Internalising health-economic impacts of air pollution into climate policy: a global modelling study

Lara Aleluia Reis, Laurent Drouet, Massimo Tavoni

Summary

Background **Climate change and air pollution are two major societal problems. Their complex interplay calls for an advanced evaluation framework that can support decision making. Previous assessments have looked at the co-benefits of climate policies for air pollution, but few have optimised air pollution benefits. In our study, we lay out a modelling framework that internalises air pollution's economic impacts on human mortality, while considering climate constraints and aerosol feedback.**

Methods **We developed a modelling framework based on an integrated assessment model (World Induced Technical Change Hybrid [WITCH]) designed to assess optimal climate change mitigation policies. We included structural and end-of-pipe measures in a detailed process integrated assessment model, that is hard-linked to air pollution and climate models. We analysed a large set of baseline scenarios, including five shared socioeconomic pathways (SSPs). SSP scenarios were also tested with three different levels of value per statistical life, and were combined with the Paris Agreement temperature targets (TTs), focusing on the 2°C and 1·5°C TTs by the end of the century.**

Findings **We found that, in the baseline scenarios, where no policies are applied, the number of annual premature deaths grew before declining slightly to 4·45 (range 3·86–6·11) million annual premature deaths by 2050. Reaching the Paris Agreement TT decreases mortality by approximately 0·47 million premature deaths by 2050 (up to 1·28 million premature deaths in SSP3 –1·5°C) with respect to the baseline. We showed that welfare-maximising policies accounting for air pollution benefits reduces premature mortality by 1·62 million deaths annually. This is three times greater than the co-benefits of climate policies. China is the region where most of the avoided mortality is possible, whereas the reforming economies (ie, non-EU eastern European countries, including Russia) region has the greatest welfare benefits. We find that global and regional welfare increases when air pollution impacts are internalised, with no negative repercussions on global inequality.**

Interpretation **Air pollution control strategies are found to be an important complement to structural emission reductions. Accounting for air pollution impacts reduces climate mitigation costs and inequality and increases global and regional welfare. Results are robust to a broad set of scenarios and assumptions, including debated normative choices on how to value improved health.**

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Introduction

Climate change affects many aspects of our societies.[1] Air pollution is responsible for millions of deaths worldwide[2–7] as well as substantial crop yield loss each year.[8,9] Climate change and air pollution share a common origin (ie, fuel burning) and a common solution (ie, a clean and fair energy transition). But which policy and technological interventions should be put in place, and when?

Considering climate change and air pollution mitigation jointly is important since they can have positive and negative interactions.[10–12] Recent integrated assessments have mainly focused on the co-benefits of climate change mitigation for air pollution[8,13–16] or have evaluated the air pollution impacts of climate change.[11] However, these analyses offer no complete guidance on how to prioritise air pollution reductions. Therefore, there is a need to design welfare-maximising interventions that balance the costs of structural (ie, technology or fuel switching) and end-of-pipe (EOP) measures against the benefits of reducing air pollution and climate impacts. EOP technologies reduce only air pollutants whereas the energy sector's structural transformations (here referred to as structural measures) reduce both air pollutants and greenhouse gases (GHGs), but mostly GHGs. A few studies have done cost–benefit integrated assessments of air pollution and climate controls.[17,18] However, their accounting of the air pollutant emissions pathways is simplistic. Consequently they do not feature important elements, such as the EOP investments, a detailed energy system representation,[17] or the aerosol reduction impact on temperature.[18] Our paper is designed to fill this gap using a detailed energy model with endogenous EOP investments, which optimally accounts for the

Research in context

Evidence before this study

We searched Web of Science for studies on global integrated assessment modelling studies that report both air pollution and climate variables between Jan 15, 2018, and June 30, 2020, in English. Our search terms were "global air pollution policy", "integrated assessment", "climate mitigation", "aerosol feedback", and "pollution pathways". Existing evidence based on global modelling studies has shown that climate policies have substantial health co-benefits through reduced air pollution. However, only a few studies have used a welfare framework that incorporates the economic impacts of air pollution accounting for the climate feedback of aerosols on the temperature targets. To our knowledge, no study has done so including both structural and air pollution control measures under climate targets with a detailed technology model. This has prevented an evaluation of a fully integrated air quality and climate strategy. One of the latest studies on integrated air pollution and climate policies shows that even considering the aerosol feedback, the health benefits from climate policy are constrained by each country's air pollution strategy.

Added value of this study

This study developed and implemented a benefit–cost, integrated air quality climate modelling framework. It maximises regional welfare internalising air pollution's economic impacts on human mortality under climate constraints. This is the first global study to optimise structural and end-of-pipe investments to mitigate air pollution and to simultaneously attain the Paris Agreement temperature objectives of 1·5°C and 2°C. The evaluation is based on a vast number of scenarios, spanning socioeconomic drivers, stringency and timing climate agreements, and normative parameters such as the value of statistical life.

