Air quality and health implications of 1.5–2°C climate pathways under considerations of ageing population: A multi-model scenario analysis

To cite this article before publication: Peter Rafaj et al 2021 Environ. Res. Lett. in press https://doi.org/10.1088/1748-9326/abdf0b

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is © 2021 The Author(s). Published by IOP Publishing Ltd.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 3.0 licence, this Accepted Manuscript is available for reuse under a CC BY 3.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence
https://creativecommons.org/licences/by/3.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the article online for updates and enhancements.
Air quality and health implications of 1.5–2°C climate pathways under considerations of ageing population: A multi-model scenario analysis.

Authors: Peter Rafaj\(^1\), Gregor Kiesewetter\(^1\), Volker Krey\(^1,7\), Wolfgang Schoepp\(^1\), Christoph Bertram\(^2\), Laurent Drouet\(^3\), Oliver Fricko\(^1\), Shinichiro Fujimori\(^4,5,1\), Mathijs Harmsen\(^6\), Jérôme Hilaire\(^2\), Daniel Huppmann\(^1\), Zbigniew Klimont\(^1\), Peter Kolp\(^1\), Lara Aleluia Reis\(^3\), Detlef van Vuuren\(^6,8\)

Affiliations:
\(^1\) International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria
\(^2\) Potsdam Institute for Climate Impact Research (PIK), Leibniz Association, PO Box 60 12 03, 14412, Potsdam, Germany
\(^3\) RFF-CMCC European Institute on Economics and the Environment, Centro Euro-Mediterraneo sui Cambiamenti Climatici, Lecce, Italy
\(^4\) Kyoto University, Department of Environmental Engineering, Kyoto, Japan
\(^5\) NIES National Institute for Environmental Studies, Center for Social and Environmental Systems Research Tsukuba, Japan
\(^6\) PBL Netherlands Environmental Assessment Agency, The Hague, Netherlands
\(^7\) Industrial Ecology Programme and Energy Transitions Initiative, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
\(^8\) Copernicus Institute of Sustainable Development, Utrecht University, the Netherlands

Email: rafaj@iiasa.ac.at and kiesewet@iiasa.ac.at

Keywords: co-benefits, air pollution, low-carbon pathways, health impacts, population ageing, Paris Agreement

Abstract
Low-carbon pathways consistent with the 2°C and 1.5°C long-term climate goals defined in the Paris Agreement are likely to induce substantial co-benefits for air pollution and associated health impacts. In this analysis, using five global integrated assessment models, we quantify the emission reductions in key air pollutants resulting from the decarbonization of energy systems and the resulting changes in premature mortality attributed to the exposure to ambient concentrations of fine particulate matter. The emission reductions differ by sectors. Sulfur emissions are mainly reduced from power plants and industry, cuts in nitrogen oxides are dominated by the transport sector, and the largest abatement of primary fine particles is achieved in the residential sector. The analysis also shows that health benefits are the largest when policies addressing climate change mitigation and stringent air pollution controls are coordinated. We decompose the key factors that determine the extent of health co-benefits, focusing on Asia: changes in emissions, urbanization rates, population growth and ageing. Demographic processes, particularly due to ageing population, counteract in many regions the mortality reductions realized through lower emissions.

1. Introduction

The central goal of the Paris Agreement – adopted in 2015 by the United Nations Framework Convention on Climate Change - is to intensify global efforts to mitigate risks of climate change by keeping a global temperature rise within century well below 2 degrees Celsius relative to pre-industrial levels, and to push further towards strategies to limit the rise in
temperature below 1.5 degrees Celsius [1]. Literature shows that reaching the Paris targets will require a major transformation of the energy and land-use systems. Specifically, it implies several or all of the following: a) reaching net zero carbon dioxide (CO₂) emissions globally around the middle of the century and simultaneous deep cuts in emissions of non-CO₂ greenhouse gases (GHGs); b) restructuring the energy system through demand reductions, decarbonization of power and fuel supply, electrification of energy end-use, c) major reductions in agricultural GHG emissions, d) possibly removal of CO₂ from the atmosphere, e) and societal changes towards low demand patterns for land- and GHG-intensive goods. The transformations required to reach the 1.5°C target need to be more rapid than for a 2°C target [2,3].

Numerous studies have pointed out that stringent GHG-mitigation strategies as outlined above may induce substantial co-benefits for air pollution and associated health impacts, and that the potential for synergies grows with the ambition level of the carbon mitigation targets [4–12]. The quantification of implications of climate strategies for air quality (AQ) is particularly relevant for policy makers due to severe impacts of air pollution on human health, which currently accounts worldwide for the most health damaging burden associated with environmental pollution [13]. The health risk posed by air pollution impacts both urban and rural communities, with the total mortality burden from indoor and ambient air pollution being fifth behind dietary, high blood pressure, tobacco and diabetes risks [14].

Recent estimates suggest that about 5-7 million premature deaths worldwide are attributable to exposure to ambient and indoor air pollution annually (about equally shared), whereby emerging economies in Asia suffer the most [13,15–19]. The World Health Organization (WHO) Guideline [14] reports that only less than 10% of the global population are currently exposed to levels of air pollution that do not pose a significant risk to their health. While ambient air pollution is especially severe in some of the fastest-growing urban regions, around 3 billion people globally continue to depend on burning solid fuels in their homes for cooking and heating, resulting in very high levels of indoor air pollution. In 2013, it was estimated that exposure to ambient and indoor air pollution cost the world’s economy some US$ 5.11 trillion in welfare losses [20].

Studies quantifying the impacts of 2°C mitigation pathways on air pollution and health [6,9,21,22] conclude that health co-benefits are substantial in terms of decreased exposure levels, premature mortality or abatement costs. Newer comparisons indicate that mitigation pathways consistent with 1.5°C would result in even stronger synergetic effects for air pollution compared to pathways that are consistent with 2°C [23–26] - e.g., that worldwide health benefits over the century for 1.5°C pathways could be in the range of 110 to 190 million fewer premature deaths compared to 2°C pathways [24]. Consistently across the literature sources, the synergies for air pollution are highest in the developing world, particularly in Asia [27–29], although the demography-related factors were not explicitly analyzed. In addition to significant health benefits, there are also economic gains and cost savings from the emission mitigation that are related to reduced mortality/morbidity and environmental impacts [12,30], as well as to lower emission control costs. McCollum et al. [31] estimated reductions in the cumulative investment needs in air pollution control technologies by about 35% globally until 2030 in 1.5°C pathways.

In this paper we advance the ongoing research by a robust multi-model comparison of air pollution impacts of 1.5°C and 2°C pathways in combination with changing bottom-up assumptions on air quality policies in an internally consistent modelling framework.
lacking insights from the aforementioned literature on the role of future demographic processes, using a novel decomposition approach we highlight impacts of underlying mid-term population dynamics in the climate mitigation scenarios for the resulting health co-benefits. In this analysis, air pollution and associated cost impacts are quantified and reported globally, whereas Asia and individual Asian countries are a focus domain for the assessment of health impacts.

