Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study

Anil Markandya, Jon Sampedro, Steven J Smith, Rita Van Dingenen, Cristina Pizarro-Irizar, Iñaki Arto, Mikel González-Eguino

Summary

Background Although the co-benefits from addressing problems related to both climate change and air pollution have been recognised, there is not much evidence comparing the mitigation costs and economic benefits of air pollution reduction for alternative approaches to meeting greenhouse gas targets. We analysed the extent to which health co-benefits would compensate the mitigation cost of achieving the targets of the Paris climate agreement (2°C and 1·5°C) under different scenarios in which the emissions abatement effort is shared between countries in accordance with three established equity criteria.

Methods Our study had three stages. First, we used an integrated assessment model, the Global Change Assessment Model (GCAM), to investigate the emission (greenhouse gases and air pollutants) pathways and abatement costs of a set of scenarios with varying temperature objectives (nationally determined contributions, 2°C, or 1·5°C) and approaches to the distribution of climate change methods (capability, constant emission ratios, and equal per capita). The resulting emissions pathways were transferred to an air quality model (TM5-FASST) to estimate the concentrations of particulate matter and ozone in the atmosphere and the resulting associated premature deaths and morbidity. We then applied a monetary value to these health impacts by use of a term called the value of statistical life and compared these values with those of the mitigation costs calculated from GCAM, both globally and regionally. Our analysis looked forward to 2050 in accordance with the socioeconomic narrative Shared Socioeconomic Pathways 2.

Findings The health co-benefits substantially outweighed the policy cost of achieving the target for all of the scenarios that we analysed. In some of the mitigation strategies, the median co-benefits were double the median costs at a global level. The ratio of health co-benefit to mitigation cost ranged from 1·4 to 2·45, depending on the scenario. At the regional level, the costs of reducing greenhouse gas emissions could be compensated with the health co-benefits alone for China and India, whereas the proportion the co-benefits covered varied but could be substantial in the European Union (7–84%) and USA (10–41%), respectively. Finally, we found that the extra effort of trying to pursue the 1·5°C target instead of the 2°C target would generate a substantial net benefit in India (US\$3·28–8·4 trillion) and China (\$0·27–2·31 trillion), although this positive result was not seen in the other regions.

Interpretation Substantial health gains can be achieved from taking action to prevent climate change, independent of any future reductions in damages due to climate change. Some countries, such as China and India, could justify stringent mitigation efforts just by including health co-benefits in the analysis. Our results also suggest that the statement in the Paris Agreement to pursue efforts to limit temperature increase to 1·5°C could make economic sense in some scenarios and countries if health co-benefits are taken into account.

Funding European Union's Horizon 2020 research and innovation programme.

Lancet Planet Health 2018; 2: e126–33

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Basque Centre for Climate Change (BC3), Leioa, Spain (Prof A Markandya PhD, J Sampedro MSc, C Pizarro-Irizar PhD, Prof I Arto PhD, Prof M González-Eguino PhD); **University of the Basque Country, Bilbao, Spain** (C Pizarro-Irizar PhD, Prof M González-Eguino); **Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD, USA** (S J Smith PhD); **Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, USA** (S J Smith); **and Joint Research Centre, Energy, Transport and Climate Directorate, Ispra, Italy** (R Van Dingenen PhD)

Correspondence to:
Prof Anil Markandya, Basque Centre for Climate Change (BC3), Leioa 48940, Spain
anil.markandya@bc3research.org

Introduction

The two main health-harmful air pollutants linked to fossil fuel combustion and greenhouse gas (GHG) emissions are fine particulate matter ($PM_{2·5}$);[1–3] and ozone (O_3).[4,5] In this context, the Paris climate agreement, which aims to significantly reduce fossil fuel use, has major health implications. The agreement sets a long-term stabilisation target of a 2°C increase and signatories have agreed to pursue efforts to limit the increase to 1·5°C.[6]

Concrete measures to achieve these targets have not yet been agreed. A key concern when evaluating different climate policies is their net cost, with a key component of overall policy cost being the associated co-benefits.[7–11] We use the term mitigation cost to refer to the direct costs of reducing GHGs and policy costs to refer to the overall costs when any co-benefits have been taken into account (we do not include avoided climate damages). Co-benefits are defined as additional benefits related to the reduction of greenhouse gas emissions that are not directly related to climate change, such as air quality improvement, technological innovation, or employment creation.[12]

