of the Shared Socioeconomic Pathways (SSPs) applied here.

Key driver	**Pathway**		
	SSP1 (Sustainability)	**SSP2 (middle of the road)**	**SSP5 (Fossil fuel development)**
Global average temperature increase by 2100	2 °C	3 °C	5 °C
European mean temperature change (°C) compared to pre-industrial levels **(adapted from IPCC WGI Interactive atlas)**	Near Term (2021-2040): 1.9°C Medium Term (2041-2060): 2.3°C Long Term (2081-2100): 2.3°C	Near Term (2021-2040 : 2.1°C Medium Term (2041-2060): 2.5°C Long Term (2081-2100): 3.3°C	Near Term (2021-2040 : 2.1°C Medium Term (2041-2060): 3.1°C Long Term (2081-2100): 5.5°C
Other reported measurements for the European average temperature increase	1.2-3.4°C by the end of the century (EEA, 2024)	1–2.5 °C at the midcentury in Northernmost latitudes (e.g., Norwegian Sea, Scandinavia, and -Russia) and in Southern-Mediterranean Europe (e.g., Iberian Peninsula and Turkey) (Carvalho et al., 2021)	3.5–5.5 °C in central Europe but reaching 5–6 °C in northern and southernmost areas (Carvalho et al., 2021)
Challenges to mitigation	Low	Intermediate	High
Capacity for climate adaptation	High	Intermediate	High
Global action for climate change mitigation	Early global collaboration as of 2020.	Some delays in establishing global action with regions transitioning to global cooperation between 2020 and 2040	Some delays in establishing global action with regions transitioning to global cooperation between 2020 and 2040
Fossil-fuel dependence	Low	Intermediate	High
CO_2 emissions	Low, reaching net-zero by 2050	Intermediate, falling after 2050 but not reaching net-zero	High, ongoing growth
EU population	Intermediate increase	Slow increase	Rapid increase
EU investment in education, technological development and health	High	Intermediate	High
Air pollution control	Strong	Medium (continues current trends)	Strong

These pathways represent a range of socioeconomic and greenhouse gas emissions trajectories. SSP1-2.6 represents a high sustainability pathway stabilizing radiative forcing of the climate to 2.6 W m^{-2} by the year 2100. The SSP2-4.5 pathway reflects an intermediate future forcing level of 4.5 W m^{-2} by the end of the century, and it is often used as the reference scenario due to its less extreme aerosol pollution and land-use developments (O'Neill et al., 2016; Pedersen et al., 2021).

In contrast, the SSP5-8.5 scenario follows a pathway of fossil-fuel development, and is characterized by high emissions, resulting in a radiative forcing of 8.5 W m^{-2} by the end of the century. Together, these scenarios effectively represent optimistic (SSP1-2.6), pessimistic (SSP5-8.5), and middle-of-the-road and most probable (SSP2-4.5)(Pedersen et al., 2021) future pathways, providing important insights for economic evaluation and policy design. For brevity, we will refer to them as SSP1, SSP2, and SSP5, respectively.

Additional details about the baseline scenarios can be found in KC & Lutz, 2017; O'Neill et al., 2016; Rao et al., 2017; Riahi et al., 2012. We analyze the impact of each scenario on PM2.5 pollution and health in Europe over the century, focusing on the near future (years 2030-2050) and the end of the century. More specifically, we estimate the future excess mortality due to long-term PM2.5 exposure at the European and national levels. Although other regional air quality and climate mitigation studies do exist (e.g., Chowdhury et al., 2018; Clayton et al., 2024), these mostly focus on non-European regions or use CMIP5 scenarios (Clayton et al., 2024). In this work, we focus on the European domain, which is underrepresented in the literature, using the most updated CMIP6 models. We present mortality estimates for the whole century, allowing for a clear comparison of the three studied SSP-RCPs scenarios. We use a recently updated relative risk model, FUSION (Burnett et al., 2022). Additionally, we investigate the role of population dynamics and demographic changes in the projected excess mortality.

Note that direct comparisons across different radiative forcing levels within the same socioeconomic pathways, such as the core scenario set used for the ACCREU project (SSP2 RCP2.6, SSP2 RCP4.5, SSP2 RCP7.0), were not possible because PM2.5 projections for these SSP-RCP combinations are not available in the CMIP6 database. Therefore, the analysis focuses on the combined effect of climate forcing and socioeconomic conditions on air quality rather than fully disentangling their individual effects.

2. Methods

2.1 Projection of PM2.5 exposure

The output data from the global numerical simulations conducted within CMIP6 were used in this work to attain future projections of PM2.5 concentrations. Specifically, three global models were used, CESM2-WACCM (Danabasoglu et al., 2020; Gettelman et al., 2019), GFDL-ESM4 (Dunne et al., 2020) and MRI-ESM2-0 (Yukimoto et al., 2019), which simulated all three climate change scenarios, SSP1-2.6, SSP2-

4.5, and SSP5-8.5 (2015–2099) (Pozzer et al., 2024). These models were selected for their data availability of monthly surface PM2.5 mixing ratios for the historical period (1980–2014) and three climate warming scenarios. We have explored the differences among the three global models in PM2.5 for the three scenarios and found relatively small differences, especially over Europe.

Monthly PM2.5 concentrations near the Earth's surface were converted into annual averages for the historical period (1980–2014) and the three future scenarios, and were downscaled and bias-corrected as described in Pozzer et al. (2024). The final data were adjusted using geographically weighted regression (GWR-adjusted PM2.5) at a spatial resolution of 0.1 × 0.1 degrees (about 8×10km at mid-latitudes). The data presented in this work are an ensemble of the three global models. Additionally, 20-year temporal means were used to assess projected future climate and air pollution changes under CMIP6. For example, the year 2050 represents the average over the period 2040–2060.

2.2 Projection of attributable mortality

To estimate excess mortality attributable to PM2.5 exposure ($M_{2.5}$), the final PM2.5 data as described above were used as input to the FUSION risk model (Burnett et al., 2022). The Fusion model is an improved relative risk (RR) model suitable for use in health benefits analysis that incorporates features of existing models. More specifically, it is a fusion of the Log−Linear model over low concentrations and functions whose derivatives decline with increasing concentrations (Burnett et al., 2022). The RRs are used to estimate the attributable fraction (AF(j,k)=RR(j,k)-1/RR(j,k)), which is the proportion of the baseline mortality that is attributed to PM2.5 exposure, as indicated in equation 1. Baseline mortality rates (BMRs) were obtained from the Institute for Health Metrics and Evaluation (IHME - https://vizhub.healthdata.org/gbd-results/) for the years 1990 to 2009 for each disease category (j).

These include: Chronic Obstructive Pulmonary diseases (COPD), Ischemic Heart Disease (IHD), Stroke, Lower Respiratory Infections (LRI), Lung Cancer (LC) and Type-2 Diabetes (T2D) for each age group (k): 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, and 80 plus. The AF and BMRs were combined with population projections (POP) at a horizontal resolution (x,y) of one-eighth degree (eq.1), which were obtained from SEDAC (Socio-Economic Data and Application Center (https://sedac.ciesin.columbia.edu/data/collection/ssp) and were age-distributed as described in Pozzer et al. (2024).

$$M_{PM2.5}(x,y) = BMR(x,y) \times POP(x,y) \times AF(j,k) \qquad \text{(eq. 1)}$$

Due to the unavailability of projections for baseline mortality rates (BMRs), attributable mortality is estimated using the 20-year mean BMR, which is maintained in future estimates. It should be noted that the average age of the population varies across SSPs, which, in turn, affects the BMRs. Typically, the higher the average age of a population, the higher the BMR. BMRs are a summary measure of a society's overall health, living conditions, and organization. It should be noted that keeping future BMRs constant in projections can lead to an overestimation of projected mortality by up to 30% (Turnock et al., 2020). The calculations were performed at each grid cell of our domain (x, y) and then aggregated to the country and regional levels.

2.3 Sectoral analysis

For the sectoral analysis, we calculated the consequences of four scenarios on air quality and attributable mortality. More specifically, the Earth System Model with Comprehensive Atmospheric Chemistry (EMAC) was used to compute the fractional changes in PM2.5 related to emission sectors based on simulations in which source categories were sequentially switched off (Lelieveld et al., 2023). The first scenario assumes that all fossil-fuel-related emission sources are phased out, consistent with the full implementation of the policies formulated under the EU Green Deal by 2050. This even exceeds the expectations under the global climate change scenarios SSP1-2.6, as outlined above. The second and third scenarios assume that 25% and 50% of the exposure reduction toward the fossil phase-out is achieved, respectively. For illustration, the fourth scenario removes all (potentially avoidable) anthropogenic sources, thus accounting only for natural sources such as aeolian dust, marine and terrestrial biosphere emissions, and natural wildfires.