The structure of the paper is as follows: in the methodology section the set of modelling tools employed in this study is described together with the key assumptions behind the scenarios under examination. The next section summarizes modeling results in terms of sector- and region-specific changes in the emission levels and pollution control costs. Thereafter, co-benefits are quantified for the ambient air quality and for associated mortality impacts. Health implications of the decarbonization pathways are analyzed further by decomposing key drivers responsible for changes in the future number of premature deaths. Discussion and conclusion sections summarize the modeling insights and policy messages derived from this study.

2. Methods

Air pollution related implications of climate pathways are computed using the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model [32], whereby the underlying projections of activity in the energy system originate from five global integrated assessment models (IAMs):

1. **AIM/CGE** (Asia-Pacific Integrated Model) [33],
2. **IMAGE** (Integrated Model to Assess the Global Environment) [34],
3. **MESSAGEix-GLOBIOM** (Model for Energy Supply Strategy Alternatives and their General Environmental Impact - Global Biosphere Management Model) [35],
4. **REMINDE-MAgPIE** (Regional Model of Investments and Development) [36],
5. **WITCH-GLOBIOM** (World Induced Technical Change Hybrid) [37].

Technical documentation for each model is summarized in the Supplementary Information (SI) and can also be found in [61]. Energy scenarios corresponding to respective climate targets have been produced by IAMs in the form of aggregated energy balances. For this study, these have been converted into the GAINS structure following the downscaling procedures reported by [4,21,38]. Each of the models has a different geographical resolution, therefore the data conversion followed a spatial mapping of IAMs and GAINS regions. Mapping matrices for activity variables and regions used for a linkage between IAMs and GAINS are provided in SI. Further details on individual IAMs as well as on the scenario design are provided in an interactive Scenario Explorer [39].

Once implemented in GAINS, the activity projections form a basis for the calculation of emission trajectories, pollution control costs, concentration levels and associated health impacts. The GAINS methodology [32,40] allows for quantification of the drivers, mechanisms and impacts of emissions, and explores options for reducing impacts on health or environment. Projections of future economic activity and energy use are derived from individual IAMs and agricultural production projections originate from the Food and Agriculture Organization of the United Nations (FAO) [41]. Current emissions are estimated based on international activity statistics, with emission factors reflecting local conditions in 180 regions/states/provinces worldwide.
The GAINS model allows for simulation of impacts of various strategies to control air pollution. The current legislation (CLE) strategy assumes country- and sector-relevant policies and measures that are already adopted today or have been announced as intended policies. For those that have been announced, the extent and timing of their implementation is assessed according to the prevailing institutional, political and economic circumstances. On the other hand, the maximum feasible reduction (MFR) strategy assumes highest feasible application rates for the most efficient abatement technologies and policy practices to reduce pollutant emissions. It implies that - for example in the 1.5°C-world - the energy investment decisions take into account air pollution and climate goals at the same time, in order to avoid undesired lock-in effects and reduce the overall costs of compliance. Details on CLE and MFR control strategies are discussed in [21,51] and in Supplementary Information (S4).

Through the implementation in GAINS it is possible to quantify impacts of low carbon pathways for the overall air pollution abatement costs. Within the GAINS cost concept, the model computes incremental expenditures needed to install and operate the add-on abatement technologies/measures such that countries comply with their respective air quality legislation. The expenditures on emission controls are differentiated into investments, fixed operating costs, and variable operating costs. Some of the cost- and technology-characteristics are common for all countries, including removal efficiencies, unit investment costs, fixed operation and maintenance costs, variable cost components like extra demand for labor, energy, and materials. A 4% discount rate is used to annualize the investment cost over the lifetime of control equipment. The calculation routine takes into account several country-specific parameters, for instance, average boiler sizes, capacity/vehicles utilization rates, emission factors [32,42]. Because GAINS computes additional costs of air pollutant abatement, the cost parameters in GAINS are not harmonized with those used by IAMs and do not enter their respective cost functions.

Considering several hundred reduction options, their impacts on ambient air quality and population exposure are computed for both urban areas and surrounding rural regions, based on the results of the European Monitoring and Evaluation Programme (EMEP) atmospheric chemistry and transport model (for more details see Chapter 2 of [27]). A linear approximation of the full model is used to estimate ambient fine particulate matter (PM$_{2.5}$) from emissions of primary PM (PPM) and secondary PM precursors (SO$_2$, NO$_x$, NH$_3$, VOC) on a 0.5°x0.5° grid. To adequately represent elevated concentrations in cities, a downscaling of PPM concentrations is done for urban areas with a population >100,000 in 2010 [43]. Here, PPM concentrations arising from low-level sources are re-distributed within the grid cell proportional to the emission density, based on a regression between emission and concentration increments. Although high concentrations of other pollutants, such as ozone and nitrogen oxides, are also known for their health impacts we focus on PM$_{2.5}$ which is the pollutant with the largest impact on human mortality [44,45].

Health impacts from exposure to PM$_{2.5}$ in ambient air are quantified following the method adopted by the World Health Organization (WHO) for the 2016 Global Burden of Ambient Air Pollution study [46]. Premature deaths are calculated as attributable fraction of total disease- and age-specific deaths for five diseases: ischemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer, and acute lower respiratory infections. The population attributable fraction ($\text{PAF}_{dca}$) of air-pollution related deaths from disease $d$ in country $c$ and age $a$ are calculated as
\[ PAF_{dca} = \frac{\sum_{popc}^{popcl} (RR_{dai} - 1)}{1 + \sum_{popc}^{popcl} (RR_{dai} - 1)} \]  

(1)

where \( i \) represents the grid cells hosting population \( pop_{ci} \) belonging to country \( c \). \( RR_{dai} \) is the disease and age specific relative risk as calculated from the integrated exposure response functions (IERs) for PM\(_{2.5}\) concentration levels in the respective spatial unit (grid cell). IERs correspond to those developed by the GBD 2013 assessment (updated from [48]) and used in the WHO 2016 Burden of Ambient Air Pollution study [13]. Premature deaths \( (pd) \) attributable to ambient PM\(_{2.5}\) exposure are calculated by multiplying the \( PAF_{dca} \) from Eq. (1) with age specific baseline cases of deaths \( d_{dca} \) from disease \( d \) in country \( c \):

\[ pd_{dca} = PAF_{dca} \cdot d_{dca} \]  

(2)

Baseline age specific mortality projections are taken from UN World Population prospects (2010 edition) [47], to which age specific shares of disease contributions to total deaths in 2010 are applied as estimated by the Global Burden of Disease (GBD) 2013 analysis [16,45]. We assume that while total age-specific deaths vary according to the UN projections, the relative shares of individual diseases contributing to age-specific deaths remain unchanged in the future. The analysis in this study is restricted to premature mortality and does not address the morbidity impacts of pollution. Furthermore, impacts of indoor air pollution are not considered in this assessment.