One of the key challenges related to the Paris goals is how to share the mitigation efforts for meeting the target. The greater the ambition of the mitigation objectives, the more difficult the distribution of targets across countries.[13,14] The current national mitigation targets reported by the different countries to the United Nations in their nationally

Research in context

Evidence before this study

We searched the literature for works related to health co-benefits, and found studies published between 2013 and 2018. A substantial amount of work has been done to estimate the numbers of current and future premature deaths due to particulate matter and ozone concentration levels. Some studies have also presented a comparison between scenarios based on different climate or air quality policies and a few have compared the potential co-benefits with or abatement cost of obtaining a climate objective. The combination of integrated assessment and atmospheric models has also been described in some reports in recent years.

Added value of this study

Our study is the first, to our knowledge, to show the benefit-cost ratio of different climate change mitigation objectives under different scenarios for sharing emissions quotas between developed and developing countries, building on the work of Robiou du Pont and colleagues. Although there is some work that has applied similar methods to estimate mitigation costs, the future health implications of air pollution, and its monetary valuation, our study goes one important step further by using an integrated framework that allows a systematic comparison of the extent to which the health co-benefits compensate the costs of reducing greenhouse gas emissions under different pathways. Finally, we also investigated the 1·5°C target, the most ambitious target and an active topic in the current climate change debate.

Implications of the available evidence

Our results will contribute substantially to understanding the important synergies between air pollution and climate change control policies. The large variations in health co-benefits of achieving in different scenarios and countries, especially in India and China, might help policy makers to understand the benefits of adopting more ambitious climate policies or measures to reduce air pollution and to consider how to share the burden of reducing greenhouse gas emissions. The health co-benefits alone can justify the 2°C target at a global level. Increasing efforts to achieve the ambitious target of 1·5°C will also generate global health co-benefits that exceed mitigation costs, but only if the equal emission per capita approach in 2050 pathway is pursued. This result will be useful to inform the International Panel on Climate Change in its special report on the 1·5°C target, which is currently in preparation. Further work is needed, however to handle the distribution of net costs across regions, depending on what distribution of abatement effort is chosen. This is a serious challenge that the global community needs to address.

determined contributions (NDCs) are not enough,[15] and, if they are not raised, a temperature increase of between 2·9–3·4°C by the end of the century can be expected.[6]

The health co-benefits of mitigation have been explored previously. The major gaps in the current literature are a failure to look at co-benefits by region, which is important given the range of different allocations of mitigation burdens and the absence of an evaluation of the co-benefits relative to mitigation costs for the 1·5°C target. As such, we compared, at the global and regional levels, several climate mitigation scenarios in terms of air pollution and health impacts, and established to what extent the extra cost of achieving a more restrictive mitigation target could be compensated with by additional health co-benefits.

Methods

Study design

Our analysis consists of three steps. First, we used the Global Change Assessment Model (GCAM) to quantify the GHG pathways and the related mitigation costs of each scenario of climate target and mitigation strategy (where each scenario has its own GHG emission pathway). GCAM also reports the emissions of air pollutants in the different regions. We then passed this information to the TM5-Fast Scenario Screening Tool air quality source-receptor model, which translates emission levels into pollutant concentrations, exposure, and premature deaths. Finally, we monetised these effects by use of a term known as the value of statistical life (VSL),[16,17] with the valuation extended to incorporate morbidity effects.[18]

Models

GCAM is an integrated assessment model originally developed by the Joint Global Change Research Institute and the Pacific Northwest National Laboratory. It has been used in most major climate and energy assessments over the past 20 years, including the last International Panel on Climate Change (IPCC) Report.[19] The model is disaggregated into 32 geopolitical regions and operates in 5 year time steps from 2005 to 2100. Details of the model and its data sources have been reported by Clarke and colleagues.[20] GCAM provides the mitigation cost of different energy and climate policies for each specific region. It also reports the emissions of the main air pollutants including organic carbon, black carbon, nitrogen oxides, non-methane volatile organic compounds, carbon monoxide, and sulphur dioxide, which are the main precursors of $PM_{2·5}$ and ozone.[21] These emissions are calculated by applying an emission factor to each technology for every pollutant; consequently, the activity level, such as fuel consumption, drives emissions per period and region. Additionally, an emission control is also applied to each activity. The emission control generally increases as gross domestic product (GDP) increases, representing historical trends that, as income levels increase, more stringent pollution control measures will be put into place.