3. Results

3.1 Future exposure to PM2.5

3.1.1 European level analysis

All three pathways project a notable decrease in the European average PM2.5 concentration by 2040, with an average decrease of more than 1 $\mu g/m^3$ per decade, depending on the scenario (Figure 1, left panel). This results from the anticipated air pollution control and emissions mitigation measures (e.g., in industry, power, and transport sectors) as a consequence of environmental, technological, or health pressures, depending on the scenario. Based on the SSP1 and SSP2 scenarios, the European average PM2.5 concentration is expected to continue decreasing by the end of the century relative to 2010, reaching European average levels of 3.9 $\mu g/m^3$ and 5.4 $\mu g/m^3$, respectively.

However, according to the SSP5 scenario, while a decrease in the average PM2.5 concentration is projected by mid-century, from 2050 onwards the European annual average PM2.5 is expected to stabilize at approximately 7 $\mu g/m^3$ (Figure 1, right panel). Although pathway SSP5 also assumes a firm air pollution mitigation policy, the climate change mitigation and adaptation actions are less pronounced than according to the SSP1 and SSP2 pathways, leading to higher radiative forcing and temperatures by the end of the century (see Table 1). Therefore, although primary PM2.5 emissions are expected to decrease under an SSP5 scenario (Carvalho et al., 2021; Coppola et al., 2021), the projected warmer temperatures can increase organic aerosols from increased emissions of biogenic Volatile Organic Compounds (VOCs) (Turnock et al., 2023), as well as aerosol lifetime (Heald et al., 2008) in some regions, which can partially explain the discontinuation of the average decrease in PM2.5.

Natural emissions can contribute to increases in PM2.5 concentrations, which are not directly affected by air pollution mitigation policies but can be affected by a changing climate (Scott et al., 2018). Following the SSP5 pathway, the future climate is projected to be drier, particularly in central-eastern Europe and the Mediterranean, compared with the SSP1 and SSP2 pathways. (Gutiérrez, J. et al, 2021). As precipitation is the main removal mechanism for natural and pollution particles from the atmosphere, aerosol lifetimes increase with reduced rainout in a drier climate, and, as a result, surface concentrations are higher (Heald et al., 2008). In addition, biogenic VOCs exhibit a strong positive correlation with temperature, which can explain increases in organic PM2.5 concentrations (Turnock et al., 2020; Boutsoukidis et al., 2024).

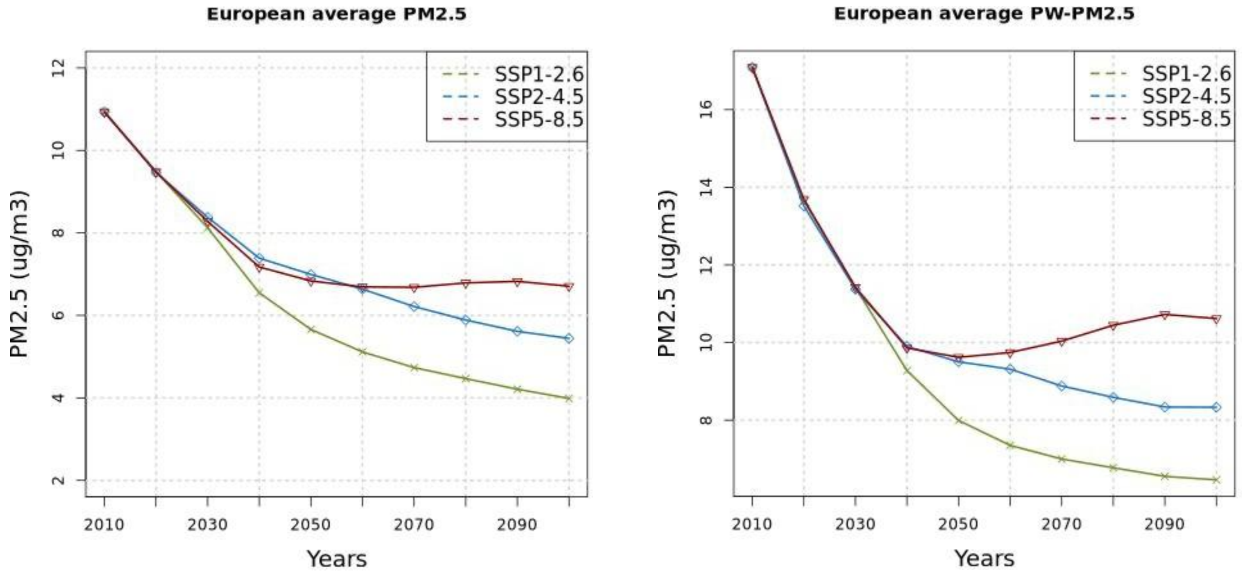


Figure 1. European annual-average PM2.5 (left) and population-weighted PM2.5 (right) across the century according to the SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios.

The population-weighted decrease in PM2.5 from 2010 to 2040 is larger than the absolute decrease, suggesting that air pollution control measures will reduce PM2.5 levels in populated areas. Following the SSP5 scenario, the population-weighted PM2.5 increases more than the European average PM2.5 (without normalizing for population), suggesting that changes in the population's distribution drive the majority of the projected increase after mid-century (Figure 1). As a result, and in contrast to what is expected in the near future, more people will be exposed to relatively higher PM2.5 levels after mid-century, following an SSP5 scenario. This is potentially due to a combination of increased urbanization (Jiang & O'Neill, 2017; Riahi et al., 2017) and the fact that most of the increases in PM2.5 levels will occur in densely populated areas (Clayton et al., 2024).

3.1.2 Country-level analysis

Considering the near future (i.e., 2050), all three SSP scenarios indicate that annual PM2.5 concentrations over Europe will significantly decrease compared to the 2010 reference (Figures 2 and 3, generally achieving PM2.5 concentrations well below 25 μg/m³ by 2050. Northern European countries and the northern UK, which already have relatively low air pollution levels compared to other European regions, are expected to achieve PM2.5 levels below 5 μg/m³ in 2050, regardless of the scenario.

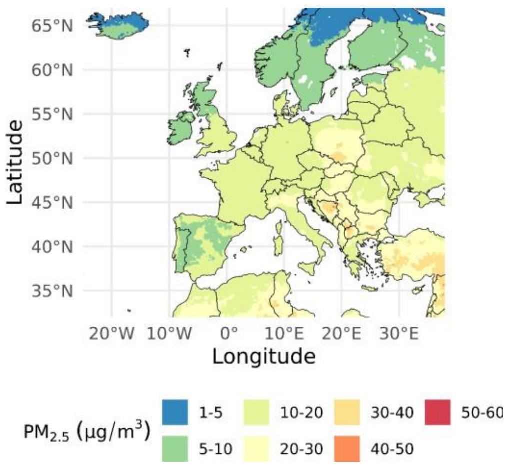


Figure 2. Annual average PM2.5 in the reference year (2010). The horizontal grid resolution is 0.125 degrees.

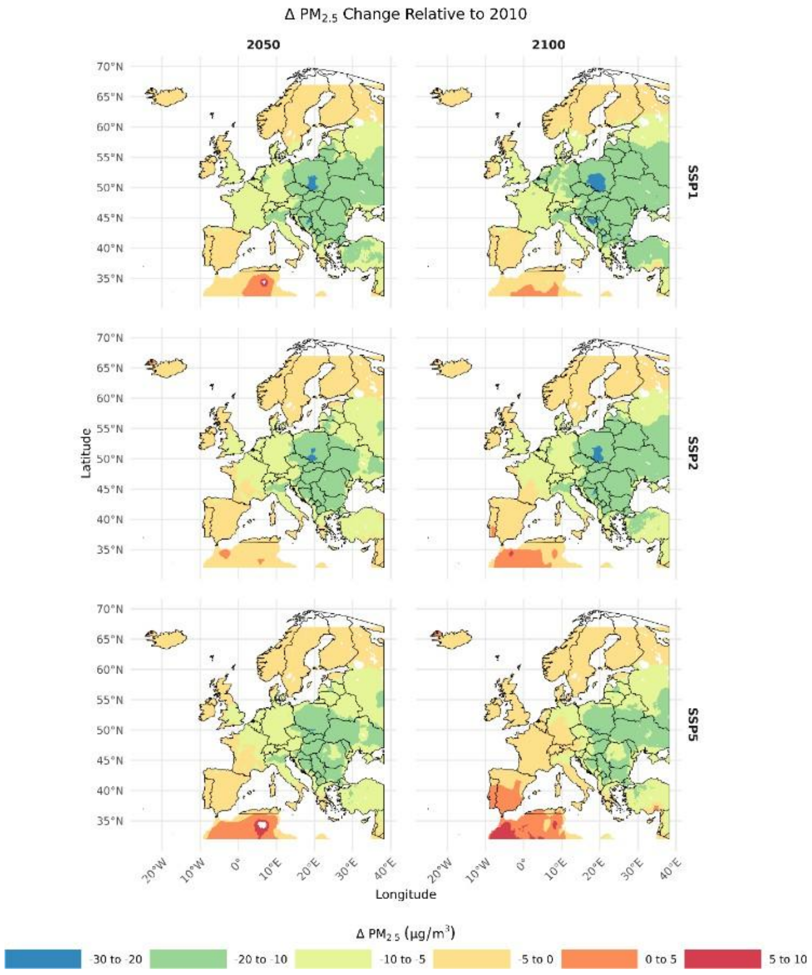


Figure 3. Differences in PM2.5 by 2050 (left) and 2100 (right) compared to the reference year (2010), according to SSP1 (top), SSP2 (middle) and SSP5 (bottom) scenarios.