Several factors determine the trends in premature deaths— in particular, there is an interplay between changes in emissions driving ambient concentrations, and changes in population structure which in many cases lead to more people in vulnerable high-age groups. To explain the modelled trends of PM\(_{2.5}\)-related health impacts over time \( (t) \) and across the different scenarios, we separate contributions from emission changes, from urbanization, and from demographic changes (population growth and aging). Writing the total (relative) change of annual PM\(_{2.5}\) related deaths \( pd \) from 2015 to 2050 as

\[ pd(t_2) = pd(t_0) \cdot f_{emis} \cdot f_{urb} \cdot f_{popgrowth} \cdot f_{aging} \]  

(3)

we can separate each of these determining multiplicative factors \( f \). A series of sensitivity calculations was conducted for this purpose, in which all possible combinations of 2015 and 2050 values were used for the different input parameters emissions \( (emiss) \), urbanization rate \( (urb) \), population size \( (popgrowth) \), population age structure \( (aging) \). The relative change in premature deaths between 2015 and 2050 was then evaluated for each parameter \( (n) \) and each scenario individually, with the other parameters left constant and set to all possible combinations, to derive different versions \( f_{nscj} \) of each factor \( f_n \) in scenario \( s \) and country \( c \), \( (j \) is a running index over the 6 possible settings of the other parameters). Owing to the complexity of the health impact calculations, it is not self-evident that it is possible to use a formulation with independent (commutative) factors as in Eq. 3. However, we find that the values of \( f_{nsc} \) are quite stable across all such combinations \( j \) – in other words, the factors are independent of each other – and thus we can use their averages \( \overline{f_{nsc}} \) as robust indicators to describe the relative influences of the different determinants.

### 2.1 Scenarios
Five scenarios examined in this study include the National Policies (NPi) scenario that considers the current energy and climate policies adopted by G20 countries up to 2030 with an equivalent carbon emission mitigation effort thereafter. This scenario serves as a reference in this study. Nationally Determined Contributions (NDC) assumes implementation of country specific NDCs by 2030, with a continuation of equivalent global climate action after 2030. Well Below 2 Degrees (2ºC) and Toward 1.5 Degrees (1.5ºC) aim at limiting the increase in global average temperature to 2ºC and 1.5ºC above the pre-industrial level, over the period until 2100. The NPi, NDC, 2ºC and 1.5ºC scenarios are combined with a set of air pollution policies that allows for a compliance with the current legislation (CLE) for air protection in each country. The fifth scenario - 1.5ºC + MFR – assumes the same climate target as in the 1.5ºC case, while to achieve the maximum feasible reduction (MFR) in air pollutants the best available technologies and abatement measures are applied. All scenarios listed above are based on the SSP2 “middle-of-the-road” narrative for future societal developments described in detail in [49]. Assumptions for each scenario are summarized in Table 1 and further information is reported by [31,50] and CD-LINKS Scenario Explorer [39].

Table 1. Definition of scenarios

| ACRONYM | Climate policies                                                                 | Air pollution policies                |
|---------|-----------------------------------------------------------------------------------|--------------------------------------|
| NPi     | National Policies until 2030, equivalent effort thereafter                         | Current legislation                   |
| NDC     | National Policies until 2020, after which implementation of Nationally Determined Contributions (NDCs) until 2025/2030, equivalent effort thereafter | Current legislation                   |
| 2ºC     | National Policies until 2020, as of 2020 staying within 1000 GtCO₂ budget for 2011-2100 period, corresponding to a >66% chance of staying below 2ºC throughout 21st century | Current legislation                   |
| 1.5ºC   | National Policies until 2020, as of 2020 staying within 400 GtCO₂ budget for 2011-2100 period, corresponding to a >66% chance of staying below 1.5ºC in 2100 | Current legislation                   |
| 1.5ºC + MFR | As in 1.5ºC                                                                       | Maximum feasible reduction            |

As the key focus of this paper are implications of climate mitigation strategies and demographic trends on air pollution related impacts, we do not provide descriptions of the evolution of energy systems in each model and the resulting CO₂ trajectories, however, underlying projections including socioeconomic drivers, are accessible in [39] and in SI (S5).

3. Results

3.1 Global trends in selected air pollutant emissions

In this section, we focus on the future trajectories of three key air pollutants that are main contributors to ambient PM₂.₅: primary particulate matter (PM₂.₅) and precursors of secondary PM (SO₂ and NOₓ). Owing to the current air quality legislation, emissions of all three pollutants remain flat or decline by 2030 in the NPi scenario (Figure 1), but without further air pollution controls or more stringent climate policies subsequently increase for SO₂ and NOₓ towards 2050. Increase in emissions of primary PM₂.₅ by 2050 is less pronounced for all models. Emissions in the NDC scenario are lower than in NPi, however, the growing trend beyond 2030 remains comparable to the reference. Significant decline of emissions, relative to NPi, is observed in the 2ºC scenario, and the reductions are even greater in the 1.5ºC case,
reaching about 20% to 40% for SO$_2$ and NO$_x$, and about 10% to 30% for PM$_{2.5}$, relative to 2015. Ranges in the emission reductions achieved by the five models are larger for SO$_2$ and NO$_x$ as compared to PM$_{2.5}$, indicating significant differences in restructuring of the energy systems across models. Combining the 1.5°C climate target with the MFR controls strategy brings about a rapid decline of each pollutant (70% to 80%) by 2030 and this reduction is maintained until 2050. Emissions in the 1.5°C + MFR scenario represent the low end of emissions levels in this modeling exercise (red line in Figure 1 – maximum reductions across models). This illustrates that a combination of stringent climate policy and air pollution control measures results in the highest air quality benefits.

![Figure 1](image1.png)

**Figure 1.** Ranges and averages of global projected change in emissions of three PM$_{2.5}$ precursors for different scenarios, relative to 2015.

Pollutant-specific reductions in the emission levels relative to 2015 are displayed in Figure 2 in relation to the changes in CO$_2$ emissions in the period up to 2050 in order to illustrate effects of climate- versus air pollution-policies. Three scenarios are depicted: 2°C, 1.5°C and 1.5°C + MFR. In the first two cases with the CLE assumptions, differences in relative reductions for SO$_2$ and NO$_x$ reflect the structural changes in individual models under the 2°C/1.5°C climate targets (fuel mix changes, efficiency measures, demand reductions). It is observed that the relative changes for PM$_{2.5}$ are less pronounced and differences across IAMs are smaller because of lesser impacts of low carbon strategies on key PM-sources (e.g., households). The combination of 1.5°C pathway with MFR strategy results in relative reductions that are nearly proportional to the CO$_2$ decline until 2040 but they are attenuated thereafter, in the period 2040-2050, by when the key polluting sources, such as fossil fired power plants, are practically eliminated from the energy system.
Different emitting sectors contribute to the changes in emission levels for each pollutant. Sectoral contributions to the emission reductions induced by the climate policies as computed in GAINS for the five models are depicted in Figure 3. For SO\textsubscript{2}, the power and industry sectors are the dominant sources of emission cuts due to a rapid phasing out of fossil fuels from the energy mix by 2050. Transport contributes the largest share of the reductions of NO\textsubscript{x} in all models except WITCH, which shows significantly lower transport activity and also NO\textsubscript{x} emissions already in the NPi scenario with a reduced need for electrification in the 2\textdegree C and 1.5\textdegree C scenarios. The dominant source of PM\textsubscript{2.5} emissions across all models and scenarios in 2050 is biomass burning in the residential sector. However, this sector is less affected by climate policies as compared to other sources – except for REMIND, which projects the strongest reduction in residential biomass use. In some cases (particularly for IMAGE) emissions even increase due to a higher biomass demand in the 2\textdegree C and 1.5\textdegree C scenarios. On the other hand, the adoption of the MFR measures combined with the 1.5\textdegree C structural changes in 2050 results in rapid PM\textsubscript{2.5} declines in each model, where the industry, residential and other sources (i.e., waste, agriculture) play the key role in the abatement process.
Figure 3. Contribution of sectors to global emission reductions (colored bars) by models and climate policy scenarios in 2050 relative to NPi. Black bar represents the remaining emissions in each scenario.
The co-benefits of climate strategies for abating air pollutants are significantly larger in the developing world compared to the industrialized regions (Figure 4). Besides the structural differences of the economies, this is also associated with the existing air pollution policies and regulations that affect the overall mitigation potential originating from the decarbonization of the energy system in all regions. The common pattern emerging from our simulations is that Asian countries account for the largest share of emission reductions in absolute terms, followed by the Middle East and Africa. An exception is the SO$_2$ abatement reported for the WITCH and MESSAGE model, where the reforming industrialized economies (REF) achieve higher reductions when compared to other IAMs. It is noted that in per capita terms, reductions by regions converge over time.
Figure 4. Contribution of regions to the emission reductions (colored bars) by models and climate policy scenarios in 2050 relative to NPi. The black bar represents the remaining emissions in each scenario. OECD = the OECD 1990 countries, EU members/candidates; ASIA = Asian countries except the Middle East, Japan and Former Soviet Union states; LAM = Latin America and the...
Caribbean; MAF = Middle East and Africa; REF = Reforming Economies of the Former Soviet Union. Regions definition is provided in SI (S6).

