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Can better technologies avoid all air pollution damages to the global economy?

François Chantret[1] · **Jean Chateau**[1] · **Rob Dellink**[1] · **Olivier Durand-Lasserve**[1] · **Elisa Lanzi**[1]

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Abstract

This paper assesses the potential role of the implementation of the best available technologies to reduce the economic consequences of outdoor air pollution in the coming decades. The paper focuses on market impacts related with additional health expenditures, changes in labour productivity and crop yield losses and also presents results on non-market costs, i.e. welfare losses from avoided premature deaths. The results show that technological improvements can potentially reduce concentrations of air pollutants to levels compatible with the WHO guidelines in most countries. However, technology measures can only reduce part of the economic costs relative with the market impacts. While those are efficient in reducing the direct costs of air pollution, there are still large indirect costs associated with current and remaining pollution levels. Policies that aim directly at avoiding economic impacts need to be implemented to further reduce air pollution damages, especially in the regions where technologies are not sufficient to reduce concentrations or where economic consequences persist despite reduced concentration levels.

Keywords Air pollution · Emissions · General equilibrium modelling · Health impacts · Technological improvements · Economic consequences

JEL classification D58 · I15 · Q43 · Q53 · Q5

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✉ François Chantret
francois.chantret@ec.europa.eu

✉ Elisa Lanzi
elisa.lanzi@oecd.org

[1] Organisation for Economic Co-operation and Development (OECD), 2 rue André Pascal, 75775 Paris Cedex, 16, France

1 Introduction

Air pollution is one of the most serious environmental risks, with strong impacts on human health. It also has consequences on the environment and on human activities, with impacts on crop yields, biodiversity, land and water, visibility, materials and buildings, including cultural heritage. Those impacts also have economic consequences, with especially high costs in countries where air pollution affects many people. Much can be done to reduce emissions and air pollution impacts, including technological development as well as public policies.

Policies targeted to reduce air pollution and its negative effects on human health have been implemented in many countries, leading to a decrease in emissions in many member countries of the Organisation for Economic Co-operation and Development (OECD). For example, the Clean Air Programme for Europe shows a renewed engagement within the European Union to reduce air pollution. Air pollution has been decreasing also in some non-OECD countries. In China, a strong policy focused on air quality has led to a recent reduction of air pollution, which should improve if the established reduction targets are met. In other areas, however, emissions of air pollutants have been increasing and are projected to further increase in the absence of further policy action. The severe impacts of air pollution on human health are the main reason for such a strong focus on air pollution. Previous work on the impacts of air pollution shows a large number of premature deaths: 5.5 million premature deaths globally in 2013 (Forouzanfar et al. 2015; Brauer et al. 2016). Lim et al. (2012) and WHO (2014) estimate that outdoor air pollution alone kills in the order of magnitude of 3 to 4 million people a year globally.

The negative impacts of air pollution on health and the environment will also affect economic growth in the coming decades (OECD 2016). The economic feedbacks from air pollution can be quantified using an impact pathway approach (ExternE 1995, 2005; USDOE 1992), which quantifies the costs of air pollution by calculating how emissions, concentrations, exposure, biophysical impacts and valuation of the economic feedback effects all link together. A recent study by Markandya et al. (2018) finds that the health co-benefits from different climate mitigation scenarios substantially outweigh the policy costs. A similar result is found by Vandyck et al. (2018), who show that the air quality co-benefits for human health and agriculture counterbalance the costs to meet the nationally determined contributions in Paris Agreement. Previous studies have focused on the USA (Matus et al. 2008), the European Union (Vrontisi et al. 2016; WHO 2013a, b; Holland 2014a, b; ExternE 2005; Rabl et al. 2014) and China (Matus et al. 2012). For ozone only, Selin et al. (2009) study global consequences.

In contrast to earlier studies, this paper goes beyond analysing the health benefits of emission reductions, but calculates the future economic costs of air pollution for a baseline scenario as well as a scenario reflecting the implementation of improved technologies to reduce air pollution emissions. While a full cost–benefit analysis of the implementation of improved technologies is outside the scope of the paper, this study highlights the potential economic benefits (or reduction in economic costs) that can derive from implementing better technologies to reduce air pollution. Part of the energy modelling forum (EMF) 30 exercise, this paper focuses on mitigation potentials for air pollutants. Previous work within the same exercise focused on mitigation potentials of methane and of short-lived climate forcers (Harmsen et al. 2019a, b).

Furthermore, this paper takes a detailed sectoral and regional approach. The regional disaggregation within a global focus is important because the various regions are linked through transboundary pollution and international trade; moreover, the regions that are most affected by air pollution are outside the EU and the OECD—where most of the existing analysis has focused. The detailed sectoral approach is essential as it allows the linking of air pollution damages to specific production factors and sectors; it also enables decomposing the overall effects into direct and indirect effects.

Different assumptions can be made on the adoption of available technologies to reduce air pollution. This paper compares two scenarios. First is the Current Legislations (CLE), which, as explained in Cofala et al. (2007), describes the policies currently in place. In particular, it is derived from collecting data on the available current national perspectives on sectoral, economic and energy development or, if that is unavailable, on results from regional modelling studies. The CLE scenario is compared with another scenario, the maximum feasible reduction (MFR), which illustrates the potentials to reduce air pollution emissions through adoption of best available technologies (Cofala et al. 2007). These technology scenarios are based on the results of the GAINS model, which explicitly includes source- and region-specific technology characteristics (Klimont et al. 2017). Emissions of primary particulate matter (PM)—black carbon (BC)—and precursors of secondary PM—incl. sulphur dioxide (SO_2) and nitrogen oxides (NO_x)—are considered under the two technology scenarios. These two scenarios highlight the importance of technology developments in reducing the consequences of air pollution. A comparison of the two scenarios with WHO guideline pollution levels and the assessment of the economic damages persisting in the MFR scenario reveal the importance of going beyond technology adoptions and complement them with economic policies.