These levels are within the World Health Organization's (WHO) health protection guidelines, which are a crucial goal for effectively reducing the health burden of air pollution. Central-West Europe (e.g., Germany, the Netherlands) is also projected to reach such low PM2.5 levels, but only under a sustainable scenario (SSP1), where annual mean concentrations are expected to decrease to about 10 µg/m^3.

It should be noted that the current European Union’s legally binding maximum annual PM2.5 level is 20 µg/m^3 (2008/50/EC, European Council, 2008), well above the WHO guideline of 5 µg/m^3. Several regions in Southeastern Europe, including Bosnia and Herzegovina and North Macedonia, are expected to still exceed these levels by 2050. This suggests that these countries require additional efforts to reduce PM2.5 concentrations to WHO guideline levels to effectively mitigate excess mortality attributable to air pollution. Further to the generally decreasing PM2.5 concentrations across European countries, other factors can affect excess mortality rates by increasing population exposure and vulnerability (see section 3.2) (Yang et al., 2023). According to the intermediate pathway (SSP2), the population-weighted annual PM2.5 levels across all EU countries are anticipated to decrease by 2050 by between ~37% (e.g., in Moldova and Portugal) and 73% (e.g., in Luxembourg) compared to 2010 levels. In most EU countries, the reduction will range from ~50% to ~60%. Under a sustainable pathway (SSP1), the reduction in PM2.5 levels relative to 2010 will be greater than under SSP2, with most EU countries experiencing reductions of ~55% to ~70%.

The lowest reduction compared to 2010 will be in Portugal (~42%) and Greece (~46%), and the highest in Luxembourg (78%) and the Czech Republic (~74%). While the fossil-fuel development pathway (SSP5) is also expected to result in decreased national annual PM2.5 averages in all EU countries by 2050 due to emission control measures, the reductions will be somewhat smaller, ranging from ~32% to ~71% relative to 2010.

Furthermore, we have examined the changes in population distribution over Europe by the middle and end of the century. According to the most probable scenario (SSP2), the European population in 2050 is expected to increase by around 20% to 60% compared to 2010 (at the grid level of approximately 8×10 km), especially in western European urban areas, where we project growth up to 80% (Figure 4). In contrast, most central European cities are expected to see a population decline of up to 20% compared to 2010.

As illustrated in Figure 4, a sustained and pronounced population growth in large cities is present by 2100, increasing it between 60% to 80% compared to 2010; meanwhile, rural areas are expected to continue losing population, declining by up to about 60% compared to 2010. Eastern Europe is projected to experience the largest population decline, while northern Europe is expected to see the largest increase, ranging from approximately 60% to 80%. The distribution of the European population projected from the SSP1 and SSP5 scenarios differs slightly.

In summary, following an SSP5 scenario, population changes are more substantial over time compared to the other scenarios, largely due to assumptions of a rapid population increase. These demographic changes can lead to greater human exposure to PM2.5 concentrations, primarily in urban areas, as well as increased vulnerability to higher temperatures due to the urban heat island effect (Marcotullio et al., 2022; Zittis et al., 2021). In addition, PM2.5 pollution in urban areas typically originates from combustion-related sources (e.g., traffic, domestic heating), which are considered particularly hazardous and can worsen health impacts (Daellenbach et al., 2020; Paisi et al., 2024). Although these factors are not reflected in our calculations, they are recommended for consideration in future calculations.

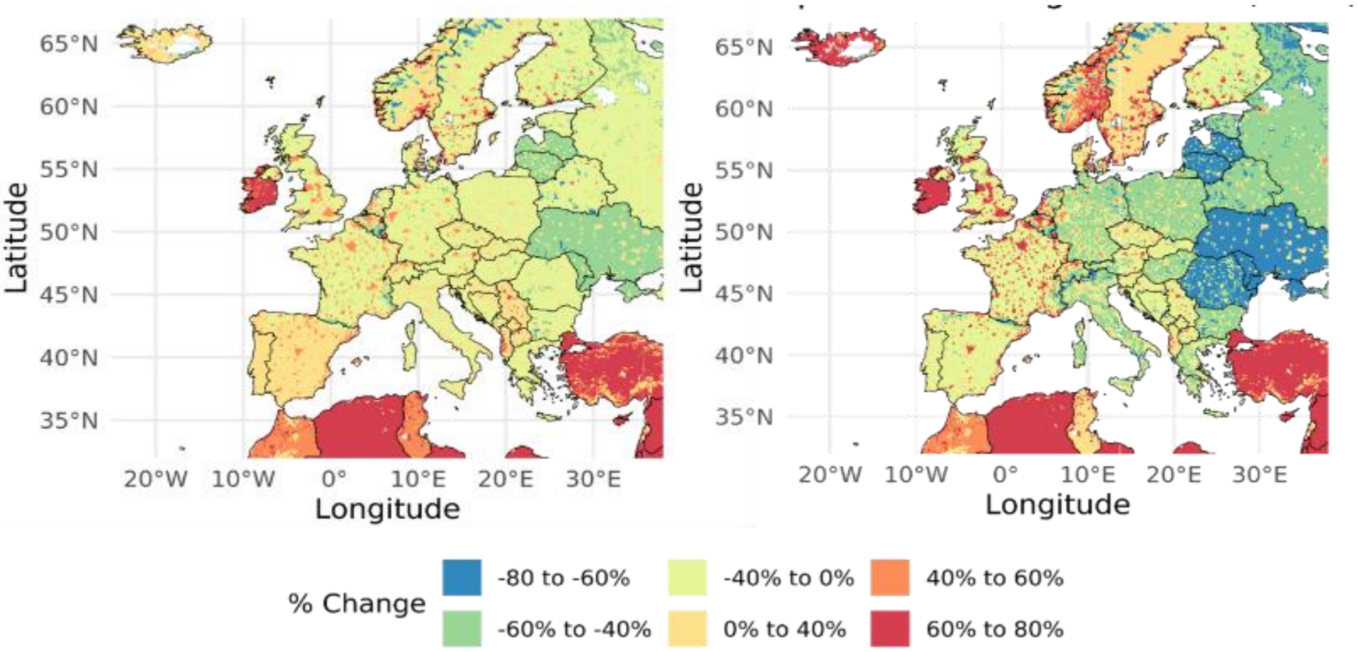


Figure 4. Relative population changes by 2050 (left) and 2100 (right) compared to 2010 according to the pathway SSP2-4.5. The horizontal grid resolution is 0.125 degrees.

3.2 Projected future mortality due to PM2.5

3.2.1 Projections for the near and long-term future

If Europe follows a sustainable pathway similar to the one outlined in scenario SSP1 over the coming decades, exposure to PM2.5 and the total projected excess mortality are expected to decrease significantly. Specifically, excess mortality is projected to decline from 482 (267-745) thousand in 2010, to 216 (69-493) thousand in 2050, and 199 (56-561) thousand by the end of the century (Table 2). These totals integrate the results for all countries. The 95% confidence intervals are given in parentheses.

On average, excess mortality due to PM2.5 exposure in Europe is expected to decrease by 37.5%, 40.6%, and 37.3% in 2030 compared to 2010, according to pathways SSP1, SSP2, and SSP5, respectively. Thus, the projected differences in health impacts across these scenarios are relatively small in the near future. The total excess mortality will continue to decrease until 2040 across all scenarios, driven by declining PM2.5 exposure; however, the decrease under SSP5 is smaller than under SSP1 and SSP2. Notably, the differences between scenarios start to diverge from 2050 onwards.

It is projected that, in 2050, the decrease in excess mortality relative to 2010 will be 55%, 43%, and 27% for pathways SSP1, SSP2, and SSP5, respectively. The average decrease in European excess mortality under SSP5 is smaller than in the other scenarios because of the very high increases (positive differences) in mortality in a few countries, such as Cyprus and Iceland (over 200% increase compared to 2010, due to population growth).

Table 2. Excess mortality in Europe (thousands per year), integrated over all countries, presenting the average and 95% confidence interval in parentheses. The numbers for each year refer to excess mortality as a 20-year average.

SSP	2010	2030	2040	2050	2100
1	482 (267-745)	301 (138-533)	244 (92-488)	216 (69-493)	199 (56-561)
2	482 (267-745)	286 (129-7509)	248 (96-483)	274 (99-551)	323 (98-719)
5	482 (267-745)	302 (138-534)	281 (112-539)	352 (136-683)	808 (341-1489)

The pathway dependent on fossil fuels (SSP5) is expected to result in an increase in excess mortality after 2050, potentially reaching up to 808 (341-1489) thousand annual excess deaths by 2100, nearly twice the excess mortality in 2010. However, this is a pessimistic future pathway that is less likely to happen.