3.2 Cost impacts

In the NPi scenario, the abatement cost reach 0.7 to 0.95 trillion EUR in 2050, while this cost is reduced by 25% to 50% in the 2°C scenario and to 40% to 70% in the 1.5°C scenario combined with the CLE assumptions. As can be seen in Figure 5, the dominant share of cost savings is reported for the transport sector, followed by power generation and industry. The cost co-benefits are significantly reduced in the 1.5°C + MFR case due to an adoption of more costly measures, which in addition control air pollution not directly impacted by the climate target (e.g., industrial processes and waste).

![Figure 5. Reductions in air pollutant abatement cost by sector in 2050, relative to the NPi scenario.](image)

Cost implications of the selected low carbon scenarios are illustrated further in Figure 6, where the savings in control costs are plotted in relation to the CO₂ abated in 2050 for each IAM. For three models (AIM, IMAGE, MESSAGE), these reductions are quantified in average at about 10€/tCO₂ to 12€/tCO₂ for 2°C and 1.5°C scenarios, respectively. Cost savings (as well air pollutant emission reductions) for the other two models (REMINd, WITCH) are comparatively smaller (5 to 6 €/tCO₂), which is explained by a combination of lower transport demand reductions and favorable fuel mix changes in the transport sector relative to NPi that in turn results in less co-benefits under mitigation strategies. Adoption of the MFR strategies over the 1.5°C target (the red square in the graph) reduces the cost gains between 20% (AIM) to 80% (WITCH).

In the right panel of Figure 6, the total air pollution control costs are shown as a fraction of global gross domestic product (GDP). In the NPi scenario, the adoption of end-of-pipe measures cost 0.6-0.8% of GDP in 2050, while these expenditures are reduced in average to
0.3-0.4% in 1.5°C and 2°C scenarios. The implementation of MFR controls leads to overall increase in air pollution control costs that partially offset the cost co-benefits induced by the decarbonization of the energy system. However, economic benefits could be significantly greater if the effects of lower mortality are monetized and internalized in the cost calculations [52,53].

Figure 6. Left panel: Reductions in global air pollution control cost in 2050 per ton of CO₂-abated by scenario and model, relative to NPi. Right panel: Share of air pollution control cost in global GDP in 2050 by scenario and model.

3.3 Impacts on air quality

For quantifying impacts on ambient PM₂.₅ concentrations and related mortality, we focus on Asia due to the high policy relevance for that region. This allows for a more detailed analysis of country level differences in a very diverse world region which contains several countries ranking among the highest ambient PM₂.₅ exposures worldwide. Figure 7 illustrates calculated PM₂.₅ concentrations for the year 2015, projected concentrations in NPi for 2050, as well as reductions under 1.5°C and 1.5°C + MFR scenarios (based on results for MESSAGE) in 2050. The highest concentration levels in 2015 and in 2050 (NPi) are estimated for the Indo-Gangetic plain in northern India, northeastern China, and parts of Pakistan and Afghanistan. Contrary to the first two regions, where the concentrations drop in 2050 is evident in 1.5°C and even more so in 1.5°C + MFR scenarios, the high concentrations in Western Asia, as well as parts of Northern China and Mongolia, are mostly influenced by wind-blown dust. Therefore, concentrations in these areas do not decrease noticeably even under strong cuts of anthropogenic emissions as in the 2050 policy scenarios.
Figure 7. Modelled ambient PM$_{2.5}$ concentrations due to natural and anthropogenic sources in Asia, 2015 (a), 2050 under the NPi, (b) 1.5 °C, (c) and 1.5°C + MFR (d) scenarios, as well as reductions in 2050 under 1.5 °C (e) and 1.5°C + MFR (f) scenarios as compared to NPi (MESSAGE model).

However, most of these arid areas that show up as PM$_{2.5}$ hot spots are very sparsely populated and thus play little role for overall population exposure, whereas some of the urban pollution hot spots hardly show up on a regional map because they are too small in size. Hence, the population exposure distribution as shown in Figure 8, resulting from an overlay...
of grid concentrations with population on the same grid, is more telling about the shares of population exposed to different levels of ambient PM$_{2.5}$ concentrations. In particular, it gives a clear indication of the fraction of population exposed to PM$_{2.5}$ levels exceeding either national ambient air quality standards, or the WHO AQ guideline [54]. This aspirational guideline recommends a maximum annual mean concentration of PM$_{2.5}$ at 10 μg/m$^3$ and introduces a set of interim targets towards improved air quality: Interim target-1 (25-35 μg/m$^3$), Interim target-2 (15-25 μg/m$^3$) and Interim target-3 (10-15 μg/m$^3$).

In 2015, less than 2% of the population in China and India lived in areas with air quality complying with the WHO guideline and less than 40% of people were exposed to concentrations below 35 μg/m$^3$ (Figure 8). By 2050, without climate policies, the situation even worsens in India. In the 1.5°C scenario, the share of population exposed to concentrations below 35 μg/m$^3$ increases to 60% in China and 45% in India. In the 1.5°C+MFR case, about 20% people enjoy air quality adhering to the WHO AQ guideline (<10 μg/m$^3$) in both countries, and nearly the whole population is projected to live within or below the Interim target-1 concentrations. Since this figure refers to total PM$_{2.5}$ concentrations including natural dust, achieving the WHO guideline for the entire population is not feasible even under strictest emission cuts.