The strength of analysis in this paper lies in how it combines a series of detailed, harmonised models for the full loop from economic activity to pollution, impacts and back to economic activity. By bringing together the state-of-the-art information on the impacts of air pollution with a detailed economic model to provide projections for the coming decades, this paper provides significant new insights in the regional and sectoral economic consequences of outdoor air pollution. This paper extends the analysis of the economic consequences of outdoor air pollution in OECD (2016) and Lanzi et al. (2018), using the same modelling framework and economic baseline calibration. However, while OECD (2016) and Lanzi et al. (2018) only assess the economic consequences of outdoor air pollution in a CLE-type baseline scenario, the novelty of the current paper lies in investigating the differences between CLE and MFR scenarios, and the analysis of the corresponding differences in economic consequences. From this, a number of important new policy insights are derived and discussed. The baseline scenario, based on CLE coefficients, is fully consistent with the modelling results provided by the ENV-Linkages model for the reference scenario of the EMF-30 scenario comparison exercise. The MFR coefficients are used in the EMF-30 exercise in the scenario aiming at the reduction of black carbon and organic carbon by end users. This paper uses these coefficients and also extends the use of MFR to all relevant sectors to reduce air pollution and study the full potential of emission reductions using the best available techniques. The core of the analysis presented in this paper is to exploit the economic nature of the ENV-Linkages model.

The remainder of the paper is structured as follows. "Methodology" presents the methodology and modelling framework. "Projected global impacts of air pollution" presents the projections of economic growth, emissions, concentrations and biophysical impacts. "Results: air pollution damages in the CLE and MFR scenarios" presents results on the comparison of the two scenarios. "Conclusion" concludes.

2 Methodology[1]

The paper considers selected impacts on health and agriculture as linked to emissions of pollutants (“Assessing outdoor air pollution impacts with a production function approach”). The analysis is based on the ENV-Linkages computable general equilibrium model (CGE) (“Modelling tools”), constructing a socio-economic baseline to 2050 and formulating projections of future air pollutant emissions (“Projected trends in economic activity in the absence of air pollution feedbacks”). Emissions of pollutants are considered under two alternative scenarios that describe different future technological developments: the baseline CLE scenario and the MFR scenario in which the best available techniques are implemented to reduce air pollution. The respective emission coefficients are obtained from the GAINS model, which holds essential information about key sources of emissions, environmental policies and mitigation opportunities (Klimont et al. 2017). Concentration projections for the CLE and MFR scenarios are then determined using the TM5-FASST model and used to calculate impacts of air pollution on crop yields and health (“Projected trends in emissions and concentrations by scenario”).

These biophysical impacts of air pollution are included in ENV-Linkages to calculate the economic feedback cost of air pollution through labour productivity losses, additional health expenditures and agricultural yield losses (“Results: air pollution damages in the CLE and MFR scenarios”). The general equilibrium framework considers both direct and indirect effects throughout the rest of the economy. For instance, a decrease in crop yields will reduce agricultural output and also induce substitution to other crops and changes in trade patterns. The welfare gains of reducing premature deaths in the MFR scenario are also evaluated.

2.1 Modelling tools

The core tool used in this paper is the global dynamic computable general equilibrium model ENV-Linkages (Chateau et al. 2014); the model distinguishes 25 regions and 35 sectors (see Section 1 of the Supplementary Material). ENV-Linkages represents how sectoral and regional economic activities are linked to each other. The model contains bilateral trade flows and capital accumulation using capital vintages, in which technological advances are adopted gradually rather than instantaneously. It also links economic activity with environmental outcomes, specifically GHG and air pollutant emissions. Sectoral and regional economic activities are projected to 2050, based on socio-economic drivers, including demographic factors, economic growth and changes in sectoral activity (see “Projected trends in economic activity in the absence of air pollution feedbacks”).

Emissions of air pollutants related to production activities are linked to sectoral production inputs; residential emissions are related to household consumption. Main emission sources are power generation and industrial energy use, through combustion of fossil fuels; agricultural production, through use of fertilisers; transport, especially through fossil fuel use in road transport; and emissions from residential and commercial sectors, through the use of energy for cooking, heating and cooling. In this study, estimates for selected air pollutants were included: sulphur dioxide (SO_2), nitrogen oxides (NO_x), black carbon (BC), organic carbon (OC), carbon monoxide (CO), volatile organic compounds (VOCs) and ammonia (NH_3). The GAINS model (Amann et al. 2013; Wagner et al. 2007) provided scenario-specific emission

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[1] The methodology presented here builds directly on OECD (2016).

coefficients for both CLE and MFR scenarios.[2] Emission coefficients change over time to reflect technological improvements, the change in the age structure of the capital stock and the influence of existing policies.

Emission projections are used to calculate concentrations of $PM_{2.5}$ and ground-level ozone (O_3). Population-weighted mean concentrations of $PM_{2.5}$ and ozone have been calculated using the TM5-FASST model (Van Dingenen et al. 2018).[3]

The effects of air pollution on health are assessed with concentration-response functions which link health impacts to the population-weighted mean concentrations of $PM_{2.5}$ and O_3, expanding the methodology of Holland (2014a, b). The health impacts included in the analysis are hospital admissions related to respiratory and cardiovascular diseases, chronic bronchitis ($PM_{2.5}$ only), lost working days ($PM_{2.5}$ only), restricted activity days and minor restricted activity days due to asthma symptoms ($PM_{2.5}$ only). The impacts of $PM_{2.5}$ on mortality in 2010 are based on the results of the global burden of disease (GBD) studies (Forouzanfar et al. 2015; Brauer et al. 2016).[4] Effects of ozone on mortality in 2010 are based on Lim et al. (2012) and Burnett et al. (2014). These impacts on mortality are not included as part of the market damages in the model but they are considered non-market damages to calculate the welfare costs of air pollution.

Crop losses for rice, wheat, maize and soybean are based on concentrations of ozone during the growing season, as described in Van Dingenen et al. (2009).[5] Crop yield changes that are not covered by TM5-FASST are projected using the information in Mills et al. (2007): yield changes for these crops are based on their relative sensitivity to ozone as compared with rice.

2.2 Assessing outdoor air pollution impacts with a production function approach

The modelling approach, which follows OECD (2016), specifies the effects of the environmental impacts on productivity and supply of production factors, as well as changes in household and government demand; this is called the "production function approach".[6] Air pollution impacts are fed into ENV-Linkages to assess implications for economic activities and economic costs. This allows teasing out direct and indirect consequences of environmental damages at global and regional level.