The middle-of-the-road SSP2 and most probable scenario will also lead to a slight increase in excess mortality after 2040, which will then stabilize by the end of the century (323 (98-719)) (Table 2, Figure 8, bottom-right). In contrast, a sustainable pathway like SSP1 will lead to a notable decrease in excess mortality by 2060, after which it will stabilize by 2100.

The projected increase in excess mortality following the SSP5 pathway is attributed to a combination of factors, including population aging, which is included in the projections for these SSP scenarios. As mentioned earlier, population growth is one of the important factors directly affecting excess mortality estimates.

However, since the population-normalized excess mortality is also projected to increase (Figure 8, top-left), this suggests that other factors play a more important role in this increase and are discussed in the following section. Overall, the health burden resulting from these three scenarios differs by up to a factor of four by the end of the century, underscoring that policy decisions related to future air quality, climate, and health are crucial.

3.2.2 Implications of population growth and aging

According to the studied projections, by 2050, excess mortality attributable to PM2.5 pollution in Europe will be highest among individuals aged 80 to 84 years across all scenarios, with no significant differences in the age distribution of excess mortality among the three scenarios (Figure 5, top panel).

The younger population (e.g., 25–49) projected for 2050 will still be smaller in number than the older population (e.g., 80+), suggesting that aging will not be the primary driver of vulnerability to PM2.5 pollution by then. However, by the end of the century, excess mortality will likely shift to older age groups (e.g., >90 years), especially under the SSP5 scenario (Figure 5, bottom panel), indicating that more elderly people will die prematurely from chronic exposure than younger people.

By 2100, the scenarios SSP1 and SSP5 project higher numbers of older people (e.g., over 80) than SSP2, as well as higher numbers of older people than of younger people (Figure 6). The more pronounced population aging projected for 2100 will increase vulnerability to air pollution-related health exposure and contribute to the higher projected excess mortality in these age categories.

In addition, by 2050, the age distribution of excess mortality following a pathway like SSP1 or SSP2 is more evenly spread, but remains shifted to older age groups. This is due to the assumptions of a slower population growth in these two scenarios than in SSP5. The differences in projected 2100 excess mortality among the three scenarios increase with age category, varying by more than a factor of two. This trend underscores the importance of population aging and its impact on the European mortality burden.

To further analyze the role of population age, we also estimated the years of life lost (YLL) in the near and long-term future in the adult population (Table 3). YLL estimates reflect both the number of deaths and the age at which they occur, providing a comprehensive measure of the mortality burden. Our results indicate a decrease in YLL in Europe by 2040 across all scenarios. After 2040, YLL is projected to continue decreasing under the SSP1 and SSP2 scenarios until 2100, whereas under the SSP5 scenario, it remains relatively constant.

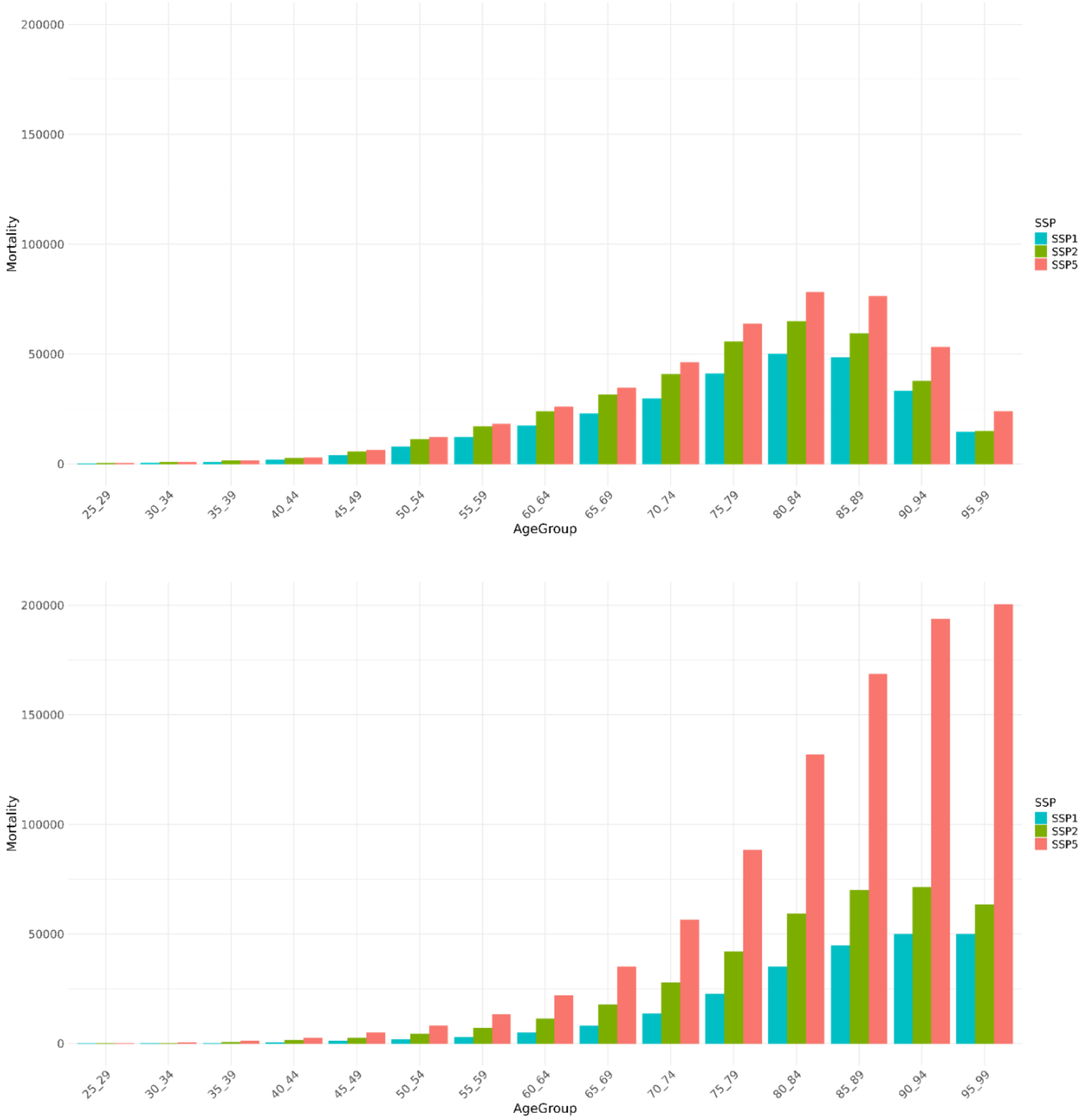


Figure 5. Excess mortality in Europe per age group projected for 2050 (top) and 2100 (bottom) according to the scenarios SSP1-2.6(blue), SSP2-4.5 (green), and SSP5-8.5 (red).

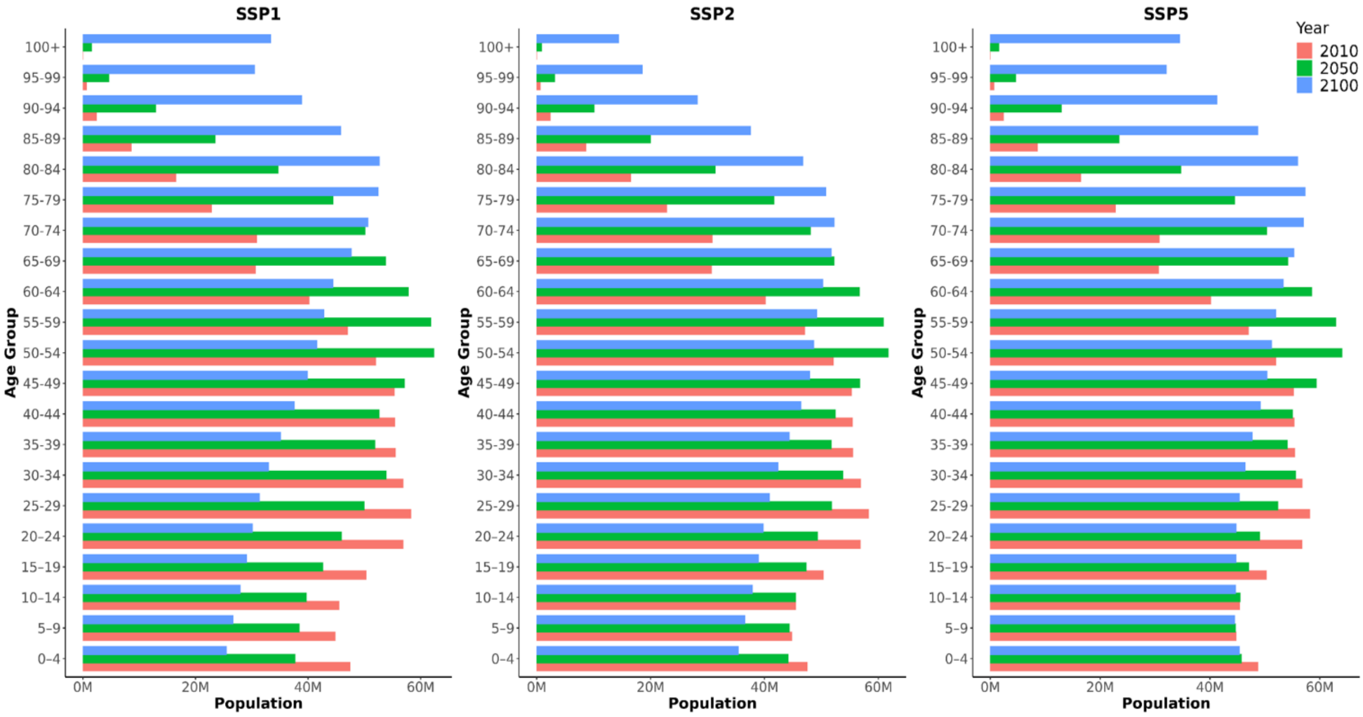


Figure 6. Projected European population by age group in 2010, 2050, and 2100 according to SSP1 (left), SSP2 (middle), and SSP5 (right).