![Figure 8. Population exposure distribution to PM$_{2.5}$ in China and India, projected for the NPi, 1.5°C, and 1.5°C + MFR scenario (MESSAGE model) until 2050.](image)

Exposure to PM$_{2.5}$ increases the likelihood to die from several diseases. One commonly used measure of health impacts of ambient air pollution is the absolute number of annual deaths attributable to this risk factor. Figure 9 shows the trends of annual premature deaths over time for different scenarios, alongside with population weighted mean concentrations and mortality rates per capita. A striking feature is that for most countries the projected premature...
mortality (in absolute terms) in 2050 shows strong increases over 2015, even under constant or decreasing emissions/concentrations. Only the most ambitious decarbonization pathway in conjunction with the strictest controls reach substantive decreases in absolute premature deaths. Compared to NPi scenario, the 1.5°C + MFR case results in 1 million people less dying prematurely (~40%) due to air pollution in China and India combined. Across the Asia domain, this reduction is approximately 2.5 to 3 million cases or 40% to 51% depending on the IAM used. In the case of Japan, it is observed that under the 1.5°C+MFR scenario, concentrations drop to very low levels (~5 μg/m³), leading to disproportionally strong and rapid decreases in mortality due to the non-linear shape of the dose-response functions applied in this study.

Figure 9. Population-weighted average PM₂.₅ concentrations, mortality rate due to air pollution per year and 10,000 population (right axis), and premature deaths attributable to ambient PM₂.₅ (left axis), as estimated in GAINS for different countries in Asia in 2015 and 2050 by scenario (MESSAGE model).
3.4 The role of demographic changes in the projected health impacts

When analyzing future projections of premature mortality associated with air quality, caution is needed in the interpretation of trends over time. To understand the reasons behind apparently counter-intuitive results discussed above, we seek to disentangle the different drivers of changes, using as an illustrative example the changes from 2015 to 2050 in terms of total numbers of deaths attributed to ambient PM$_{2.5}$ exposure. The variations of PM$_{2.5}$ precursor emissions under different scenario assumptions have been described in Section 3.1. In addition to the pure emission related changes, however, demographic changes play a major role. While emissions determine the spatial distribution of ambient PM$_{2.5}$, exposure is given by ambient PM$_{2.5}$ times population, so a changing population pattern through urbanization results in different exposure. If we quantify absolute numbers of premature deaths, the absolute size of the population matters. Finally, population ageing results in more people in vulnerable age groups with high baseline mortality rates, and therefore higher attributable numbers of premature deaths.

As described in Section 2, we decompose the relative change in premature deaths between 2015 and 2050 for each scenario $s$ and each country $c$ into four independent factors $f_{nsc}$ related to emission changes, population growth, urbanization, and population aging. Figure 10 shows results of the decomposition analysis. Each of the parameters $f_{nsc}$ is displayed for a range of countries and all scenarios. While the emission trends differ strongly across scenarios and countries (panel a), the influence of the demographic factors - urbanization, population growth and population aging - is almost independent of the emission scenario, as the scenario assumptions do not vary these parameters. Impacts of demographic factors (panels b-d), in particular population aging, are typically positive and show a strong variability across countries. While population growth in its own can be eliminated by analyzing trends in mortality rather than absolute deaths, it is remarkable that in several countries the effect of population aging on PM$_{2.5}$-related mortality (panel d) is much larger than the combined effects of decarbonization and emission control policies.
Figure 10. Modelled changes from 2015 to 2050 in total annual premature deaths attributable to ambient PM$_{2.5}$ (panel e) into different factors: (a) emission changes, (b) urbanization, (c) population growth, (d) population aging. The range between different IAMs is shown as bars, different scenarios are indicated as colors.
4. Discussion

In agreement with earlier scenario literature [55–57], we project substantial co-benefits for abating air pollution as a result of deep decarbonization transformations of the energy sector. However, our multi-model assessment suggests that low carbon pathways alone will not be sufficient to provide the majority of highly impacted population - in particular in Asia - with air quality complying with the WHO standards. As suggested by [27,38,40], to achieve this objective, a mix of policies is needed which combines targeted end-of-pipe controls, instruments for clean energy access, as well as the whole range of carbon mitigation measures. At the same time, potential tradeoffs such as reoccurrence of biomass use for cooking and heating in households – as a result of higher prices for cleaner combusting fuels [58] – should be avoided due to its negative impacts on outdoor as well indoor air quality.

Our results emphasize the importance of strict emission controls for reducing the health burden on population. However, we note that even decreasing emissions and associated PM$_{2.5}$ concentrations can be over-compensated by increasing vulnerability of an aging population. At the same time, while absolute numbers of premature deaths may be a useful indicator to compare health impacts between emission scenarios at a given point in time, caution is needed when analyzing them over time, as demographic factors potentially play a strong (even dominant) role. To further complicate the situation, the calculation requires projected disease specific baseline mortality rates which are inherently uncertain and strongly dependent on assumptions. In our calculations, we assume the relative contributions of individual diseases to total deaths within each age group to remain constant over time.

By this analysis, we intend to highlight the sensitivity of the calculations to the demographic development, rather than generating a precise forecast of numbers of premature death. Absolute numbers of premature deaths are uncertain estimates for several reasons – not least the exposure-response relationships (ERRs) used, of which several versions have been developed in recent years [13,48,59,60]. For China, recent studies [62-64] report significant uncertainties from PM$_{2.5}$ exposure, ERR parameters and baseline death rates (95% confidence interval approx. ±40% in [63]), as well as large differences in absolute premature deaths calculated with different sets of ERRs. The IERs used in our study lead to estimates of premature deaths at the lower end of the range, while in particular the Global Exposure Mortality Model (GEMM) [60] leads to systematically higher numbers (+70% in China [63]). Here, we do not aim to undertake a full uncertainty analysis but rather quantify the importance of different factors for trends projected over time.

The sensitivity to demographic factors induces rather counter-intuitive trend results in several regions: that decreasing emissions are still associated with increasing premature deaths. Few options remain to circumvent it: Most straightforwardly, forgoing the premature death calculation altogether, the analysis could stop at the quantification of population weighted mean PM$_{2.5}$ concentrations, or exposure distribution. Though perhaps more robust, these indicators may not be satisfactory for analyses targeting human health. Secondly, we note that the difficulties arise from analyzing time series. When comparing emission scenarios at one given point in time, this issue is avoided. Thirdly, if the evolution over time should be analyzed, the attributable fraction of total deaths seems a more suitable measure than the absolute number of premature deaths.

5. Conclusions
This paper summarizes implications of low carbon pathways consistent with objectives of Paris Agreement for the air pollution and associated health impacts from the multi-model perspective. Trajectories of key air pollutants derived from five IAMs under the 1.5°C and 2°C climate targets show strong declining trend relative to current emission levels as well as in comparison to the moderate reductions achieved by the NDC mitigation policies. By 2050, primary PM$_{2.5}$ and precursor emissions decline by about a third in the low-carbon scenarios, compared to 2015. These reductions more than double when decarbonization policies are combined with ambitious air pollution controls. Furthermore, in the 1.5°C + MFR scenario, the total reductions in air pollutants and CO$_2$ are nearly proportional by 2040, following structural changes in the global energy system simulated by IAMs.