The projection of economic activity with environmental damages is contrasted with the "no-damage 'baseline' projection", which reflects socio-economic trend developments without environmental impacts. This approach does not deny that environmental impacts already affect the economy, but serves to build a comparison point to measure their economic consequences.

Changes in health expenditures due to increased incidence of illnesses are implemented in the model as a change in demand for health services (part of the aggregate non-commercial

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[2] The emission coefficients from the GAINS model are adapted to the sectoral and regional aggregation of ENV-Linkages.

[3] Population-weighted averages are used as impacts relate to exposure.

[4] By building on the GBD studies, the implicit weaknesses of those studies are included also here. For instance, there may be a risk that interactions between air pollution and tobacco smoking are not adequately addressed in attributing mortality to outdoor air pollution. Nonetheless, the GBD studies provide the most robust and comprehensive information available for assessing the impacts of air pollution on mortality at a global level.

[5] Rice, wheat, maize and soybean represent more than half the total volume of global agricultural production, but less than half of the value.

[6] For a general framework, see Sue Wing and Fisher-Vanden (2013). Dellink et al. (2017b) uses this approach for an analysis of the economic consequences of climate change; Lanzi et al. (2018) for an analysis of the economic consequences of outdoor air pollution; and Vrontisi et al. (2016) for the assessment of the EU's clean air policy package.

services sector) by both households and governments. *Changes in labour productivity* due to increased incidence of illnesses are directly implemented as percentage changes in regional productivity of the labour force. Productivity losses are calculated from lost work days, following the methodology used in Vrontisi et al. (2016). *Changes in mortality* are captured as changes in labour supply. This however only accounts for the market costs linked to the premature deaths; non-market damages are assessed outside the CGE model. *Changes in crop yields* are implemented as a change in factor productivity in agriculture. Section 2 of the Supplementary Material provides further details on how the production function approach is implemented and how impacts have been modelled.

The *indirect economic consequences* are the combination of changes in the economy that are induced by the three direct impact categories (labour, health care and agriculture). These include indirect effects on labour markets through adjustments in wages and labour allocation, changes in capital markets through changes in savings and capital accumulation, and changes in other components of GDP, such as value added generated by land and natural resources and changes in tax revenues. On the household side, they include changes in consumption and savings patterns to accommodate changes in income and relative prices, as well as the increased health expenditures.

Linking air pollution impacts to sectoral economic variables works well for impacts that directly affect economic markets. For non-market impacts, such a link with a part of the production function does not exist. In principle, the utility function could be used to incorporate both market and non-market damages in a single quantitative framework, but specifying such a utility function is far from obvious and left for future research. The welfare costs associated with non-market mortality impacts are therefore calculated separately, using value of a statistical life estimates as elaborated in OECD (2014) and OECD (2016).

3 Projected global impacts of air pollution

The integrated modelling framework is used to make scenario projections to 2050. A first step, presented in "Projected trends in economic activity in the absence of air pollution feedbacks", consists of projecting economic activity in the absence of the pollution feedbacks. This then forms the basis for the scenario-specific projections of emissions and concentrations ("Projected trends in emissions and concentrations by scenario"). Finally, the biophysical impacts of changes in concentrations on health and agricultural impacts are presented in "Projected impacts of air pollution on human health and agriculture". These form the basis for the analysis of economic consequences in "Results: air pollution damages in the CLE and MFR scenarios".

3.1 Projected trends in economic activity in the absence of air pollution feedbacks

The regional GDP projections indicate that global economic activity will continue to grow in the coming decades. These projections are driven by a multitude of factors, including assumptions on country-specific developments in demography, technology and other acting forces. While long-run global economic growth rates are gradually declining, Fig. 1 shows that GDP levels in the projection without air pollution feedbacks increase more than linearly over time. The largest growth is projected to be in Asia and Africa, where a huge economic growth potential exists. The share of the OECD in the world economy is projected to shrink from 64%

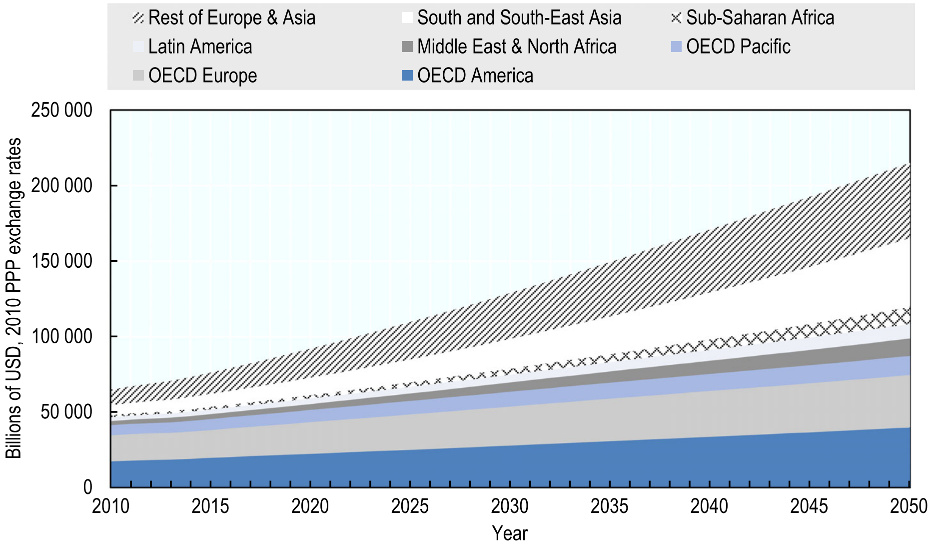

Fig. 1 Trend in real GDP, no-feedback projection, by aggregate region

in 2010 to 38% in 2050. These projections are fully aligned with OECD (2014) and follow the projections presented in OECD (2016). They are close to the OECD projections of GDP for the SSP2 scenario (Dellink et al. 2017a) and are built on the same modelling framework, but the quantification differs somewhat as they follow UN projections for demographics and follow official OECD long-term projections for the economic drivers of GDP growth.