Implications of all the available evidence

Our results provide evidence of the need to jointly address air pollution and climate change. We show that accounting for air pollution's economic impacts leads to 1·62 million lives saved by 2050, three times the co-benefits of climate policies. Air quality controls are needed even if ambitious decarbonisation policies are in place. Air pollution strategies that save lives do not jeopardise the fight against climate change. On the contrary, we find that global and regional welfare increases when air pollution impacts are internalised, with no negative repercussions on global inequality.

economic impacts of air pollution (based on the cost of human mortality) and aerosol-related climate feedbacks.

Literature suggests that internalising air pollution impacts might increase the social benefits of climate policy compared with cost minimisation approaches.[19] However, economic valuation of health benefits remains contentious. For example, the willingness to pay to avoid an infinitesimal death risk, known as value per statistical life (VSL), contains a number of statistical and normative uncertainties.[20] In particular it is questionable to extrapolate VSL to regions where data on preferences to reduce mortality risk from air pollution are scarce and where income is low.[21] Some studies have overcome this issue by using unit value transfers.[8,15]

See Online for appendix

This study aims at designing policies that internalise the impact of air pollution policies into the decision process, taking into account all the exiting physical and economic feedbacks.

Methods

Modelling framework

To assess how the internalisation of air pollution impacts into optimal climate policy changes and influences scenario pathways, we have developed a modelling framework based on an integrated assessment model—World Induced Technical Change Hybrid (WITCH)—[22] designed to assess optimal climate change mitigation policies. This model optimises each of the 13 regions' welfare subject or not to temperature target (TT) constraints. It has been widely used in previous studies[23] and is one of the contributors to the Intergovernmental Panel of Climate Change scenarios. A more detailed definition of the WITCH model can be found in the appendix (pp 2–18).

We develop a comprehensive optimisation modelling framework, which internalises the air pollution impacts on human mortality into the optimisation of climate policies, and accounts for the aerosol reductions from the air pollution policies. The model allows choosing both EOP and structural abatement and technology investments in different sectors and pollutants. The technical emission factors of air pollutants are endogenously computed. The framework is schematised in figure 1 and includes three models interacting simultaneously, similar to the work by Scovronick and colleagues,[17] unlike previous studies where a cascade modelling framework was used.[8,24] The EOP costs were calculated using the GAINS data,[25] which were pre-loaded into the WITCH model (appendix pp 8–15), providing the investment costs as a function of air pollution removal efficiency per pollutant and technology. We compute the linear EOP cost from the GAINS ECLIPSE V5 scenarios, namely the difference between current legislation and the maximum feasible reduction scenarios (appendix pp 8–15). Both these scenarios differ in EOP reductions implemented and provide information on cost and air pollution reductions. The WITCH integrated assessment model is linked to the MAGICC climate model[26] and the FASST(R)[14,27] air pollution model. The WITCH model optimises the welfare of a given region by balancing the marginal cost of reducing air pollution and meeting the climate constraint (in the case there is one), either by investing in changing the energy system's structure or by investing in EOP control measures, with the marginal benefit of reducing mortality risk due to air pollution. Mortality is calculated using the FASST(R) air pollution model, a source–receptor model that calculates concentrations based on the air pollutants' emissions projected from the WITCH model. Methane emissions are also considered because they contribute to ozone formation. The FASST(R) model uses methane and air pollutant emissions to calculate regional mortality due to fine particulate matter ($PM_{2·5}$) and ozone. We then assign these impacts an economic value: we use three EU VSL as in the Organisation for Economic Cooperation and Development[28] and extrapolate it to non-EU regions according to Robinson and colleagues[21] based on gross domestic product (GDP) purchasing power parity (PPP) per capita. In this study, we do not consider the impacts of air pollution morbidity on welfare. Nevertheless, we have done sensitivity analyses on the VSL and VSL elasticity that account for uncertainties on the impact of air pollution on welfare. The MAGICC model uses GHGs (including CO_2, methane, nitrous oxide, and fluorinated gases) and pollutant emissions (such as black carbon and other aerosols) and calculates the resulting global average temperature increase. We have summarised the limitations of this framework in the appendix (pp 14–15).