The contribution of air pollution emitting sectors to the overall emission reductions is pollutant specific. Power sector and industry are most important for the abatement of the sulfur emissions, while the road-transport sector plays the key role in reducing emissions of NO$_x$. Biomass combustion in residential sector is a major source of primary PM$_{2.5}$ pollution, however, this source is less impacted by climate strategies. The risk of tradeoffs in this sector needs to be addressed by a mix of measures comprising clean energy access policies as well as accelerated deployment of efficient cooking and heating devices. The scenario analysis indicates that the emerging Asian countries, followed by Africa and Middle East, might benefit the most from air pollution cuts brought about through GHG mitigation. At the same time, the potential co-benefits depend on the rate of implementation and enforcement of air quality legislation and emission standards.

Implementation of add-on controls to curb air pollutants at levels complying with the current legislation will cost global economy little less than 1 trillion Euros by 2050, which corresponds to about 0.6-0.8% of global GDP (depending on model-specific assumptions). Decarbonization of the most polluting sectors invoke halving of these expenditures, nevertheless, the economic co-benefits are less pronounced if the most efficient (and costly) technologies are applied without any cost considerations. Savings in pollution abatement cost per carbon removal achieved by individual models and scenarios in 2050 range between 5 to 12 €/tCO$_2$, and it is expected the co-benefit values would be even higher if the gains from lower mortality are monetized and accounted for [12,30].

Emission changes affect concentrations of ambient PM$_{2.5}$, which we analyze here for Asia. While details differ across IAMs, the trends in different scenarios are robust. In most regions, NPi leads to a stagnation or even increase of ambient PM$_{2.5}$ concentrations, while the stronger mitigation scenarios result in ever greater decreases of ambient PM$_{2.5}$. The 1.5°C+MFR scenario decreases premature deaths by 40-50% across Asia, compared to NPi. However, absolute numbers of premature deaths are a difficult indicator to interpret, particularly when compared over time. Demographic factors and the assumptions about disease-specific baseline mortality in the projections may well dominate changes of calculated absolute premature deaths over time, resulting in some cases in seemingly counter-intuitive increases of premature deaths, despite decreasing ambient concentrations. These point to the higher vulnerability of aging populations and emphasize the need for strong emission cuts if absolute numbers of premature deaths from PM$_{2.5}$ exposure are to be decreased.

Future analysis will focus on quantification of global co-benefits when climate mitigation and pollution control are realized using the cost optimization framework of the GAINS model, assessment of the synergies achievable in non-energy sectors (i.e., industrial processes, waste
treatment, agriculture), impacts for indoor air pollution, and finally impacts on other pollutants (e.g., $O_3$, $NH_3$) and related human and environmental indicators.

Acknowledgements

The authors acknowledge funding provided by the European Union Horizon 2020 research and innovation programme under grant agreement No 642147 (‘CD-LINKS’) and No 821471 (ENGAGE). SF is supported by the Environment Research and Technology Development Fund (JPMEERF20202002) of the Environmental Restoration and Conservation Agency of Japan and The Sumitomo Foundation.

References

[1] UNFCCC 2015 The United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement

[2] IPCC 2018 Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (Geneva: Intergovernmental Panel on Climate Change (IPCC))

[3] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kleshgi H, Kobayashi S, Kriegler E, Mundaca L, Seferian R and Vilarino M V 2018 Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development In: Global Warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. (Geneva, Switzerland: World Meteorological Organization)

[4] Rafaj P, Schöpp W, Russ P, Heyes C and Amann M 2013 Co-benefits of post-2012 global climate mitigation policies Mitig. Adapt. Strateg. Glob. Change 18 801–24

[5] Rao S, Klimont Z, Leitao J, Riahi K, Dingenen R van, Reis L A, Katherine Calvin, Dentener F, Drouet L, Fujimori S, Harmsen M, Luderer G, Chris Heyes, Strefler J, Ravani M and Vuuren D P van 2016 A multi-model assessment of the co-benefits of climate mitigation for global air quality Environ. Res. Lett. 11 124013

[6] Rao S, Klimont Z, Smith S J, Van Dingenen R, Dentener F, Bouwman L, Riahi K, Amann M, Bodirsky B L, van Vuuren D P, Aleluia Reis L, Calvin K, Drouet L, Fricke O, Fujimori S, Gernaat D, Havlik P, Harmsen M, Hasegawa T, Heyes C, Hilaire J, Luderer G, Masui T, Stehfest E, Strefler J, van der Sluijs S and Ravani M 2017 Future air pollution in the Shared Socio-economic Pathways Glob. Environ. Change 42 346–58
[7] Shindell D, Borgford-Parnell N, Brauer M, Haines A, Kuylenstierna J C I, Leonard S A, Ramanathan V, Ravishankara A, Amann M and Srivastava L 2017 A climate policy pathway for near- and long-term benefits Science 356 493–4

[8] Gi K, Sano F, Hayashi A and Akimoto K 2019 A model-based analysis on energy systems transition for climate change mitigation and ambient particulate matter 2.5 concentration reduction Mitig. Adapt. Strateg. Glob. Change 24 181–204

[9] Vandyck T, Keramidas K, Kitous A, Spadaro J V, Dingenen R V, Holland M and Saveyn B 2018 Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges Nat. Commun. 9 4939

[10] Braspenning Radu O, van den Berg M, Klimont Z, Deetman S, Janssens-Maenhout G, Muntean M, Heyes C, Dentener F and van Vuuren D P 2016 Exploring synergies between climate and air quality policies using long-term global and regional emission scenarios Atmos. Environ. 140 577–91

[11] McCollum D L, Krey V, Riahi K, Kolp P, Grubler A, Makowski M and Nakicenovic N 2013 Climate policies can help resolve energy security and air pollution challenges Clim. Change 119 479–94

[12] Rauner S, Bauer N, Dirmaicher A, Dingenen R V, Mutel C and Luderer G 2020 Coal-exit health and environmental damage reductions outweigh economic impacts Nat. Clim. Change 10 308–12

[13] WHO 2016 Ambient air pollution: A global assessment of exposure and burden of disease (Geneva, Switzerland: World Health Organization (WHO))

[14] HEI 2019 State of Global Air 2019. Special Report. Boston, Health Effects Institute.