Figure 2 shows how the sectoral structure evolves in the regional economies. The sectoral shares in OECD economies tend to be relatively stable, with the service sectors accounting for more than half of GDP. The major oil exporters in the Middle East and Northern Africa are projected to gradually diversify their economies and rely less on energy resources. In developing countries, the decline of the share of agriculture is projected to continue strongly. Energy and extraction rise markedly in South and South-East Asia and rest of Europe and Asia, reflecting a growing reliance on fossil fuels and a strong increase in electricity use. That has significant consequences for emissions of air pollutants.

3.2 Projected trends in emissions and concentrations by scenario

Following these economic trends and the CLE emission coefficients, emissions of most air pollutants are projected to increase in the coming decades (Fig. 3). In particular, NO_x emissions are projected to increase rapidly until 2050, following the projected increase in demand for energy and limited control of NO_x emissions from power plants and industrial boilers in the developing world. Global emissions of other pollutants also increase (see Section 3 of the Supplementary Material). The mild increase in OC emissions corresponds to lower emissions from household energy demand, reflecting energy efficiency improvements, use of cleaner fuels and the switch from open fire biomass to cleaner energy sources.

The majority of NO_x emissions originate from fuel combustion in transport and industry, whereas SO_2 emissions are dominated by fuel combustion in industry and power generation. Primary sources of BC and OC emissions are the transport sector (dominates emissions in the

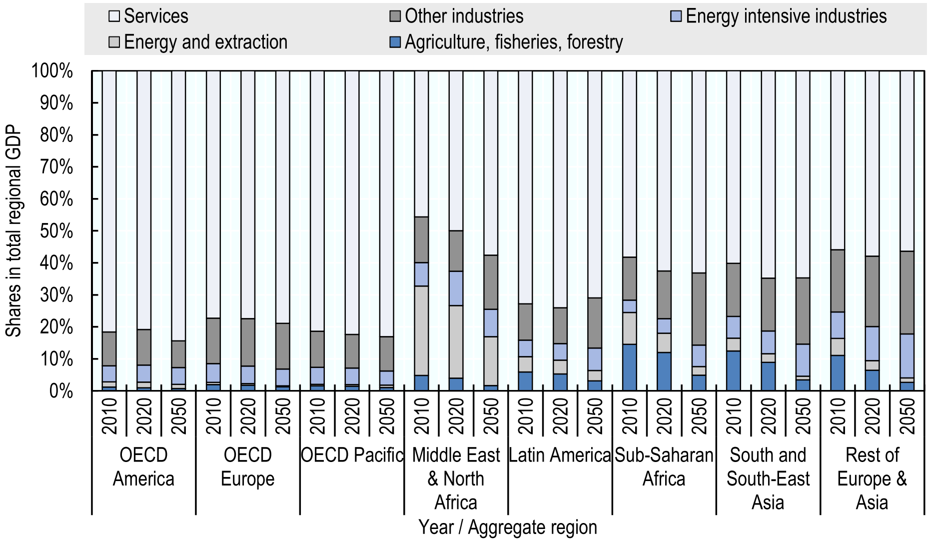

Fig. 2 Sectoral composition of GDP by aggregate regions

developed world) and residential and commercial use of solid fuels. The contribution of emissions from industrial sources is projected to increase over time for all gases. The contribution of emissions from residential and commercial services for CO is projected to remain relatively stable. Emission reductions from the residential sectors due to technological improvements are offset by higher emissions from transport and industry energy use.

Gradual move to the best available technologies, as described in the MFR scenario, will strongly reduce emissions of air pollutants in the coming decades. In particular, the technologies considered in the MFR scenario aim at reducing emissions of SO_2, NO_x, OC and BC, which are thus reduced by 71%, 78%, 81% and 86% in 2050, respectively (see Section 3 of the Supplementary Material for more details and a comparison of regional and sectoral emissions across both scenarios). As illustrated in Fig. 3, with the implementation of better technologies in the MFR scenario, emissions substantially decrease for all gases. The emission reductions are strongest between 2010 and 2030 as in this period all technologies are projected to be implemented. They are then stable as it is assumed that there are no additional technologies to reduce emissions. The MFR scenario leads to emission reductions that reflect the maximum technically feasible improvements in the different regions and for the different pollutants. For example, most emission reductions for BC can be achieved from end use emissions in the residential and services sectors. On the other hand, most emission reductions for NO_x are achieved in transport, industry and power generation.

With emissions generally rising over time in the CLE scenario, concentrations are also projected to increase in most regions, albeit not all (Fig. 4). In the base year, $PM_{2.5}$ concentrations are highest in South and East Asia, and particularly in China and India. They are also high in some areas of North America, Europe and Africa. According to the projections, the average concentrations will increase significantly in South and East Asia and in some areas of Africa. Concentrations are projected to slightly decrease in North America and Europe. Average concentrations of ground-level ozone are highest in the Mediterranean region, the Middle East, parts of Sub-Saharan Africa and parts of continental Asia, including major regions in India and China. These areas are most affected in the base year and in the projections.