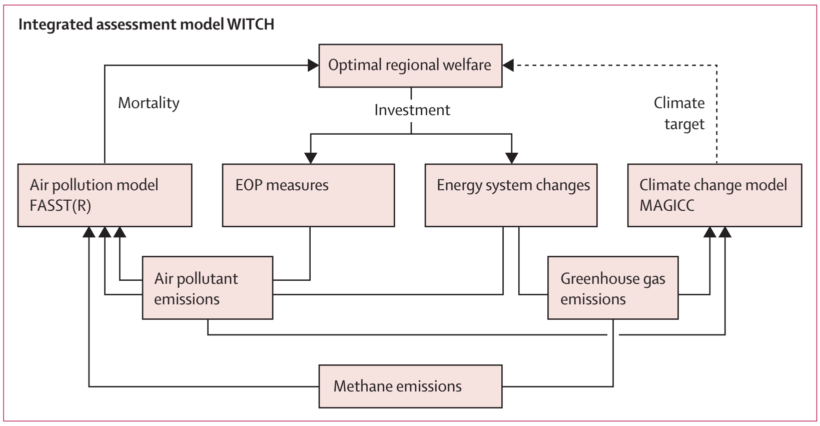

Figure 1: **Modelling framework schematic**
The WITCH integrated assessment model is linked to the MAGICC climate model[26] annd the FASST(R)[27] air pollution module to iterate climate and air pollution information. The WITCH model optimally allocates investments in EOP and structural measures. The dashed line represents the climate target, which might or might not be included as a constraint. EOP=end-of-pipe. WITCH=World Induced Technical Change Hybrid.

	Socio-economic baseline (SSP)	Temperature targets	International climate agreement	CBAP	Value per statistical life
Baselines	SSP1, SSP2, SSP3, SSP4, and SSP5	Baseline (no temperature target)	..	Yes and no*	High, medium, or low
Climate policy	SSP1, SSP2, SSP3, SSP4, and SSP5	2°C and 1·5°C	Carbon tax starts in 2020	Yes and no*	Low
Delayed policy	SSP2	2°C and 1·5°C	Carbon tax starts in 2025 or 2030	Yes and no*	Low

CBAP=cost–benefit assessment of air pollution. SSP=shared socioeconomic pathway. *All SSPs and temperature targets within the row are run with and without the CBAP.

Table: **Scenario matrix description**

Scenarios

We analyse a large set of scenarios, including five socioeconomic baselines (the shared socioeconomic pathways [SSPs]),[29] two climate targets consistent with the Paris Agreement (1·5°C and 2°C), immediate and delayed action on climate, three VSL formulations, and three VSL elasticities, in baselines scenarios. The scenario matrix is shown in the table. The inclusion of such a comprehensive set of scenarios allows us to deal with uncertainties related to our assumptions and identify robust conclusions.

We include all the most relevant dimensions. Socio-economic underlying developments are captured by reference to the five SSP scenarios.[29] The SSPs are baseline scenarios that follow current policy from 2015, and then follow a narrative on economic, demographic, and technology growth. They span a range of possible business as usual futures but do not explicitly include a climate target. These baselines differ regarding their socioeconomic assumptions (such as GDP and population) and air pollution control deployment, as detailed in the study by Rao and colleagues.[30] The SSP baseline scenarios assume different air pollution control pathways,[30] capturing the results' sensitivity to the air pollution control deployment assumptions. In this way, the baseline model range represents the sensitivity to these assumptions. The most optimistic SSP baselines in terms of deployment of air pollution controls are SSP1 and SSP5. Contrarily, SSP3 and SSP4 assume the most pessimistic pathway, and SSP2 assumes good deployment of air pollution controls, although less drastic than in SSP1 and SSP5.[30] The SSP baseline scenarios are also tested with three different levels of VSL, using values of US\$2·1 million, \$4·2 million, and \$6·3 million for low, medium, and high values, respectively, for the EU in 2005.[28] The values are extrapolated to other regions according to the GDP PPP per capita in 2005[21] using an elasticity of 1; more details on VSL (appendix pp 6–7) and sensitivity analyses on the VSL elasticity (appendix pp 19–20) are provided.

Finally, we combine the SSP baselines with the Paris Agreement TT, focusing on the 2°C and 1·5°C TTs by the end of the century. We model the achieved TTs by imposing a global uniform carbon tax from 2020 onwards. A more stringent TT corresponds to a higher carbon tax (appendix p 31). The TTs are calculated with the MAGICC