Table 3. Projected years of life lost (in thousands) due to PM2.5 pollution in Europe related to the adult population (>25 years) in the coming decade, mid-century, and end of the century.

Pathway	2020	2030	2040	2050	2100
SSP1	261 (279-331)	222 (245-281)	162 (179-207)	121 (132-155)	52 (56-68)
SSP2	256 (274-324)	215 (238-272)	173 (192-222)	156 (172-200)	95 (104-124)
SSP5	260 (279-330)	222 (245-281)	182 (202-234)	175 (194-226)	175 (198-234)

Even if excess mortality in 2100 increases in older age groups compared to younger ones (Figure 5), the remaining high number of YLL projected by 2100 in SSP5 suggests that premature deaths (in the younger population) will still occur in significant numbers, thereby negatively influencing the European health burden. Another reason is the expected mean life expectancy that will be higher by the end of the century (98.8 years for Europe) compared to 75.5 years in 2020–2025) (Wittgenstein Centre Human

Capital Data Explorer), which increases the remaining years of life, which can potentially be lost due to the increased chronic exposure.

Furthermore, we have examined the future changes in excess mortality and population at the country level. There is no doubt that the overall decrease in excess mortality in Europe by mid-century results from reduced exposure to PM2.5, which may be influenced by the decarbonization of the energy sector. However, certain countries, including Portugal, Iceland, and Cyprus, are expected to experience an increase in excess mortality by 2050, up to ~40% compared to 2010, regardless of the scenario (Figure 7). The decrease in PM2.5 in these countries is projected to be less than 5 µg/m^3. This relatively small decrease in PM2.5, combined with the significant projected increase (up to 80% compared to 2010) in the population by 2050, for example, in Cyprus, Portugal, and Iceland (Figure 4, left panel), partially explains the projected increase in excess mortality in these countries.

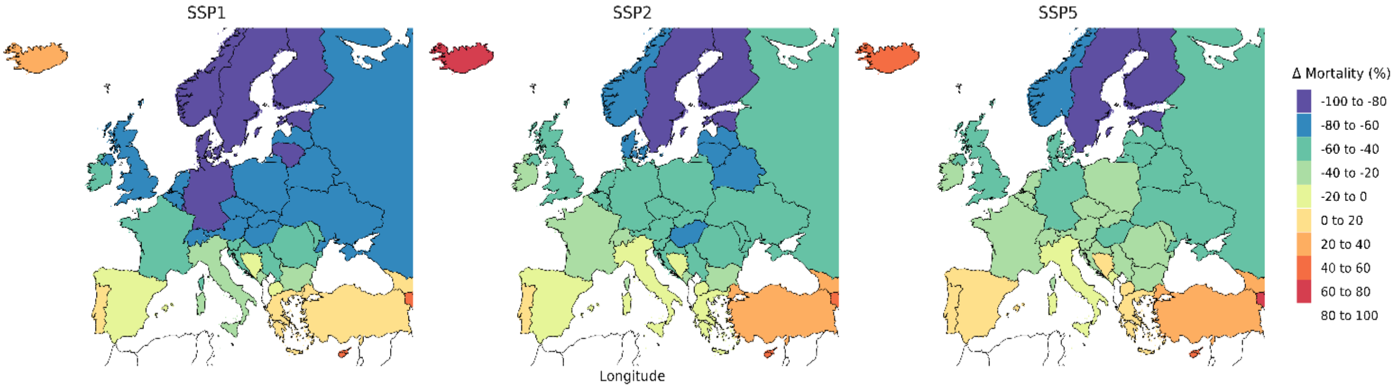


Figure 7. Relative change in population-normalized excess mortality by 2050 compared to 2010, per country and SSP scenario.

It is important to note that the European average age of the population is expected to increase from around 50 in 2010 to 55 by mid-century, and over 60 by the end of the century (Figure 8). Aging of the population is anticipated to occur across Europe; according to the SSP2 pathway, by 1.3 to 4.5 years in 2050 relative to 2010. Population aging is most pronounced following the SSP1 scenario. Demographic shifts are crucial in excess mortality estimates. Aging increases exposure duration, vulnerability, and baseline mortality rates, hence, excess mortality.

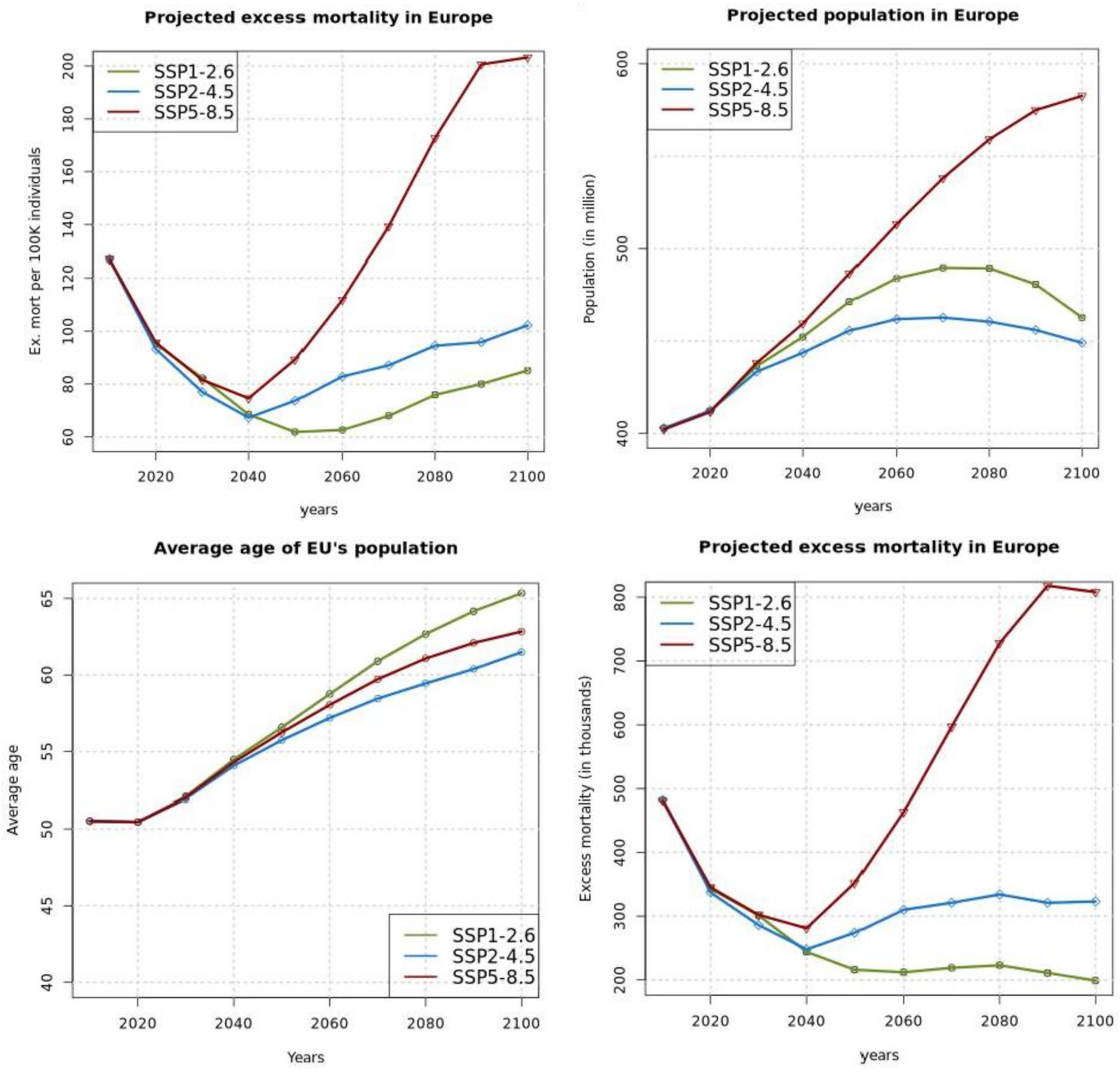


Figure 8. Projected population-normalized excess mortality (top-left), population (top-right), average population age (bottom-left), and total excess mortality (bottom-right) for the three SSP scenarios in Europe.