To link GCAM with TM5-FASST, we downscaled the output of the 32 regions to the country level and then aggregated to the 56 TM5-FASST regions (appendix). TM5-FASST is a reduced-form global air quality source-receptor model developed by the European Commission's Joint Research Centre. The name TM5-FASST derives from the native TM5 chemistry-transport model from which an air quality source-receptor model version was derived; FASST is an acronym of Fast Scenario Screening Tool, which refers to the current source-receptor version (Van Dingenen R, unpublished). The model analyses how the emissions of a source region affect receptor points (grid cells) in terms of concentrations, and subsequently, premature deaths. Given the concentration levels for each region, the model calculates the premature deaths derived from exposure to ozone and $PM_{2·5}$, disaggregating by different causes of death (for ozone coverage is for respiratory disease and for $PM_{2.5}$ it is for ischaemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer, and acute lower respiratory airway infections), defined by the GBD 2015 Risk Factors Collaborators.[22] These calculations require baseline mortality rates, which are taken from WHO data (Van Dingenen R, unpublished). More details of the data are available on the website of the Institute for Health Metrics and Evaluation and details for the calculations will be reported (Van Dingenen R, unpublished).

Finally, to monetise the estimated health impacts, we applied the VSL. VSL is the monetary value of a relative change in mortality risk reduction (usually taken to be in the range from 3/10 000 to 2/10 000). Given the absence of empirical studies that estimate VSL for all countries, procedures have been developed to transfer the results of existing studies to other regions, aiming to overcome this limitation.

In this study we used the "unit value transfer approach",[10,23] which is based on adjustment of the VSL to all countries according to their GDP and GDP growth rates, using the widely accepted VSL of the OECD for 2005 as a reference. This value, according to the literature,[23] ranges between US\$1·8 and \$4·5 million in 2005. In this method, the VSL of a country *c* in the year *t* is defined as

$$\mathrm{VSL}_{c,t}=\mathrm{VSL}_{\mathrm{OECD},2005}\times\left(\frac{Y_{c,2005}}{Y_{\mathrm{OECD},2005}}\right)^{b}\times(1+\%\Delta Y)^{b}$$

Where $\mathrm{VSL}_{c,t}$ is the VSL for country *c* in year *t*; $\mathrm{VSL}_{\mathrm{OECD},2005}$ is the base value; *Y* is the GDP per capita; *b* is the income elasticity of the VSL (the income elasticity generally used for the VSL ranges from 0·8 to 1·2; we applied the figure of 0·8 as proposed by the Organisation for Economic Co-operation and Development [OECD]);[24] and %Δ*Y* is the income growth rate. Given the VSL for each region, the associated morbidity costs can be added to the mortality cost. These costs include a wide range of effects covering direct market costs, as well as indirect costs arising from disability and loss of earnings. Because there is no well accepted method to estimate these effects, we followed the OECD's guidelines[24] and took morbidity costs to be 10% of the mortality costs.

Given that VSL is based on GDP, it places a higher value on human life in developed countries than in developing ones. Although this approach carries this moral dilemma, VSL is a well known and widely used method that enables users to analyse climate policy and cover health costs in a way that reflects how such costs are treated within different regions.

Scenarios

The scenarios have three main components: first, a general socioeconomic storyline represented by the Shared Socioeconomic Pathways (SSP) of the IPCC framework,[25,26] second, a model quantification of that storyline, and, third, a set of mitigation strategies based on those described by Robiou du Pont and colleagues,[27,28] wherein current national mitigation targets are extended in accordance with different equity criteria to allocate the carbon budgets for different temperature stabilisation objectives.