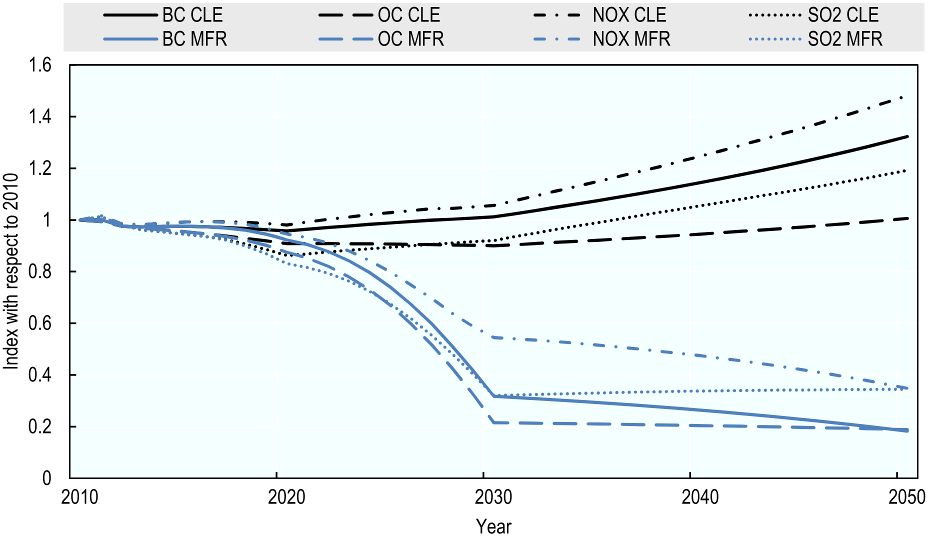

Fig. 3 Emission projections over time

The technological improvements described in the MFR scenario can lead to a reduction in average annual concentrations of $PM_{2.5}$ below the WHO guidelines (WHO 2006) in most countries, showing that these technical measures can be very efficient in reducing pollution. The MFR scenario is particularly efficient in reducing emissions in regions with high concentrations, such as Korea, China, India and Other Asia. Nevertheless, in a few regions, the measures are not sufficient to achieve the WHO guidelines, and most notably in China for which concentrations are much higher than the guidelines even in the MFR scenario.

3.3 Projected impacts of air pollution on human health and agriculture

With increasing emissions and concentrations in the CLE scenario, the number of cases of illness is also projected to increase, leading to a substantial increase in health expenditures relative to bronchitis and asthma. The health expenditures increase from USD bln 15 in 2010 to USD bln 91 in 2050 in the CLE scenario (Table 1).[7] The additional cases of illness in the CLE scenario also lead to almost 2.8 bln lost working days globally. This has a negative impact on labour productivity in all regions.

While health expenditures increase and labour productivity decreases in all regions, there are regional differences in the sizes of the impacts, which reflect the levels of concentrations of pollutants, of exposure in the different areas and the demographic characteristics of the population. In particular, the labour productivity losses are in absolute terms predominantly located in non-OECD countries.[8] The additional health costs associated with these impacts also vary across the world, reflecting differences in health systems and costs of hospital admissions.[9]

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[7] Throughout the paper, economic values are expressed in 2010 US dollars, using 2010 purchasing power parity exchange rates.

[8] In percentage of total working days, the difference is less stark: 0.2% for OECD, 0.3% for non-OECD.

[9] Section 2 of the Supplementary Material provides more details on the regional impacts in 2050.

Table 1 Overview of global air pollution impacts in 2050

		Health expenditures	Labour productivity	Agricultural productivity
		million USD	million lost working days	range of losses in pct
CLE scenario	OECD	22,356	233	0–23%
	non-OECD	68,378	2548	0–11%
	World	90,733	2781	0–23%
MFR scenario	OECD	11,708	119	0–14%
	non-OECD	20,373	754	0–6%
	World	32,081	873	0–14%

High concentration levels of pollutants affect agricultural productivity. Crop yields are lower, especially in areas with high pollution levels or where climate change and climatic characteristics lead to high concentrations of the pollutants. In line with Mills et al. (2007) and Chuwah et al. (2015), crop yields are negatively affected in all regions, with big differences between regions and crops. In most regions, oil seeds are most affected, with high losses in several OECD countries, including Japan, Korea and the USA.

All three types of impacts are considerably smaller in the MFR scenario, but still sizable. Global impacts are reduced by roughly two-thirds, with relatively minor variation between the different impacts. The largest reductions in impacts are found in the regions with the highest exposure to air pollution. The impacts in the non-OECD region are reduced by around 70%, while in the OECD, they are only halved.

4 Results: air pollution damages in the CLE and MFR scenarios

4.1 Market damages

Air pollution impacts on human health and on crop yields have economic consequences that can be studied in ENV-Linkages using a production function approach. When impacts are incorporated in ENV-Linkages, the reduced labour productivity, increased health expenditures and lower agricultural productivity have a negative effect on economic production and income. Although the impacts are smaller in the MFR scenario than ion CLE, some impacts remain. As a consequence, GDP decreases below the no-damage projection (but not below 2017 levels) in most regions in both the CLE and MFR scenarios (Fig. 5).[10] The economic consequences depend on the pollution levels, but the non-linearities in the system cause the changes in GDP to be non-proportional to the changes in pollution levels.[11]

The projected losses for the CLE scenario are by far the largest in the rest of Europe and Asia region, which includes e.g. China, the Caspian region and Russia. Not only are concentrations projected to be very high in this region; the impacts on labour productivity and especially health expenditures are significantly larger than in other regions. Projected 2050 GDP losses in India are much smaller than in China, despite both countries having very high projected concentrations. One key difference is that India has a much younger population,

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[10] These economic consequences are presented here as deviation from the no-damage baseline projection.

[11] Lanzi et al. (2018) discuss the economic consequences of the air pollution impacts in the CLE scenario in more detail.