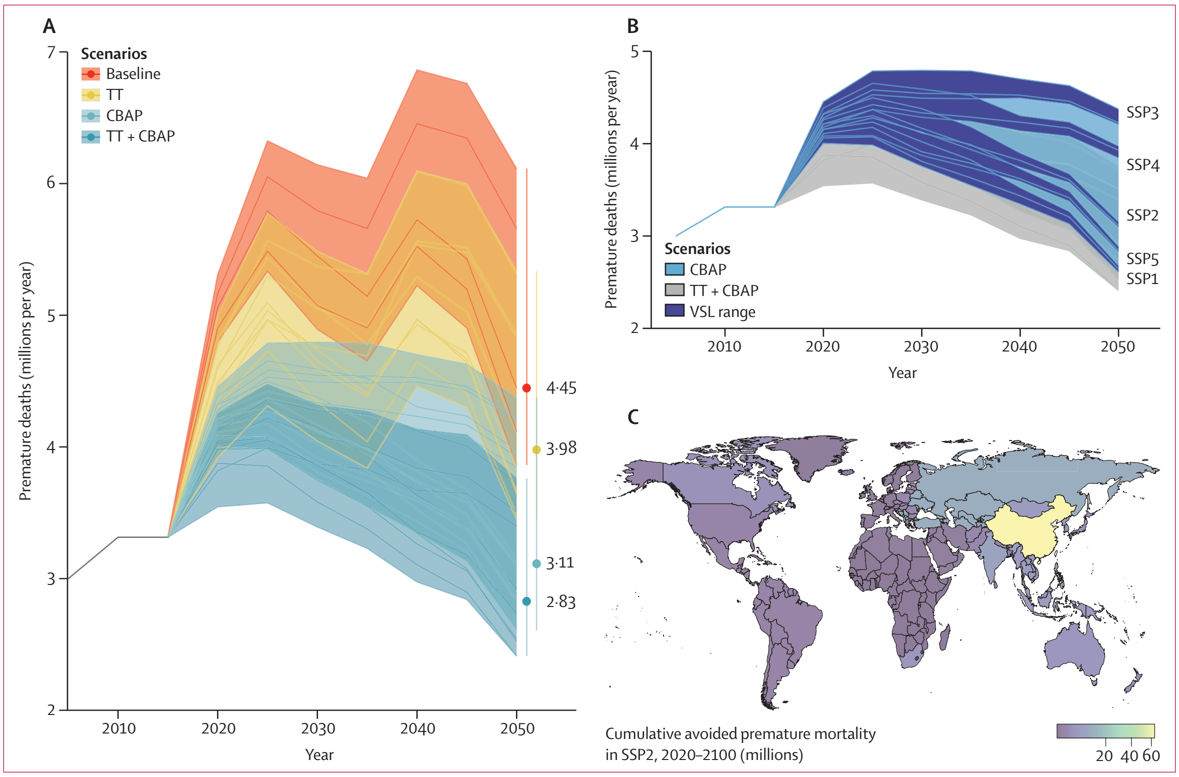

Figure 2: **Impact of cost-benefit assessment of air pollution on premature mortality**
(A) The annual premature mortality until 2050 in millions for the four types of policies considered (baseline, CBAP, TT, and TT+ CBAP) across all the SSPs. The Paris Agreement TT include both the 2°C and the 1·5°C targets in 2100, as described in the table. 2050 ranges are also highlighted. Points represent the median value. (B) The influence of the VSL to the CBAP scenarios (all SSPs) are shown in blue and the TT + CBAP scenarios are shown in grey. (C) The regional cumulative avoided premature mortality in SSP2 when internalising air pollution benefits and costs for the 13 regions of the WITCH model. CBAP=cost–benefit assessment of air pollution. SSP=shared socioeconomic pathway. TT=temperature target. VSL=value per statistical life. WITCH=World Induced Technical Change Hybrid.

model to include the aerosol radiative forcing. This assesses the co-benefits for air pollution due to climate policy and can then be compared with the cost–benefit analysis scenarios, where the air pollution impacts are included in the optimisation (cost–benefit assessment of air pollution [CBAP] scenarios). In the CBAP scenarios, the marginal benefit of abatement equals the marginal cost of abatement and, in the case of the TT, the costs of achieving the temperature constraint are minimised. We also consider the possibility of delayed international climate action, with the carbon tax starting in 2025 or 2030. The delayed scenarios were run only for SSP2, considered as the middle-of-the-road baseline.[29]

Role of the funding source

This work has been funded by several EU projects: COMMIT and INNOPATH have contributed mainly to the data collection and model development; and ENGAGE and NAVIGATE have funded the analysis, interpretation, and writing of the manuscript.

Results and Discussion

In the baseline scenarios, where no policies are applied, the number of annual premature deaths grew before declining slightly to 4·45 (range 3·86–6·11) million annual premature deaths by 2050 (figure 2). The large range is due to the different SSPs' socioeconomic developments (GDP and population) and their associated air pollution controls (emission factors). However, even with optimistic assumptions, air pollution exposure remains high because of population growth. Reaching the Paris Agreement TT decreases mortality by approximately 0·47 million premature deaths by 2050 (up to 1·28 million premature deaths in SSP3 –1·5°C) with respect to the baseline. These co-benefits of climate policy for air pollution are in line with previous studies[8,24] and somewhat lower than those reported by Shindell and colleagues[31] (except for SSP3). But our results suggest that, even under stringent climate policies, mortality will remain high.