[15] WHO 2018 WHO Global Urban Ambient Air Pollution Database (update 2018) (Geneva, Switzerland: World Health Organization (WHO))

[16] Global Burden of Disease Study 2016 Global Burden of Disease Study 2015 (GBD 2015) Results. Seattle, United States: Institute for Health Metrics and Evaluation (IHME) (http://ghdx.healthdata.org/gbd-results-tool)

[17] GBD MAPS Working Group 2018 Burden of Disease Attributable to Major Air Pollution Sources in India (Boston, MA: Health Effects Institute)

[18] Cohen A J, Brauer M, Burnett R, Anderson H R, Frostad J, Estep K, Balakrishnan K, Brunekreef B, Dandona L, Dandona R, Feigin V, Freedman G, Hubbell B, Jobling A, Kan H, Knibbs L, Liu Y, Martin R, Morawska L, Pope C A, Shin H, Straif K, Shaddick G, Thomas M, Dingenen R van, Donkelaar A van, Vos T, Murray C J L and Forouzanfar M H 2017 Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015 The Lancet 389 1907–18

[19] Rauner S, Hilaire J, Klein D, Strefler J and Luderer G 2020 Air quality co-benefits of ratcheting up the NDCs Clim. Change

[20] World Bank 2016 The cost of air pollution : strengthening the economic case for action. (Washington, D.C.: The World Bank Group)
[21] Rafaj P, Kiesewetter G, Gütl S, Schöpp W, Cofala J, Klimont Z, Purohit P, Heyes C, Amann M, Borken-Kleefeld J and Cozzi L 2018 Outlook for clean air in the context of sustainable development goals Glob. Environ. Change 53 1–11

[22] Harmsen M J H M, van Dorst P, van Vuuren D P, van den Berg M, Van Dingenen R and Klimont Z 2020 Co-benefits of black carbon mitigation for climate and air quality Clim. Change

[23] Markandya A, Sampedro J, Smith S J, Van Dingenen R, Pizarro-Irizar C, Arto I and González-Eguino M 2018 Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study Lancet Planet. Health 2 e126–33

[24] Shindell D, Faluvegi G, Seltzer K and Shindell C 2018 Quantified, localized health benefits of accelerated carbon dioxide emissions reductions Nat. Clim. Change 8 291

[25] Vandycck T, Keramidas K, Tchung-Ming S, Weitzel M and Van Dingenen R 2020 Quantifying air quality co-benefits of climate policy across sectors and regions Clim. Change

[26] Fujimori S, Hasegawa T, Takahashi K, Dai H, Liu J-Y, Ohashi H, Xie Y, Zhang Y, Matsui T and Hijioka Y 2020 Measuring the sustainable development implications of climate change mitigation Environ. Res. Lett. 15 085004

[27] Amann M, Jiming H, Borken-Kleefeld J, Cofala J, Gomez Sanabria A, Heyes C, Höglund Isaksson L, Kiesewetter G, Klimont Z, Nguyen B, Purohit P, Rafaj P, Sander R, Wagner F, Schöpp W, Kuylenstierna J, Wang S, Ye W, Shindell D, Seltzer K and Borgford-Parnell N 2019 Scenarios and Solutions Air Pollution in Asia and the Pacific: Science-based solutions (Bangkok, Thailand: United Nations Environment Programme (UNEP)) pp 61–100

[28] Xie Y, Dai H, Xu X, Fujimori S, Hasegawa T, Yi K, Masui T and Kurata G 2018 Co-benefits of climate mitigation on air quality and human health in Asian countries Environ. Int. 119 309–18

[29] Kim S E, Xie Y, Dai H, Fujimori S, Hijioka Y, Honda Y, Hashizume M, Masui T, Hasegawa T, Xu X, Yi K and Kim H 2020 Air quality co-benefits from climate mitigation for human health in South Korea Environ. Int. 136 105507

[30] Scovronick N, Budolfson M, Dennig F, Errickson F, Fleurbaey M, Peng W, Socolow R H, Spears D and Wagner F 2019 The impact of human health co-benefits on evaluations of global climate policy Nat. Commun. 10 2095

[31] McCollum D L, Zhou W, Bertram C, Boer H-S de, Bosetti V, Busch S, Despré J, Drouet L, Emmerling J, Fay M, Fricko O, Fujimori S, Gidden M, Harmsen M, Huppmann D, Iyer G, Krey V, Kriegler E, Nicolas C, Pachauri S, Parkinson S, Poblete-Cazenave M, Rafaj P, Rao N, Rozenberg J, Schmitz A, Schöpp W, Vuuren D van and Riahi K 2018 Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals Nat. Energy 1

[32] Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Höglund-Isaksson L, Klimont Z, Nguyen B, Posch M, Rafaj P, Sander R, Schöpp W, Wagner F and Winiwarter W 2011 Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications Environ. Model. Softw. 26 1489–501

[33] Fujimori S, Hasegawa T and Masui T 2017 AIM/CGE V2.0: Basic Feature of the Model Post-2020 Climate Action: Global and Asian Perspectives ed S Fujimori, M Kainuma and T Masui (Singapore: Springer) pp 305–28
[34] Stehfest, E., van Vuuren, D., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P., van Minnen, J., Müller, C., Prins, A. 2014 Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications (The Hague, Netherlands)

[35] Krey V, Havlik P, Fricko O, Zilliacus J, Gidden M, Strubegger M, Kartasasmita G, Ermolieva T, Forsell N, Gusti M, Johnson N, Kindermann G, Kolp P, McCollum D L, Pachauri S, Rao S, Rogelj J, Valin H, Obersteiner M and Riahi K 2016 MESSAGE-GLOBIOM 1.0 Documentation (Laxenburg, Austria: International Institute for Applied Systems Analysis (IIASA))

[36] Luderer G, Leimbach M, Bauer N, Kriegler E, Baumstark L, Bertram C, Giannousakis A, Klein D, Levesque A, Moraubertia I, Pehl M, Pietzcker R, Piontek F, Roming N, Schultes A, Schwanitz V J and Strefler J 2015 Description of the REMIND Model (Version 1.6) (Rochester, NY: Social Science Research Network)

[37] Bosetti V, Carraro C, Galeotti M, Massetti E and Tavoni M 2006 WITCH A World Induced Technical Change Hybrid Model Energy J. 27 13–37

[38] Li N, Chen W, Rafaj P, Kiesewetter G, Schöpp W, Wang H, Zhang H, Krey V and Riahi K 2019 Air Quality Improvement Co-benefits of Low-Carbon Pathways toward Well Below the 2 °C Climate Target in China Environ. Sci. Technol. 53 5576–84

[39] IIASA and the CD-LINKS consortium 2020 CD-LINKS Scenario Explorer hosted by IIASA CD-LINKS Scenar. Explor. Hosted by IIASA - Release 2.0 (https://data.ene.iiasa.ac.at/cd-links/#/about)

[40] Amann M, Kiesewetter G, Schoepp W, Klimont Z, Winiewart R, Cofala J, Rafaj P, Hoglund-Isaksson L, Gomez Sanabria A, Heyes C, Purohit P, Borken-Kleefeld J, Wagner F, Sander R, Fagerli H, Nyiri A, Cozzoli L and Pavarini C 2020 Reducing global air pollution: The scope for further policy interventions Philos. Trans. R. Soc. A

[41] Alexandratos N and Bruinsma J 2012 World agriculture towards 2030/2050: the 2012 revision (ESA Working paper Rome, FAO)

[42] Cofala J and Syri S 1998 Sulfur emissions, abatement technologies and related costs for Europe in the RAINS model database (Laxenburg, Austria: IIASA)

[43] Liu J, Zhang S and Wagner F 2018 Exploring the driving forces of energy consumption and environmental pollution in China’s cement industry at the provincial level J. Clean. Prod. 184 274–85

[44] Jerrett M, Burnett R T, Pope C A, Ito K, Thurston G, Krewski D, Shi Y, Calle E and Thun M 2009 Long-Term Ozone Exposure and Mortality N. Engl. J. Med. 360 1085–95