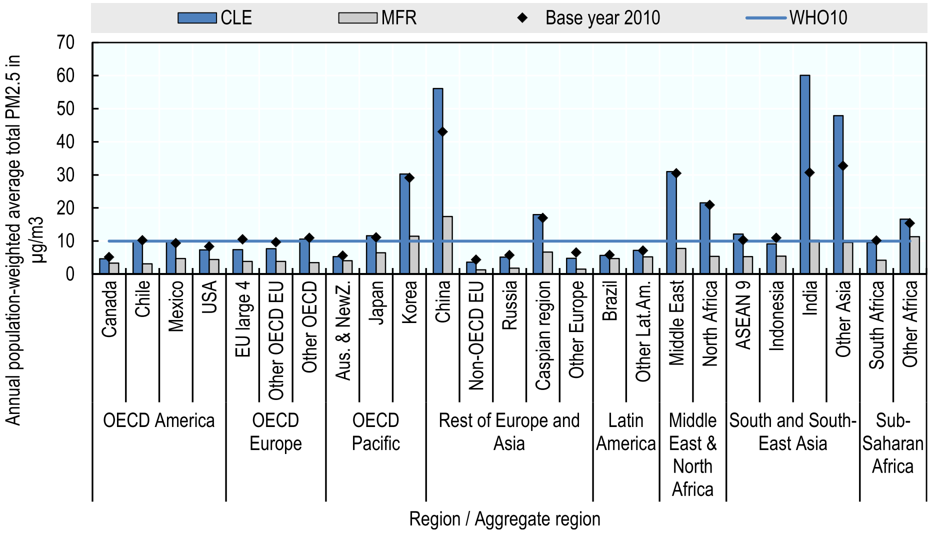

Fig. 4 Concentration levels in 2050

while aging is projected to become a more severe problem in China. This means that the Chinese population structure is more vulnerable to air pollution, so that for example additional health expenditures are higher in China.[12] Furthermore, current savings and investment rates are substantially larger in China than in India, while in the longer run, the opposite is projected. That implies a different response between those countries to a reduction in income or increased expenditures. In both scenarios, there is a small economic gain in Brazil. That is due to relatively minor domestic yield losses, combined with large opportunities for expanding agricultural land by converting natural areas, implying improving relative competitive position of Brazil in the global crop market vis-à-vis their main competitors (see Dellink et al. 2017b, for a detailed discussion of trade effects from agricultural yield shocks caused by climate change; similar trade effects occur here).

In the MFR scenario, the economic damages are lower, showing that the implementation of improved technologies cannot only be beneficial for human health and the environment but also reduces damages that may counterbalance the necessary investment costs for the new technologies that are not considered in this analysis. Figure 6 presents a comparison of the reduction in damages and concentrations in the MFR scenario.[13] Avoided damages are consistently smaller than the change in concentrations, showing that a change in concentrations does not imply a corresponding reduction in damages. The first and main reason for this is inertia in the economy: damages from current pollution lead to negative consequences for the current economy, which in turn affects the potential for future economic growth, and thus leads to future damages. In the MFR scenario, concentration levels are gradually declining, but there is still an economic effect of past pollution levels that lingers. Secondly, even at low

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[12] The implications of the age structure of the population also affect other parts of the economy, such as labour participation rates.

[13] From moving from CLE to MFR, in Brazil the damages increase by 28%, and the concentrations decrease by 16%; in Other Latin America, the damages decrease by 115%, and the concentrations decrease by 27%.

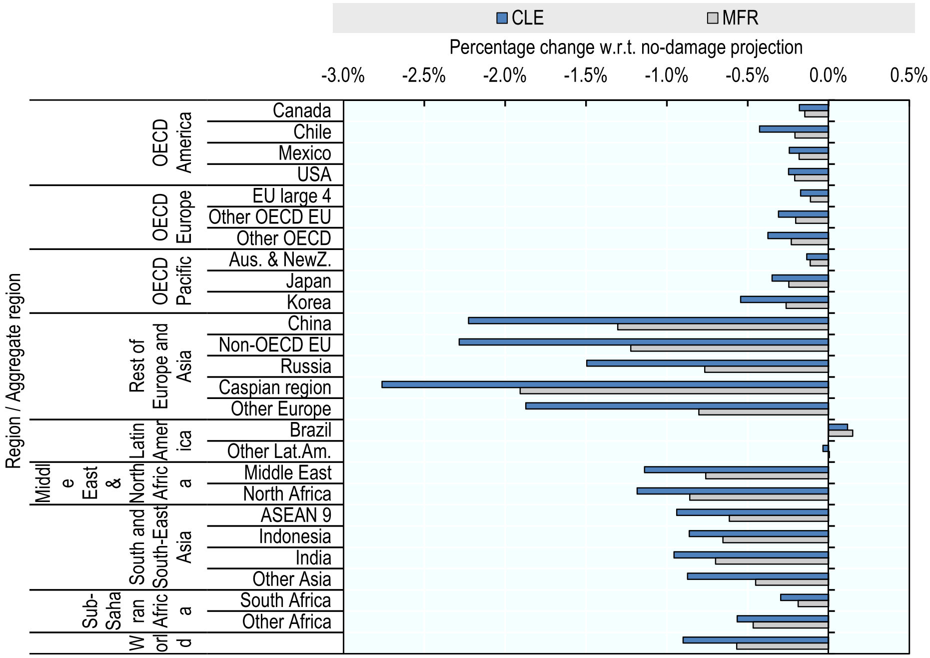

Fig. 5 Regional GDP consequences in 2050

levels of pollution, some health care costs and labour productivity impacts remain, albeit at much smaller scales. Shi et al. (2016) suggest that there is no lower cutoff level regarding impacts, and even concentration levels below the WHO guideline may lead to health impacts. Thirdly, the MFR scenario aims at reducing PM concentration levels, but does not have an equivalent effect on the damages from ozone, which remain relatively high. While ozone

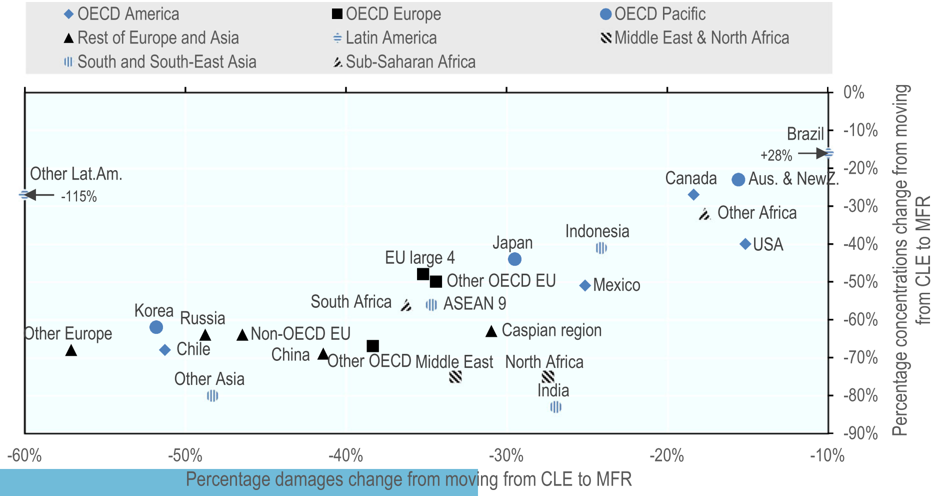

Fig. 6 Comparing changes in concentrations and damages in 2050 between MFR and CLE scenarios

damages are considerably smaller than PM-related damages in the CLE scenario, their share of total damages increases in the MFR scenario.