When internalising the economic benefits of reducing mortality from baseline to CBAP without climate policies, mortality drops by approximately 30%, from 4·45 (range 3·86–6·11) to 3·11 (range 2·61–4·38) million premature deaths in 2050. Given that, in this case, society cares only about air pollution, pollution abatement is achieved mainly via air pollution controls. These reduce air pollution emissions mainly of the $PM_{2·5}$ precursors, which have the highest health impact (appendix p 22).

This result highlights the urgency of air pollution controls in the short term. Adding TTs on top of the CBAP (TT+CBAP) lowers mortality pathways even more (to approximately 2·83 million) with respect to median baseline. It also reduces the variation over the two TTs and five socioeconomic baselines. When including both air quality and climate concerns, air pollution reductions are achieved both via EOP and structural measures. However, the additional reduction in mortality pathways relative to only TTs shows the importance of EOP investments even with stringent climate policy. The policy portfolio that generates the best outcomes in terms of avoided premature mortality is the combination of CBAP with the most stringent TTs and the least polluted baseline (SSP1; appendix p 21). An intertemporal non-cooperative optimal climate policy foresees a drastic energy system decarbonisation in the early years. Those are also the years where most of the co-benefits for air pollution can be seen. If a global climate agreement is delayed to 2030—a more realistic assumption given the current policy environment—a green paradox effect arises, and mortality increases slightly over the baseline. In this case, integrating air pollution impacts is essential to avoid mortality increases and save approximately one million people annually (SSP2 case; appendix pp 41–42).

Previous studies show that cost–benefit analysis is sensitive to assumptions about how to value health, including the choice of the VSL.[8,21,24] We have thus done a sensitivity analysis on the VSL. Our results indicate that the choice of VSL for premature mortality has a small impact in optimal cost–benefit analysis at the global level (figure 2B), and matters less than the socioeconomic assumptions or TTs. Economic quantification of air pollution's health impacts warrants very stringent action to reduce pollution, even when considering low VSLs. In our study, we assume the same discount rate for VSL as the one used to compute the WITCH regional welfare. Using a lower discount rate for VSL would increase the relative importance of air pollution reduction with respect to other objectives. In that case the marginal rate of substitution between wealth and survival probability does not follow the same path as the regional welfare function. This might happen with the increase of information on the health impacts of air pollution and with increasing wealth worldwide. For consistency, we use the same discount for VSL as the one for the regional welfare (appendix pp 37–40).

From here onwards, we use the low VSL, unless stated otherwise, to assure that our results hold even in using the more conservative normative values. The benefits of reduced premature mortality are geographically varied, but all regions experience mortality reductions (figure 2C). China has the highest avoided mortality (approximately 64 million cumulative avoided deaths from 2020 to 2100), followed by reforming economies (ie, non-EU eastern European countries, including Russia; appendix p 3), India, and southeast Asia (in line with Cohen and colleagues[6] and Dingenen and