For **details of the equity of climate pledges** see http://paris-equity-check.org

The background socioeconomic conditions are a key element of the analysis because they provide baseline values for population and GDP in each country over time. The socioeconomic scenario that we have chosen, SSP2, is regarded as an intermediate framework. The features of SSP2 are that current trends continue with some progress towards the Sustainable Development Goals, with reductions in energy and material intensity consumption and a decline in fossil fuel dependency; the development rate is unequal between low-income countries, and global and in-country inequalities persist; the low level of investment in education prevents declines in population growth; and global governance achieves an intermediate level of environmental protection. Further details have been reported by Van Vuuren and colleagues.[26]

For the **Institute of Health Metrics and Evaluation website** see http://www.healthdata.org/

The SSP database, hosted by IIASA, provides the country-level population figures used by TM5-FASST and the GDP figures used to estimate monetised damage to health by VSL. Both population and GDP are also used by

For the **SSP database** see https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about

	Code	IPCC Category	Allocation characteristics
Constant emission ratios	CER	Staged approach	Maintains current emission ratios, preserves status quo; this approach is also referred to as grandfathering, is not considered as an equitable option in terms of climate justice, and is not supported as such by any party
Capability	CAP	Capability	Countries with high GDP per capita have low emissions allocations
Equal per capita	EPC	Equality	Convergence towards equal annual emissions per person by 2040

Further details of the approaches to the equitable distribution of mitigation efforts are available online. IPCC=International Panel on Climate Change. GDP=gross domestic product.

Table 1: **Mitigation equity approaches**

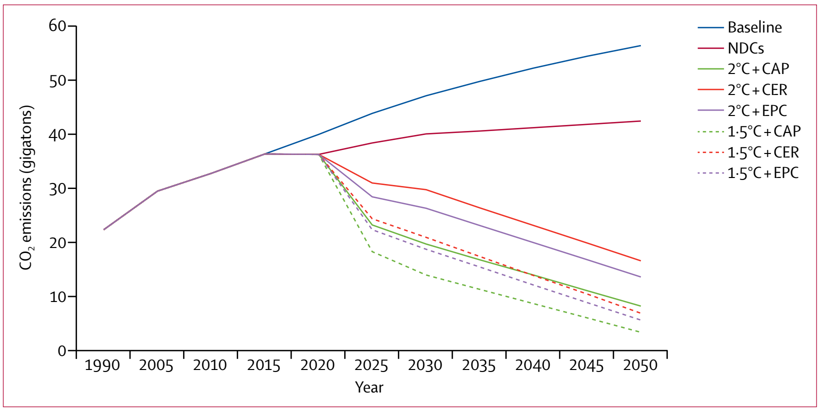


Figure 1: **Total CO_2 emissions per period and scenario**
CO_2=carbon dioxide. NDCs=nationally determined contributions. CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario.

See **Online** for appendix

	2°C + CAP	2°C + CER	2°C + EPC	1·5°C + CAP	1·5°C + CER	1·5°C + EPC
China	–69%	–35%	–52%	–75%	–54%	–65%
USA	–40%	57%	–16%	–52%	8%	–37%
EU-27	–43%	35%	–4%	–55%	–7%	–31%
India	–60%	–71%	–36%	–72%	–79%	–58%
ROW	–50%	–47%	–46%	–64%	–63%	–62%
Total	–55%	–35%	–42%	–67%	–55%	–59%

CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. EU-27=the 27 countries of the European Union in 2007–13. ROW=the rest of the world.

Table 2: **Variation in 2020–50 cumulative emissions relative to the nationally determined contributions scenario**

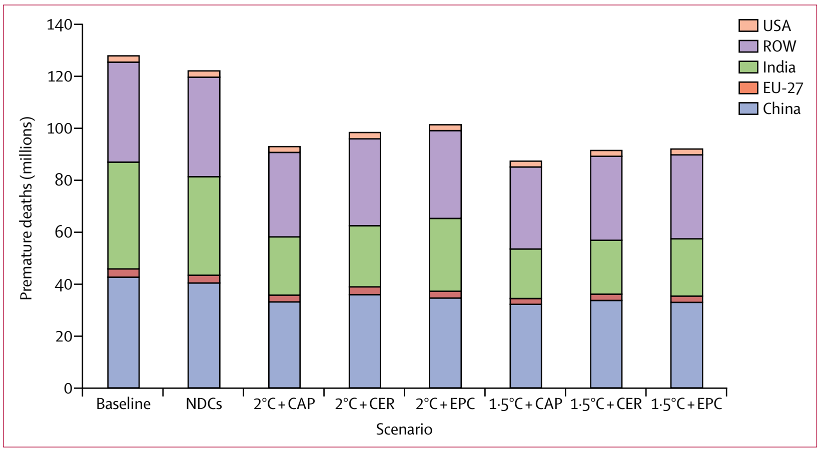


Figure 2: **Cumulative premature deaths per region and scenario, 2020–50**
NDCs=nationally determined contributions. CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. EU-27=the 27 countries of the European Union in 2007–13. ROW=the rest of the world.

the GCAM model, combined with additional assumptions about the country's economic structure, and energy and agricultural systems.[29,30] In this study we used the SSP2 emission factors to calculate the air pollutant emission trajectories as released with GCAM version 4.3.