Generally, countries with high base-year levels of PM and ozone concentrations (mostly in Asia) have a relatively large gap between concentration reductions and damage reductions between the MFR and CLE scenarios in 2050 (the correlation coefficient is around 60%). In these countries, high damages in the early years have lasting economic effects and thus lead to lower GDP levels (i.e. high damages) in 2050; the indirect economic consequences have a permanent effect through the implications for capital stocks and thus long-term economic growth (see “Assessing outdoor air pollution impacts with a production function approach”). But there are other effects at play as well, such as the importance of agricultural damages (esp. China, North Africa and India), which generally remain high in the MFR scenario.

In Brazil, the gain is larger in the MFR scenario (shown by the positive increase in economic gains), while in other Latin America, there is a small gain in the MFR scenario instead of a small loss in the CLE scenario (i.e. the reduction in damages is more than 100%). As explained above, these countries can benefit from an improved competitive position on the world market, even though air pollution impacts also affect them negatively.

Differences in the effect of the MFR technology options on damages and concentrations are mostly due to indirect damages, confirming the central role of economic inertia. As illustrated in Fig. 7, remaining damages keep growing over time, largely caused by indirect capital costs. The slowdown of capital accumulation due to air pollution has permanent effects, even if concentration levels are brought down under the WHO guideline levels. At global level, MFR can effectively reduce direct damages to near-zero levels, but fails to stabilise indirect damages.

Although direct damages rapidly disappear at global level, they do not disappear in all regions (Fig. 8). Especially in regions where a reduction in labour productivity has a large impact on GDP, or where agricultural impacts are large, some remaining direct damages will continue to affect the economy. However, these impacts together are not large enough to have significant consequences on global GDP.

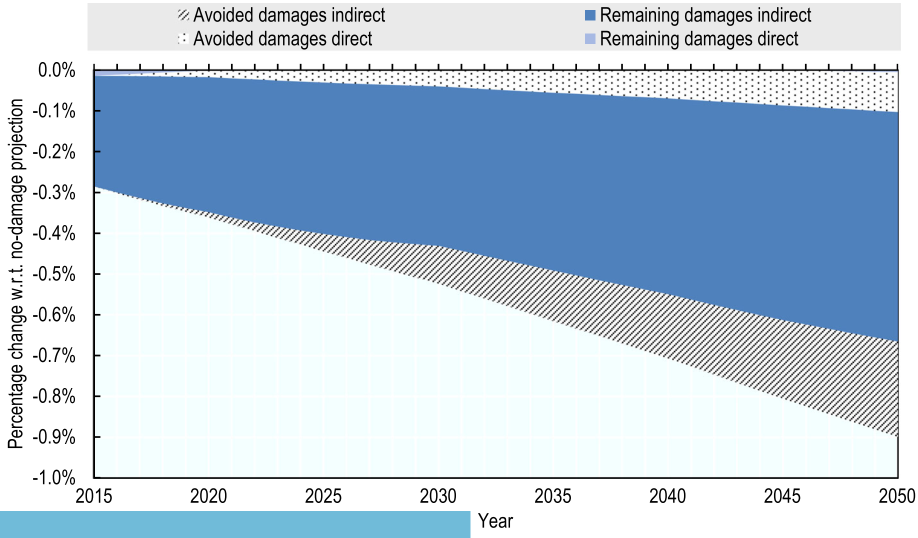

Fig. 7 Direct and indirect global damages over time

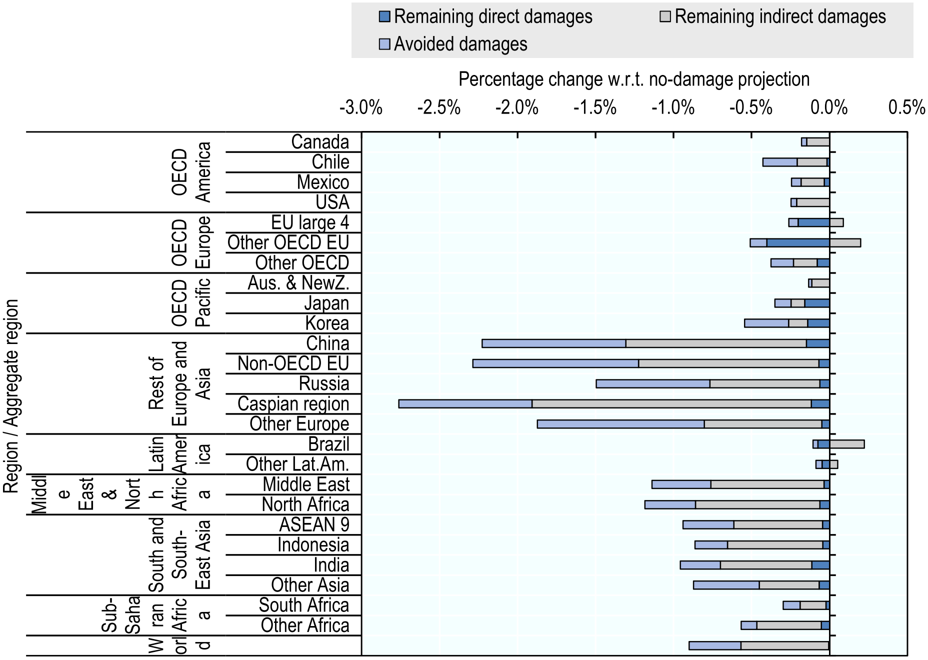

Fig. 8 Direct and indirect regional damages in 2050

4.2 Non-market damages

Within the CLE scenario, by 2050 outdoor air pollution could cause 5.2–6.6 million premature deaths per year at global level.[14] Most premature deaths take place in South and South-East Asia. Africa also has a high number of premature deaths. While levels of premature deaths are lower in OECD and European countries, they are significant in some regions, such as the USA, and parts of Europe. In per capita terms, premature deaths in the OECD countries are highest in Japan and Korea, where population aging implies a significant increase in the vulnerability of the population to air pollution, even without increasing concentration levels.