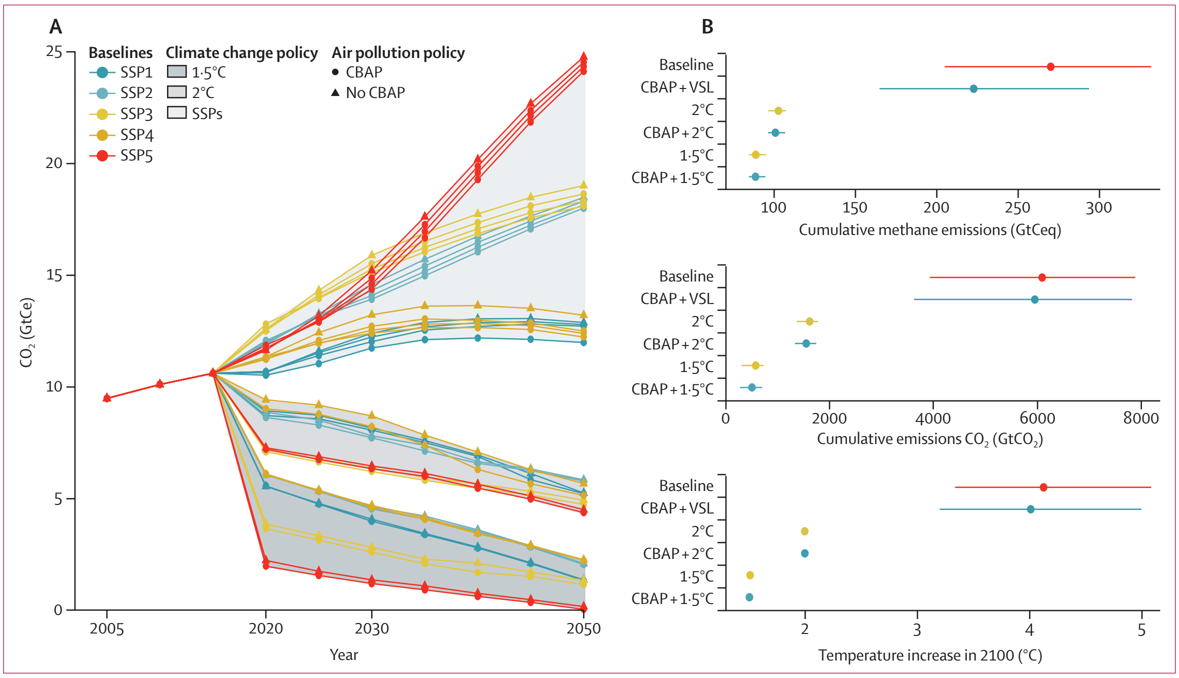

Figure 3: **Impact of CBAP on emissions and climate**

(A) CO_2 emissions trajectories for all the policies. (B) Ranges across SSPs (baseline) of cumulative CO_2 and methane emissions, and 2100 temperature as a function of policy type. CBAP+VSL represents the SSP baselines with different values for VSL. The 2°C and 1·5°C represent the Paris Agreement temperature targets. CBAP=cost-benefit assessment of air pollution. GtCe=Gigaton of carbon equivalent. GtCeq=Gigaton of carbon equivalent. $GtCO_2$=Gigaton of carbon dioxide. SSP=shared socioeconomic pathway. VSL=value per statistical life.

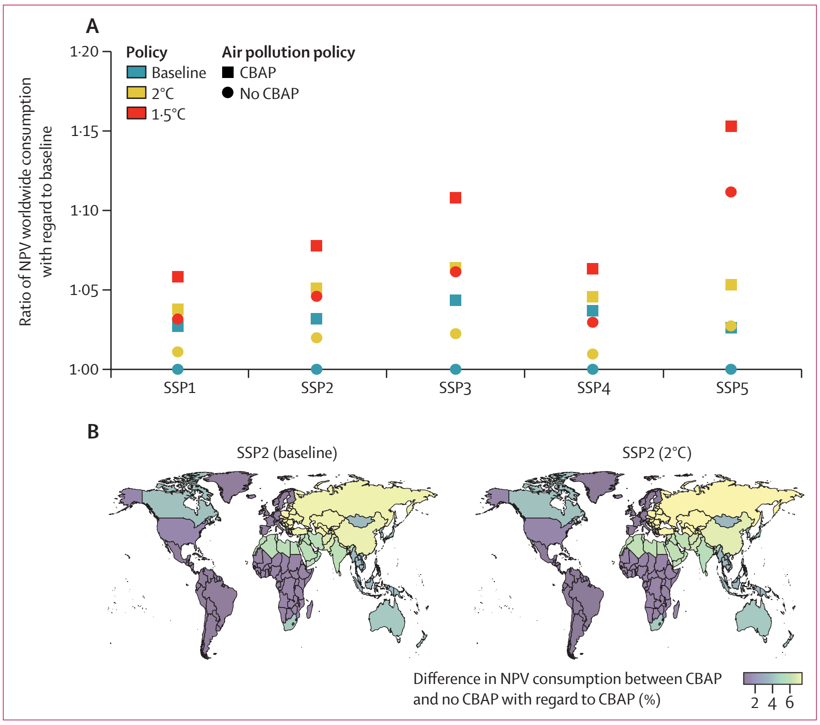

Figure 4: **Impact of cost-benefit assessment of air pollution on economic welfare**
(A) Ratio of the global NPV of consumption with respect to baseline for the five SSPs considering the impacts of air pollution. Colours identify policies, and squares and circles represent the integration or not of air pollution impacts. (B) Regional gains in NPV of consumption from CBAP to no CBAP, for SSP2, in baseline and in the 2°C temperature target for the 13 WITCH regions. WITCH regions are described in the appendix (p 3). The NPV is computed using the standard discounting Ramsey rule, with a pure rate of time preference of 1% per year and an inter-temporal elasticity of substitution of 0·66 (appendix pp 37–40). CBAP=cost–benefit assessment of air pollution. NPV=net present value. SSP=shared socioeconomic pathway. WITCH=World Induced Technical Change Hybrid.

colleagues.[27] Regarding the annual mortality in 2050, China is the region that benefits the most from reduced mortality, avoiding approximately 820 000 (median) deaths. These differences are driven by the cost and availability of air pollution mitigation options and by the regional VSL (appendix pp 9–11, 19–20). In regions with low VSL, such as sub-Saharan Africa or India, even with high premature deaths, the economic impacts will not trigger major investments in EOP and especially in structural measures. On the other hand, high VSL regions, such as the USA or Europe, are likely to be more responsive to the economic impacts of air pollution. In China, even with medium VSL, the very high premature mortality numbers are likely to drive policies designed to avoid the high economic impacts of air pollution. The same reasoning can be applied to the sensitivity of the VSL. Low sensitivity to VSL is mainly driven by mid-to-low VSL countries, for which an increase in VSL still yields low economic impacts. In high-income regions, such as the USA and Europe, the premature mortality pathways are more sensitive to changes in the VSL assumed but limited to maximum availability EOP reductions (appendix p 46).