The mitigation strategies are divided on the basis of two criteria: the global temperature target and the regional distribution of the mitigation effort associated with each target. For the temperature target, in addition to a baseline scenario in which no climate policy is set, we chose three scenarios: the NDC scenario (domestic mitigation measures with targets set at the national level), the 2°C stabilisation target, and the 1·5°C stabilisation target (both stabilisation targets are objectives for the year 2100).

Regarding the regional distribution of mitigation effort, Robiou du Pont and colleagues[28] suggest five distributional approaches, of which we chose to investigate three. The allocation approaches that we selected were the constant emission ratios (CER) approach, the capability (CAP) approach, and the equal per capita (EPC) approach. Table 1 summarises the characteristics of these allocations. The two excluded allocations are ones involving very unequal allocations to developed countries and, moreover, require huge negative emissions to be realised, which we considered unrealistic.

In accordance with Robiou du Pont and colleagues,[28] we divided the world into five regions: China, the 27 countries of the European Union in 2007–13 (EU-27), India, the USA (which together cover 60% of global emissions in 2015), and the rest of the world (ROW). The results are presented up to 2050.[28]

Although each scenario has a similar global carbon budget up to 2100, the carbon budgets up to 2050 are different as the criteria selected also affect the timing of mitigation. Figure 1 shows the notable differences in carbon dioxide (CO_2) emissions pathways under the different combinations of temperature targets and mitigation effort distributions. In the NDC scenario, the emissions are reduced by around 25% compared with the baseline by 2050. Although substantial, this reduction is not sufficient to achieve the Paris climate target. Compared with the NDC scenario, the 2°C scenarios require a reduction in CO_2 emissions across the five regions ranging from –71% to +57%. Logically, the reduction in the 1·5°C scenarios is greater, ranging from –79% to +8%, depending on the approach for sharing the mitigation effort (table 2).

While the restrictiveness of the climate target is an important factor in explaining the variations, the distributional approach is also important. As figure 1 shows, the reduction in emissions up to 2050 is greatest under the CAP scenario and least under the CER scenario. These differences translate into different mitigation efforts for the different regions.

It is notable that, for the 2°C target, China has to make a further 69% reduction under the CAP scenario, but only 35% under the CER scenario. The CER scenario imposes the greatest burden on India, and allows the USA and the EU-27 to reduce emissions by 57% and 34% less, respectively, than they have committed to under the NDCs (table 2).

	NDCs	2°C + CAP	2°C + CER	2°C + EPC	1·5°C + CAP	1·5°C + CER	1·5°C + EPC
USA	66·3% ($4·9 trillion)	20·2% ($8·4 trillion)	9·4% ($2·1 trillion)	22·5% ($6·4 trillion)	17·7% ($9·9 trillion)	12·4% ($5·0 trillion)	19·3% ($7·7 trillion)
EU-27	28·9% ($2·2 trillion)	11·5% ($4·8 trillion)	4·5% ($1·0 trillion)	9·0% ($2·5 trillion)	10·4% ($5·8 trillion)	6·9% ($2·8 trillion)	9·4% ($3·7 trillion)
China	3·2% ($0·2 trillion)	31·1% ($13·0 trillion)	18·6% ($4·1 trillion)	28·1% ($8·0 trillion)	27·9% ($15·6 trillion)	21·8% ($8·8 trillion)	26·1% ($10·4 trillion)
India	1·0% ($0·1 trillion)	9·4% ($3·9 trillion)	23·0% ($5·1 trillion)	6·2% ($1·8 trillion)	10·2% ($5·7 trillion)	16·0% ($6·5 trillion)	7·8% ($3·1 trillion)
ROW	0·6% ($0·0 trillion)	27·8% ($11·6 trillion)	44·5% ($9·8 trillion)	34·2% ($9·7 trillion)	33·9% ($19·0 trillion)	43·0% ($17·4 trillion)	37·4% ($14·9 trillion)
Total	100% ($7·5 trillion)	100% ($41·6 trillion)	100% ($22·1 trillion)	100% ($28·3 trillion)	100% ($56·1 trillion)	100% ($40·6 trillion)	100% ($39·7 trillion)

Regions are ordered according to their income per capita. Percentages are the proportion of global mitigation cost borne by each region and values in parentheses are absolute mitigation costs in US$. The discount rate used for the calculation is 3%. NDCs=nationally determined contributions. CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. EU-27=the 27 countries of the European Union in 2007–13. ROW=the rest of the world.