Figures 9 and 10 illustrate the population-normalized (top) and total excess mortality (bottom) per country, as well as per population-weighted PM2.5, for the years 2030 and 2050, based on the most probable intermediate (SSP2) scenario. The figures also display the population size (rounded to the nearest million) for these years. Our results indicate a notable shift towards lower PM2.5 exposure across all countries from 2030 to 2050, alongside an aging population. This demographic shift reflects both the projected increase in life expectancy and the moderating fertility rates in this scenario (KC & Lutz, 2017).

Figure 9. Population-normalized excess mortality (top) and total excess mortality (bottom) due to PM2.5 per country versus the average age of the population for the years 2030 (green) and 2050 (orange), according to the SSP2 scenario. The size of the bullets indicates the population size.

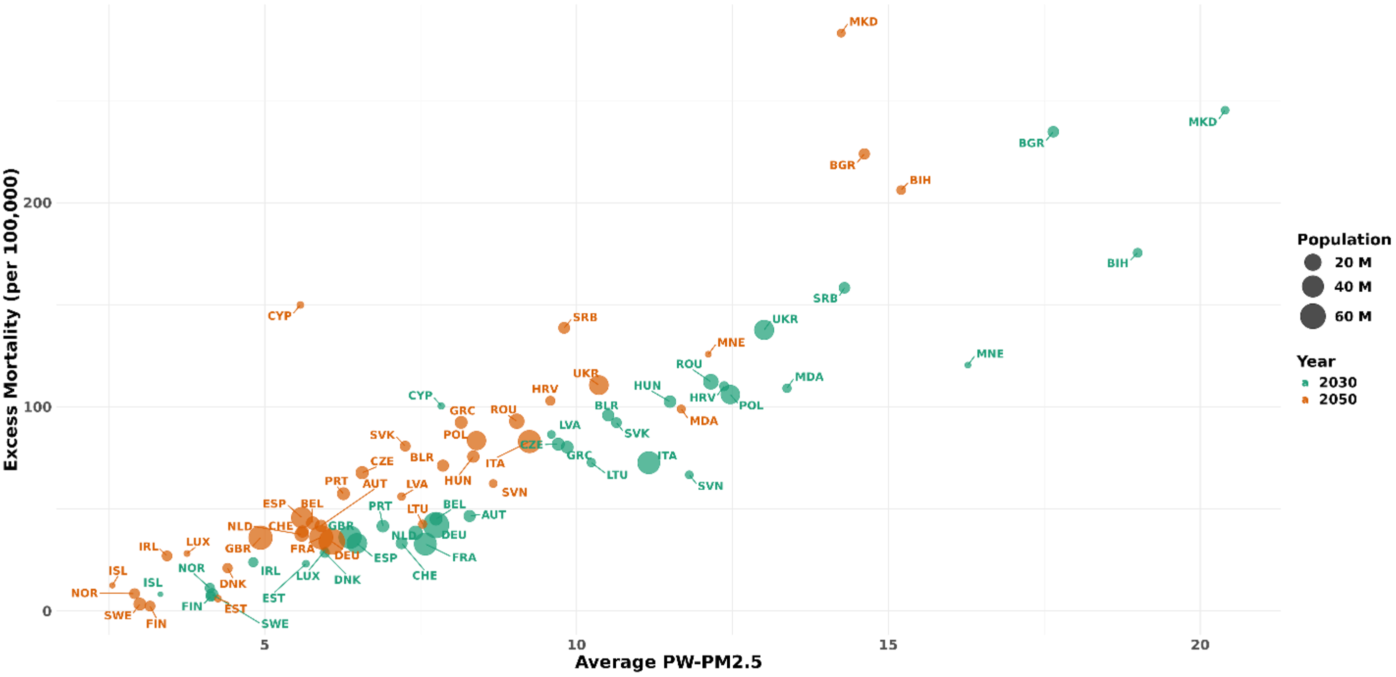


Figure 10. Population-normalized excess mortality due to PM2.5 per country versus the population-weighted PM2.5 for the years 2030 (green) and 2050 (orange), according to the SSP2 scenario. The size of the bullets indicates the population size.

Moreover, as expected, we find a positive relationship between population-weighted PM2.5 and excess mortality: countries with higher PM2.5 concentrations have higher excess mortality rates. Despite a decrease in population-weighted PM2.5 concentrations by 2050 compared to 2030 (Figure 10), the excess mortality rates increase, possibly due to the abovementioned demographic changes in population. By mid-century, some countries may experience an increase in their total population (e.g. Iceland, Ireland, UK, France, Spain, Belgium, Germany, Portugal, Sweden, Finland, Denmark, Cyprus, North Macedonia, Austria, The Czech Republic, France, Italy, Netherlands, Switzerland, Serbia), and others a decrease (e.g., Ukraine, Poland, Rumania, Greece, Bosnia & Herzegovina, Belarus, Bulgaria, Estonia, Hungary).

By mid-century, excess mortality from PM2.5 exposure is projected to increase in North Macedonia, Cyprus, France, Greece, Iceland, Ireland, Italy, Montenegro, Portugal, Spain, and Switzerland, whereas in other European countries it will likely decrease. Since PM2.5 exposure will decrease across all countries by mid-century, sociodemographic factors will drive these changes. For example, in Bulgaria, Bosnia and Herzegovina, and Greece, the population is expected to decrease, as is the age structure, which explains the slightly increasing PM2.5-related excess mortality. In countries where the population is both aging and increasing, the increase in excess mortality is larger (e.g. in North Macedonia). In countries like

Ukraine, excess mortality is projected to decrease by 2050 despite population aging, due to a decline in the population relative to 2030.

Furthermore, we have explored the contribution of each sociodemographic factor (population aging and growth) and PM2.5 pollution to the change in future excess mortality based on the most realistic scenario (SSP2-4.5). The decomposition analysis was performed with the Brute force method, as described in Geng et al (2021). For the three factors, we used six decomposition sequences, and the mean value of the incremental impact of each factor through all six sequences was calculated. For the first half of the century (2010-2050), we find that the reduction in PM2.5 concentration contributes the most (-87%) to excess mortality reduction, followed by population aging (+55%) and growth (+2%).

After the middle of the century, PM2.5 pollution contributes less to excess mortality change (-19%), with population aging and growth being the most (+75%) and least (-7%) significant factors, respectively (Figure 11). It should be noted that the individual effects of climate on air quality and health were not included in this analysis; however, we emphasise that societal behaviour is what strongly affects air quality and PM2.5-attributable mortality. While the RCP-based scenarios for different SSPs reach the same level of warming, how society gets there, as described by the SSPs, strongly changes air quality and health impacts, as shown in this report.

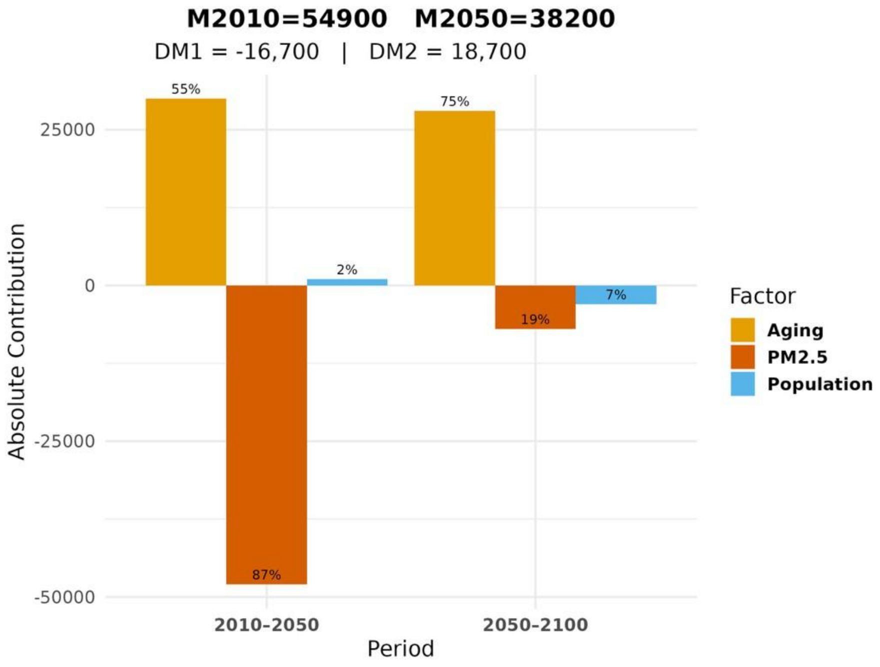


Figure 11. Contribution of population growth, population aging, and PM2.5 pollution to excess mortality changes between 2010 and 2050, and between 2050 and 2100, under the SSP2-4.5 scenario.