With concentrations significantly lower in the MFR scenario, less people are affected by air pollution (Fig. 9). As a consequence, the number of premature deaths attributable to air pollution also decreases. In the MFR scenario, premature deaths decrease to 2.3–3.2 million, thus potentially decreasing by more than 50%. Large reductions take place in several OECD countries, as well as in North Africa, Eastern European countries, Russia and the Caspian region. In many of these regions, the initial level of premature deaths is high. Large differences in the curved and linear projections for avoided premature deaths apply to countries such as China and India, for which the CLE scenario reaches high levels of premature deaths when a linear concentration-response function is used.[15]

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[14] Non-market damages are presented as a range, using linear and non-linear versions of the dose-response function.

[15] In other words, the range of premature deaths is much smaller in the MFR scenario than in the CLE scenario, as the curvature of the concentration-response function matters most for very high concentration levels.

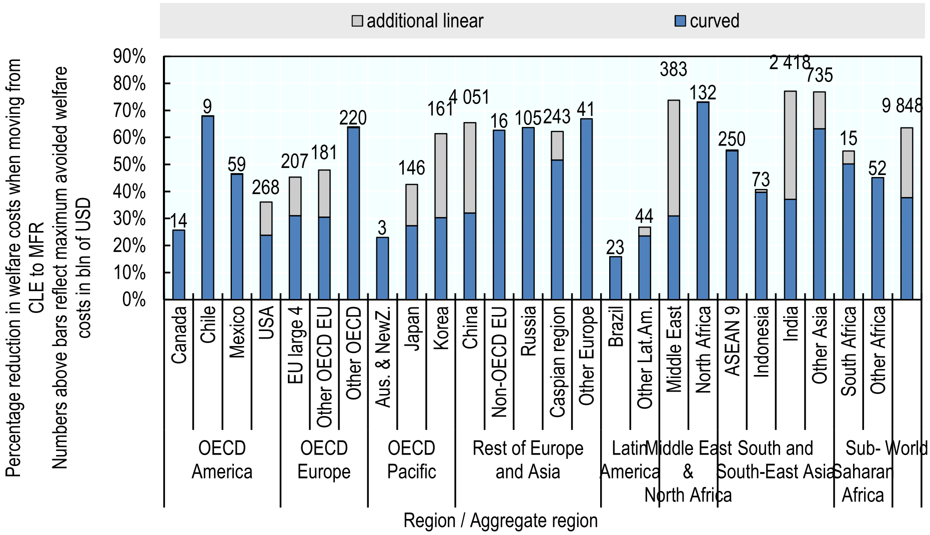

Fig. 9 Avoided welfare costs from premature deaths in 2050 from moving from CLE to MFR

The annual avoided welfare costs from preventing these premature deaths amount to almost 10 trillion USD globally by 2050, reflecting 38–64% of total mortality welfare costs in the CLE scenario. In relative terms, the largest percentage gains are achieved in North Africa when the curved projection is used, while in the linear projection, the relative gains are largest in the Middle East, India and Other Asia, although there are several other regions with avoided welfare costs that may exceed 70%. In absolute terms, China alone accounts for 1.6–4.1 trillion USD, and India another 0.7–2.4 trillion USD. The OECD countries as a group are projected to have 0.8–1.3 trillion USD avoided welfare costs by 2050. As these are welfare costs, rather than changes in market transactions as in the case of the market damages, they cannot be directly expressed as share of GDP.

5 Conclusion

This paper has shown that the implementation of the best available technologies can greatly reduce the negative impacts of outdoor air pollution not only to human health and the environment, as already shown in the previous literature, but also to the economy through lowering the negative impacts of air pollution on labour and crop productivity, and decreasing pollution-related health expenditures.

However, technology options alone cannot completely solve the air pollution problem, for which a broader set of public policies are needed. Further work could focus on the implementation of the best available techniques with policy actions aimed at further reducing air pollution, also through structural changes in the economy. These policies can include both regulatory instruments and market-based mechanisms and also policies that can reduce exposure to air pollution or the damages it causes, such as improvements to access to health care, housing and transport policies or policies improving work flexibility. Policies that directly address the impacts of temporal and local hotspots, i.e. dealing with pollution peaks, either by reducing the peak level concentrations, reducing vulnerability, can also significantly reduce the economic consequences. Given the inertia in the economic system and the long-term damages from pollution, it is important that such policies are implemented as quickly as possible. The model findings clearly highlight the economic benefits of early action, as reduced impacts in the short run can lift the economy onto a quicker growth path by boosting capital accumulation.

There are several uncertainties surrounding the projections in this paper, which could not be quantified. These include uncertainties on the drivers of emissions, and the corresponding uncertainties in emissions and concentration levels. To carry out a structured uncertainty analysis, the socio-economic projections of the SSPs could be used (Dellink et al. 2017a), coupled with ad hoc assumptions on the evolution of sectoral economic activity levels. How uncertainties in concentrations in turn affect premature deaths and the other biophysical impacts is even further beyond the reach of this paper. It is difficult to assess even the order of magnitude of the various uncertainties, and the fact that they interact with each other and compound through the impact pathway chain further complicates such analysis. But one can speculate that changes in economic growth rates tend to have more significant effects on emissions (and thus impacts) than population uncertainties, due to smaller inertia and the fact that demographic assumptions affect GDP projections.

A second type of uncertainty relates to policy. Energy and environmental policies are not constant over time, and it is logical to assume that there will be some evolution, not least for climate policies. But these policy constraints have on purpose been excluded from the current analysis. The aim of the paper is not to provide a prediction of future air pollution damages, but rather to highlight the (economic) mechanisms at work. Projections under constant policy assumptions are then the appropriate reference point. But that does not mean that climate mitigation and other energy and environmental policies will not affect damage levels of air pollution; Lanzi and Dellink (2019) explore these interactions in detail.

This paper does not provide a full assessment of the costs and benefits of the implementation of better technologies. For that it would be necessary to have access to the costs of the technologies or of the necessary investments for the implementation of the technologies at global and regional levels. This is outside the scope of this paper, which looks instead at the possible health and economic benefits of implementing improved technologies.

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