CBAP reduces premature mortality, but it also has consequences for GHG emissions. We observe a modest reduction in CO_2 emission pathways in baselines when the impact costs of air pollution are internalised in the decision process (figure 3). The EOP reductions are not available for all technologies in all regions (appendix pp 9–11) and, therefore, some structural emission reduction measures are still a valuable option given the cost of air pollution impacts. The reduction in CO_2 emissions increases with increasing VSL, although the contribution of air pollution (CBAP) to climate mitigation remains modest even with the highest VSL.

When the Paris Agreement TTs are in place, a climate target is imposed, forcing the model to find synergies between climate mitigation costs and air pollution measures. In this case, the benefit of air pollution to the climate is less clear. Indeed, CBAP+TT might increase the carbon price because air pollution measures can increase temperature by reducing the amount of reflecting aerosols in the atmosphere (appendix pp 23–37).[10]

Figure 3B shows the climate impacts of welfare-maximising air pollution strategies. The CBAP does not show substantial reductions in CO_2 emissions. We find that CBAP policies alone, without TTs, can reduce temperature increases in 2100 by approximately 0·11°C (median). Greater reductions are found in the case of methane emissions. Methane is also an air pollutant, a precursor of ozone, and therefore its reduction creates a synergy between the climate and the air pollution goal. The co-benefits of air pollution for climate have a low magnitude but are important mainly without a TT, unlike the co-benefits of climate mitigation, which substantially reduce premature mortality due to air pollution.

We report the welfare implications, as a function of consumption, for all scenarios (figure 4). Figure 4A shows that across all cases, global welfare increases with respect to baseline, when internalising air pollution benefits. This holds even under stringent TTs, which are by themselves costly to attain (net gain 1·99%, range 0·96–2·73 in net present value [NPV] for 2°C; and 4·59%, 2·96 (SSP4)–11·14 (SSP5) for 1·5°C). Nonetheless, the economic benefits of reduced air pollution impacts outweigh the direct CO_2 emission reduction costs. This is true across all SSPs and especially for the most stringent interpretation of the Paris Agreement, extending recent results.[8,24] By far, the greatest welfare gains materialise when air pollution is internalised (figure 4). In SSP2, welfare gains increase by 7·77% and 5·10% for the 1·5°C and 2°C temperature goals, respectively.

Regional welfare benefits from internalising air pollution impacts, as consumption increases in all regions in the baseline scenario (figure 4B). This is also the case under climate constraints, despite the need to compensate aerosol reductions with additional GHG emission cuts. Some regions benefit more than others; these are the reforming economies, China, eastern Europe, and central Asia, in line with the avoided premature mortality shown in figure 2C. The Middle East and North Africa, and India benefit somewhat less.

These are the regions where investments in EOP are more effective in reducing exposure, therefore avoiding mortality. Highly populated regions, such as India, might see modest air pollution optimal reduction due to very low VSL but could gain on other consumption components such as the lowering price of international fossil fuels.

This outcome calls for more equitable ways to extrapolate the economic health benefits across countries and support policies to prevent pollution leakage. Although the VSL is higher in high-income countries, air pollution's internalisation does not increase global income inequality. The 90:10 income deciles ratio and the Gini coefficient, between WITCH regions, decrease by 3·20% (range 0·90–5·83) and 0·76% (0·43–1·22), respectively, when internalising the air pollution impacts (appendix p 37). This result has high policy relevance, given the regressivity of climate change impacts and the unevenly distributed costs of reducing CO_2 emissions. For example, major fossil fuel exporters such as the Middle East and Russia might oppose the low carbon transition for fear of trade losses. Our analysis shows that these regions have much to gain (NPV consumption gains with respect to baseline are 5·99% [range 4·70–26·84] for the Middle East and North Africa, and 8·15% [5·97–11·81] for the reforming economies) from cleaner air and climate policies.

In the case of a global TTs, the gains' magnitude might even grow (figure 4A). For the regions of the Middle East and North Africa and the reforming economies, the internalisation of the air pollution impacts generates greater gains when a TT is in place than the internalisation of the air pollution impacts baseline (appendix p 39). These are regions for which greater synergies can be found between both policy objectives. The imposition of the TT optimally reduces air pollution mortality, because in the CBAP scenarios the avoided mortality has an economic benefit and, therefore, these regions see more benefits.