3.2.3 EU Green Deal: phasing out fossil fuels

The European Green Deal is the EU27's major policy initiative to make Europe the first climate-neutral continent by 2050; it was proposed in 2019 and formally approved in 2020. It sets out a comprehensive roadmap to transform the EU's economy by reducing greenhouse gas emissions, promoting sustainable industry, and protecting natural ecosystems. A central pillar of the Green Deal is the gradual phase-out of fossil fuels across key sectors, including energy production, transportation, industry, and buildings.

In the energy sector, the transition focuses on replacing coal, oil, and natural gas with renewable energy sources such as wind, solar, and hydropower. Many EU countries have already committed to closing coal-fired power plants within the next decade, which can be expected to yield significant air-quality and health benefits. In transport, policies promote the adoption of electric vehicles, stricter emissions standards, and investment in public transportation and rail infrastructure. Meanwhile, industries are encouraged to adopt cleaner technologies, improve energy efficiency, and shift toward green hydrogen and electrification. The building sector is also undergoing change, with efforts to improve insulation, reduce heating demand, and replace fossil-fuel-based heating systems with heat pumps or district heating powered by renewables.

The consequences of these measures for atmospheric pollution are significant. Phasing out fossil fuels reduces emissions of carbon dioxide (CO_2), the main driver of climate change, as well as harmful pollutants such as nitrogen oxides (NOx), sulfur dioxide (SO_2), volatile organic compounds (VOCs), and fine particulate matter, in particular the most hazardous fraction, such as black and organic carbon. Urban areas, where traffic and heating emissions are concentrated, are likely to see the greatest benefits. However, the transition also presents challenges, including economic adjustments for fossil-fuel-dependent regions and the need for large-scale investment in infrastructure and innovation. Overall, the European Green Deal, when implemented, represents a major step toward a cleaner environment and a more sustainable future.

Here, we assess the consequences for air quality and associated excess mortality by assuming a full phase-out of fossil fuels by 2050, which, when realized, would even exceed the ambitions of the SSP1 scenario in Europe, with intermediate steps of 25% and 50% achievements of the phase-out to illustrate the health benefits of partially achieving a fossil fuel phase-out towards 2050, representing "quarterway" and "halfway" scenarios (Lelieveld et al., 2023).

Figure 12 illustrates the excess mortality across all EU27 countries linked to pollution emissions, notably from fossil fuel use. These emissions mainly originate from industrial activities (such as iron, steel, and aluminum production), chemical and transformation processes (including coal and coke production and combustion, as well as petroleum refining), transportation, and power generation based on coal, oil, and gas. Coal combustion alone accounts for about half of these emissions.

Globally, 61% of the total excess mortality burden (both avoidable and unavoidable) is linked to fossil fuel-related air pollution. In the EU27, this fraction is even higher, in line with most high-income regions. If all anthropogenic pollution emissions in Europe could be eradicated, attributable mortality would be reduced by 95%. Remarkably, if fossil fuels were phased out, it would decline by 92%; hence, it accounts for the majority of excess mortality attributable to human-made air pollution in the EU27.

4. Conclusions

Air pollution in Europe is expected to continue to decrease over the coming decades; however, we find that future exposure to PM2.5 and the associated health impacts will depend heavily on changes in population and demographic factors, such as age structure, location, and growth rates.

We find that the strong and current air pollution control measures assumptions in SSP1 and SSP2, respectively, are effective in stabilizing future excess mortality due to PM2.5 pollution by the end of the century. However, even the strongest air pollution control measures will not be sufficient to offset the excess mortality in a future with much higher population growth rates and aging (e.g., SSP5).

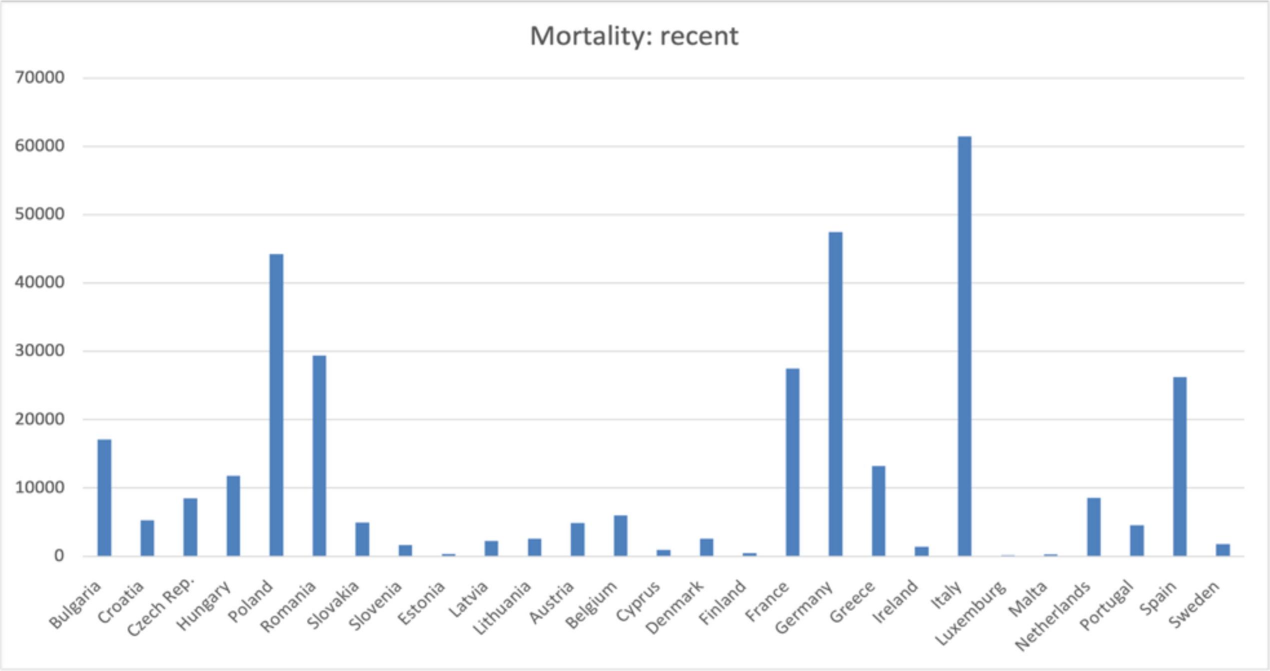
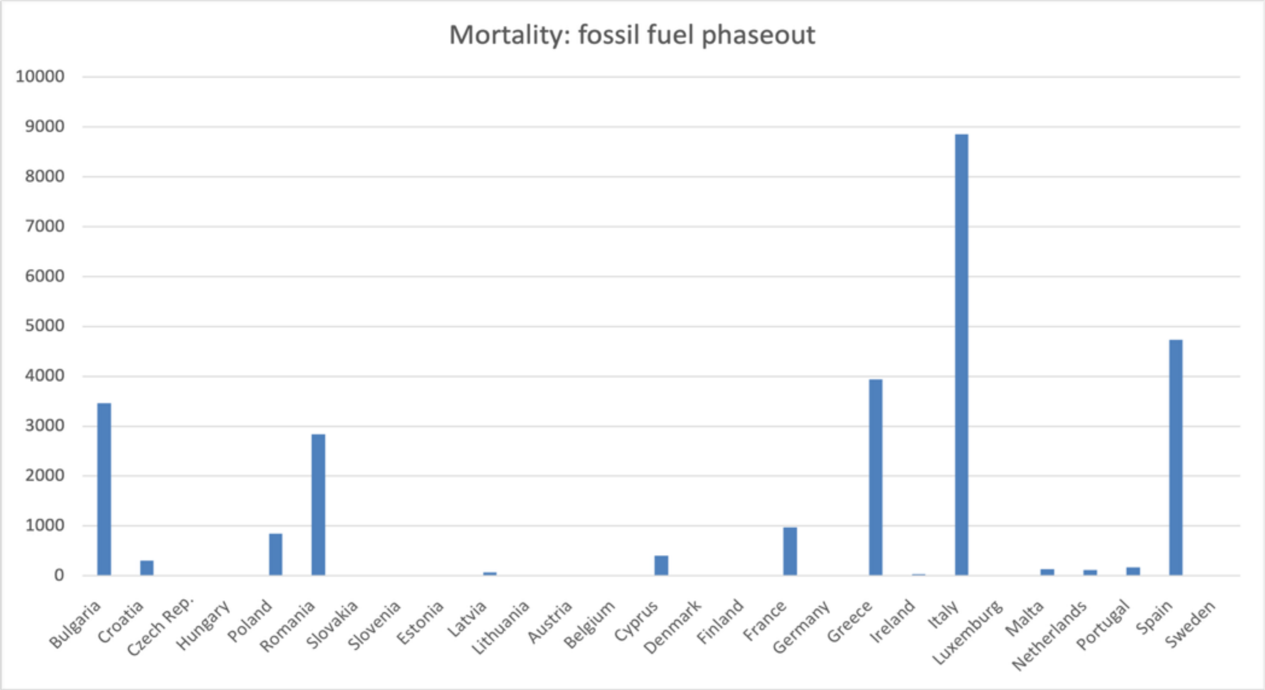


Figure 12. Annual attributable mortality for the EU27, from 2019 (recent) to 2050, assuming 25%, 50%, and 100% reductions in fossil fuel-related emissions. The EU's Green Deal aims for carbon neutrality by 2050. Note scale changes of the y-axis below.