[45] Forouzanfar M H, Alexander L, Anderson HR, Bachman V F, Biryukov S, Brauer M, Burnett R, Casey D, Coates M M, Cohen A, Delwiche K, Estep K, Frostad J J, Kc A, Kyu H H, Moradi-Lakeh M, Ng M, Slepak E L, Thomas B A, Wagner J, Aasvagen G M, Abbafati C, Ozorgon A A, Abd-Allah F, Abera S F, Aferyans V, Abraham B, Abraham J P, Abubakar I, Abu-Rmeileh N M E, Aburto T C, Achohi T, Adelekan A, Adofo K, Adou A K, Afshin A, Agardh E E, Khabouri M J A, Lami F H A, Alam S S, Alasfoor D, Albittar M I, Alegretti MA A, Aleman A V, Alemuz Z A, Alfonso-Cristancho R, Alhabib S, Ali R, Ali M K, Alla F, Allebeke P, Allen P J, Alsharif U, Alvarez E, Alvis-Guzman N, Amankwaa A A, Amare A T, Ameh E A, Ameli O, Amini H, Ammer W, Anderson B O, Antonio C A T, Anwari P, Cunningham S A, Arnlov J, Arsenijevic V S A, Artaman A, Asghar R J, Assadi R, Atkins L S, Atkinson
C, Avila M A, Awuah B, Badawi A, Bahit M C, Bakfalouni T, Balakrishnan K, Balalla S, Balu R K, Banerjee A, Barber R M, Barker-Collo S L, Barquera S, Barregard L, Barrero L H, Barrientos-Gutierrez T, Basto-Abreu A C, Basu A, Basu S, Basulaiman M O, Ruvalcaba C B, Beardsley J, Bedi N, Bekele T, Bell M L, Benjet C, Bennett D A, et al 2015 Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the Global Burden of Disease Study 2013 The Lancet 386 2287–323

[46] WHO 2016 WHO Global Urban Ambient Air Pollution Database (update 2016) WHO

[47] UN-ESA 2011 World Population Prospects: The 2010 Revision (New York, U.S.: United Nations, Department of Economic and Social Affairs, Population Division)

[48] Burnett R T, Pope C A III, Ezzati M, Olives C, Lim S S, Mehta S, Shin H H, Singh G, Hubbell B, Brauer M, Anderson H R, Smith K R, Bruce N G, Kan H, Laden F, Prüss-Ustün A, Turner M C, Gapstur S M, Diver W R and Cohen A 2014 An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure Environ. Health Perspect.

[49] Fricko O, Havlik P, Rogelj J, Klimont Z, Gusti M, Johnson N, Kolp P, Strubegger M, Valin H, Amann M, Ermolieva T, Forsell N, Herrero M, Heyes C, Kindermann G, Krey V, McCollum D L, Obersteiner M, Pachauri R, Riebel A, Roelfsema M, Schaeffer R and Riahi K 2017 The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century Glob. Environ. Change 42 251–67

[50] Roelfsema M, van Soest H L, Harmsen M, van Vuuren D P, Bertram C, den Elzen M, Höhne N, Iacobuta G, Krey V, Kriegler E, Luderer G, Riahi K, Ueckerdt F, Després J, Drouet L, Emmerling J, Frank S, Fricko O, Gidden M, Humpenöder F, Huppmann D, Fujimosi R, Fragkiadakis K, Gi K, Keramidas K, Köberle A C, Aleluia Reis L, Rochedo P, Schaeffer R, Oshiro K, Vrontis Z, Chen W, Iyer G C, Edmonds J, Kannavou M, Jiang K, Mathur R, Safonov G and Vishwanathan S S 2020 Taking stock of national climate policies to evaluate implementation of the Paris Agreement Nat. Commun. 11 2096

[51] IEA 2016 World Energy Outlook Special Report: Energy and Air Pollution (Paris, France: International Energy Agency (IEA))

[52] Rafaj P and Kypreos S 2007 Internalisation of external cost in the power generation sector: Analysis with Global Multi-regional MARKAL model Energy Policy 35 828–43

[53] Markandya A and Chiabai A 2009 Valuing Climate Change Impacts on Human Health: Empirical Evidence from the Literature Int. J. Environ. Res. Public. Health 6 759–86

[54] WHO 2006 Air quality guidelines. Global update 2005. Particulate matter, ozone, nitrogen dioxide and sulfur dioxide (Copenhagen, Denmark: World Health Organization Regional Office for Europe)

[55] Aleluia Reis L, Drouet L, Van Dingenen R and Emmerling J 2018 Future Global Air Quality Indices under Different Socioeconomic and Climate Assumptions Sustainability 10 3645

[56] Erickson L E 2017 Reducing greenhouse gas emissions and improving air quality: Two global challenges Environ. Prog. Sustain. Energy 36 982–8
[57] Landrigan P J 2018 The health and economic benefits of climate mitigation and pollution control 
Lancet Planet. Health 2 e107–8

[58] Cameron C, Pachauri S, Rao N D, McCollum D, Rogelj J and Riahi K 2016 Policy trade-offs between climate mitigation and clean cook-stove access in South Asia Nat. Energy 1 1–5

[59] S. Henschel, G. Chan 2013 Health risks of air pollution in Europe - HRAPIE project : New emerging risks to health from air pollution - results from the survey of experts (Copenhagen, Denmark: WHO Regional Office for Europe)

[60] Burnett R, Chen H, Szyszkwicz M, Fann N, Hubbell B, Pope C A, Apte J S, Brauer M, Cohen A, Weichenthal S, Coggins J, Di Q, Bruneckreef B, Frostad J, Lim S S, Kan H, Walker K D, Thurston G D, Hayes R B, Lim C C, Turner M C, Jerrett M, Krewski D, Gapstur S M, Diver W R, Ostro B, Goldberg D, Crouse D L, Martin R V, Peters P, Pinault L, Tjepkema M, Donkelaar A van, Villeneuve P J, Miller A B, Yin P, Zhou M, Wang L, Janssen N A H, Marra M, Atkinson R W, Tsang H, Thach T Q, Cannon J B, Allen R T, Hart J E, Laden F, Cesaroni G, Forastiere F, Weinmayr G, Jaensch A, Nagel G, Concin H and Spadaro J V 2018 Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter Proc. Natl. Acad. Sci. 115 9592–7

[61] IAMC (Integrated Assessment Modelling Consortium) - The common Integrated Assessment Model (IAM) documentation (https://www.iamcdocumentation.eu/index.php/IAMC_wiki)

[62] Yan M, Wilson A, Bell M L, Peng R D, Sun Q, Pu W, Yin X, Li T and Anderson G B 2019 The Shape of the Concentration–Response Association between Fine Particulate Matter Pollution and Human Mortality in Beijing, China, and Its Implications for Health Impact Assessment Environ. Health Perspect. 127 067007

[63] Giani P, Anav A, Marco A D, Feng Z and Crippa P 2020 Exploring sources of uncertainty in premature mortality estimates from fine particulate matter: the case of China Environ. Res. Lett. 15 064027

[64] Xiao Q, Liang F, Ning M, Zhang Q, Bi J, He K, Lei Y and Liu Y 2021 The long-term trend of PM2.5-related mortality in China: The effects of source data selection Chemosphere 263 127894