When a climate policy (via a TT) is in place, CBAP + TT policies on air pollution impact the global carbon price. If air pollution measures are structural, meaning that they would reduce air pollutants and GHGs, the marginal global carbon price could decrease. On the other hand, using only EOP measures reduces the reflecting aerosols in the atmosphere without reducing GHGs. Therefore, to meet the TTs, extra decarbonisation needs to be undertaken. This generates the so-called climate penalty, which might raise the global carbon price—a dynamic that depends on both the TT and baseline. Considering air pollution, the baseline order of ascending air pollution emissions is SSP1, SSP5, SSP2, SSP4, and SSP3, whereas for climate the ascending order of GHG emissions is SSP1, SSP4, SSP2, SSP3, and SSP5. This mismatch between the baselines for both environmental issues creates a non-obvious dynamic in the carbon tax (appendix pp 31–37, 43–45).

When structural and EOP measures are being put into place, the carbon price decreases if air pollution is reduced through structural measures in regions where the marginal carbon abatement cost is the lowest. If air pollution and climate mitigation coincide regionally, then the carbon price is reduced, as is the case in the SSP2 baseline (appendix pp 34–35). Contrarily, increases in global carbon price might happen for three reasons: first, when the extra decarbonisation, due to aerosol reduction, leads to substantial aerosol reductions due to very dirty baselines, resulting in a high carbon penalty (as in SSP3, a very air pollution intensive baseline); second, when the energy system is already very green (ie, very little carbon left) and the carbon penalty forces the model to choose marginal costly abatement options (as in SSP5); and third, when the extra decarbonisation needed is not aligned with the local air pollution mitigation strategies (as in SSP4). The climate penalty is compensated in regions with higher marginal carbon abatement costs such as the USA, EU, and the Middle East, where the marginal air pollution benefits are lower because these regions already have relatively good air pollution policies in the baseline. This is illustrated in the appendix (p 36), where we observe for these regions high GHG emission reductions. Overall, air pollution control impacts on carbon price depend on several factors, such as the alignment between both policy objectives, GDP regional heterogeneity, air pollution control baseline assumptions, and climate target stringency. The complexity of these interactions has been often overlooked.

The limitations of this study have been summarised in the appendix (pp 14–15, 46), which include scarce availability of data on EOP costs, not accounting for morbidity as a direct impact in the model, the omission of indoor air pollution, and the use of reduced-form models.

In this paper, we show that welfare-maximising policies substantially reduce premature mortality while not compromising climate action, for a sufficiently wide range of parameters. Stringent air pollution controls are warranted for a broad range of preferences about socioeconomic and technology development, climate feedback, and the choice of contentious normative parameters such as the VSL.

We have developed a comprehensive integrated assessment modelling framework capturing the most crucial interactions between air pollution, climate mitigation, and the economy. Accounting for air pollution control investments in an integrated assessment model coupled with an air pollution model allows for the evaluation and optimisation of complex policy trade-offs, including the health, climate, welfare, and inequality impacts of internalising air pollution strategies. In this study, unlike in previous literature, we do not access the co-benefits and trade-offs of air pollution and climate mitigation policies but rather include them simultaneously in the decision making process. We ran a broad set of scenarios that have different air pollution control baselines, several assumptions about how to economically value health, and how deep and fast international climate policies will unfold. We find that welfare-maximising strategies generate considerable health benefits, avoiding 1·62 million annual premature deaths by 2050. The health benefits of optimised air pollution interventions are greater than climate mitigation co-benefits alone and, in the case of delayed climate action, are essential to keep mortality at lower levels. Air pollution reductions are mainly achieved via EOP, especially at the beginning of the century and when no climate policies are in place. This result speaks to the importance of EOP measures throughout the world in the first half of the century. Results are robust to multiple sources of uncertainties, including socioeconomic and technological development and normative choices such as the VSL.

Additionally, we show how air pollution strategies that save lives do not jeopardise the fight against climate change. The impact on CO_2 pathways is modest, and the climate penalty of reducing aerosols has a mixed impact on the carbon price needed to stabilise climate change. The relationship between air pollution and climate strategies is moderated by underlying policy and economic development. Global and regional welfare is largely enhanced by internalising air pollution interventions, with no negative repercussion on global inequality. Designing economically integrated policies that simultaneously generate cleaner air and less global warming increases global wellbeing, and facilitates the political economy of a sustainable energy transformation in key emitting regions. Future research could explore more egalitarian ways of extrapolating VSL regionally to avoid pollution leakage, and include sensitivity on the discounting assumptions of the VSL, EOP costs, and further improvement of the FASST(R) emulator.

Contributors

LAR collected the data, developed the modelling framework, ran the scenarios, and drafted, wrote, and revised the manuscript. LD supported the development of the modelling framework, helped with the graphical design, participated in the analysis of the results, and revised the manuscript. MT supervised all the work, contributed to the study design, participated in the analysis of the results, and wrote and revised the manuscript. LAR and LD have verified the data. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Data are available on request from the corresponding author.

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