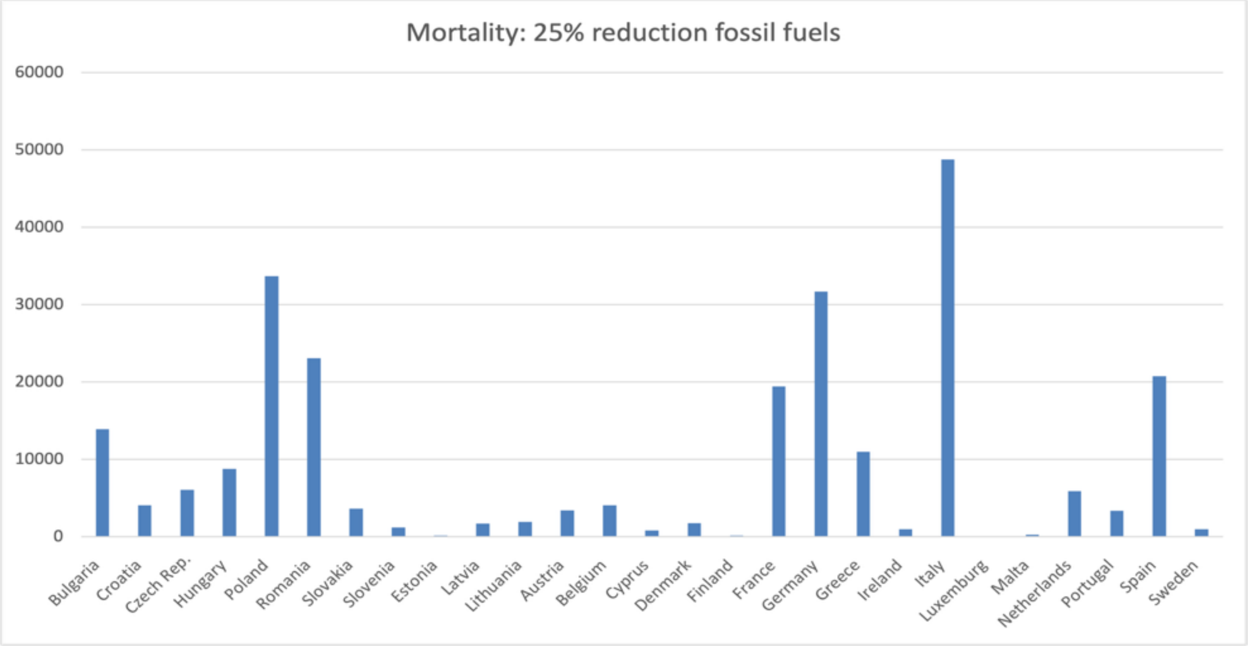


Figure 12. Continued.

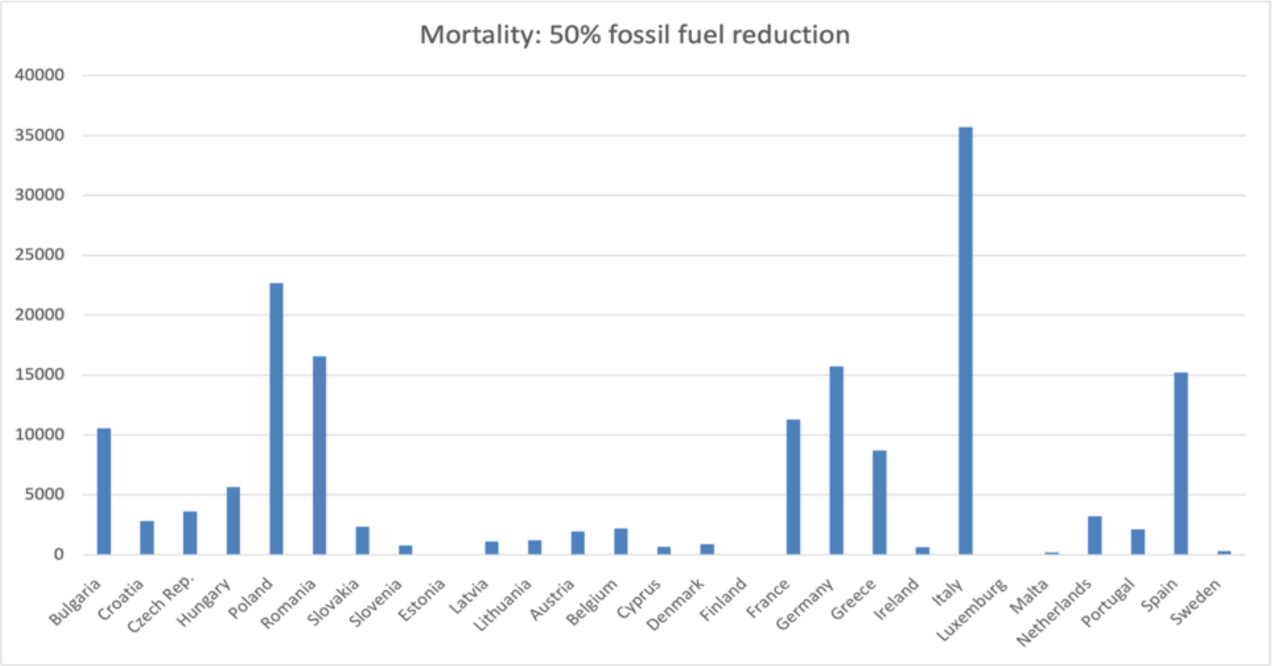


Figure 12. Continued.

Despite improvements in air quality, PM2.5 concentrations in most European regions (excluding northern countries) may still exceed the WHO guideline limits regardless of the scenario. It is essential to reach PM2.5 levels below the WHO guideline concentrations to offset any increases in excess mortality driven by changes in population characteristics, which could be achieved by a full phaseout of fossil fuels, partially accompanied by additional air pollution control measures in some countries.

Our results indicate that urbanization is expected to increase population exposure to PM2.5. In a pessimistic future scenario, such as SSP5-8.5, PM2.5 exposure is projected to rise, particularly in densely populated areas at risk of PM2.5 exposure exacerbated by climate change. The differential toxicity of PM2.5 is not taken into account in this study; we expect that the health impacts due to PM2.5 are anticipated to be more severe in urban settings, due to the increased hazardousness of PM2.5 in these areas compared to those in rural locations, as well as the effects of rising temperatures, including the exacerbating urban heat island effect. In addition, the combined effects of projected temperature increases by 2100, particularly in SSP5, and urban air pollution can affect both younger and relatively older populations.

Importantly, the CMIP6 models account for the effects of climate change on PM2.5, and therefore, the climatic effects related to air pollution are included in this work. However, we find that the projected excess mortality varies significantly between countries, age groups, diseases, years, and scenarios. The multiple factors that can affect excess mortality numbers make the projections challenging to interpret. In addition, the different assumptions (socioeconomic or climate-related) applied in each SSP require different lag periods to take effect, highlighting the importance of observing the effects of each SSP-RCP scenario over the whole century. Overall, our results indicate that the effects of each SSP-RCP scenario on air pollution and human health differ after mid-century.

Unlike population dynamics, anthropogenic PM2.5 and precursor emissions can be regulated; therefore, controlling PM2.5 concentrations should remain a priority in Europe. We also highlight the importance of climate change mitigation and the co-benefits it can provide in reducing health impacts due to air pollution. As a result, urban areas should implement effective PM2.5 pollution mitigation measures, sustainable planning, and other strategies to enhance resilience.

Furthermore, we find that the age distribution of excess mortality changes over time. Sociodemographic changes are crucial factors shaping the health burden attributable to air pollution in Europe. The pressing issue of population aging and its implications for the mortality burden underscore the need to protect the elderly and other vulnerable populations and to invest in the public health sector. Close collaboration and communication among environmental scientists, health professionals, and policymakers are called for. Continued source-attribution studies will be necessary to identify which economic sectors and source categories contribute to enhanced PM2.5 levels in each country and region, thereby helping to develop optimally effective mitigation strategies.

Finally, our results suggest that a full phase-out of fossil fuels in the EU27 could yield substantial health benefits. In many countries, exposure to PM2.5 could fall below the strict WHO guideline concentration of 5 $\mu g/m^3$, nearly eliminating attributable mortality, except in some southern and southeastern European countries (e.g., Italy, Spain, Greece), where additional measures to reduce emissions will be needed. This provides strong support for increasing the share of clean, renewable energy, as advocated by the United Nations through the Sustainable Development Goals for 2030 and the EU’s ambition of climate neutrality for 2050, which is legally binding under the European Climate Law.

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