***Table 3:* Cumulative policy cost per region and scenario, 2020–50**

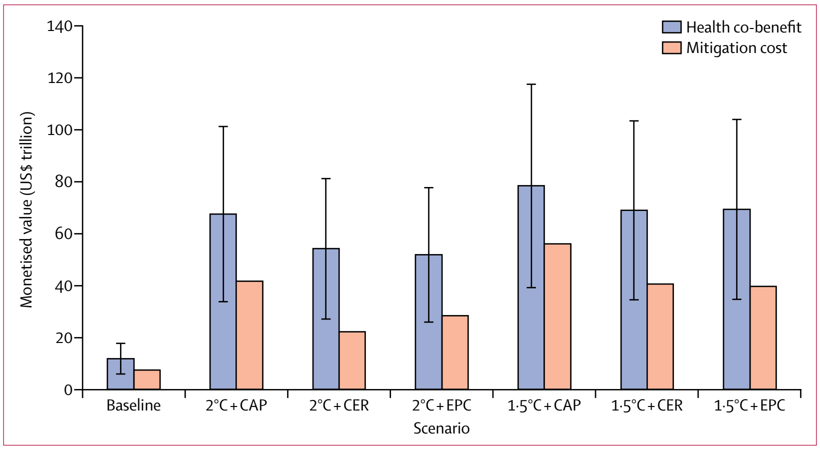


***Figure 3:* Cumulative health co-benefits and mitigation costs by scenario, 2020–50**

The discount rate used is 3%. Black uncertainty bars represent the range of values with lower and upper values of the VSL given in the literature.[23] CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. VSL=value of statistical life.

Results

Figure 2 shows the cumulative premature deaths from 2020–50 for each scenario. Globally, this cumulative number decreases substantially between the reference scenario and the scenarios using the 2°C and 1·5°C targets. In the NDC scenario, the number of deaths decreases by around 5% relative to the reference, whereas the reductions for the mitigation scenarios are from 21–27% for the 2°C target and from 28–32% for the 1·5°C target.

It is noticeable that the results for each region relative to the others are similar, irrespective of the scenario analysed. The largest proportions of premature deaths are in China (33–37% of the global deaths) and India (24–32%). About 37% of the global population lives in China and India and many of these people are exposed to pollution levels far above those recommended by WHO.

The mitigation costs for the defined scenarios (excluding the baseline scenario, which is not supposed to have any policy cost) and regions are shown in table 3. Under the CAP scenarios, China bears most of the cost, followed by the ROW, whereas India has the lowest share of the cost. However, the ranking changes substantially in the CER scenarios, with India now having a much greater share and China much smaller one. Generally, compared with what countries have committed to under the NDCs, the increases in costs are smallest for the USA and EU-27 and largest for the ROW, India, and China, in that order. Overall, the additional cost of going from a 2°C target to a 1·5°C target is around 20%.

The absolute costs of achieving the NDCs are around $7·5 trillion, the majority of which will be spent in the USA (66%) and EU-27 (29%). Mitigation costs are highest under the CAP scenarios as this approach requires the greatest short-term reductions in emissions: the cost of the 2°C+CAP scenario is 45% less than the cost under CER and 80% higher than the cost under EPC. When comparing the 1·5°C scenarios, the cost of the 1·5°C+CAP scenario is around 40% greater than that obtained with the other criteria.

From a macroeconomic perspective, these costs are relatively low. For the 2°C target, the global costs range from 0·5% to 1% of global GDP, whereas for the 1·5°C target, the range is 1% to 1·3%. Between these scenarios, the lowest costs emerge under the CER or EPC scenarios and the highest ones under the CAP scenario. These numbers are in line with those reported in the fifth IPCC assessment report,[30] in which the values for different years for the 2°C scenario range from around 0% to 2% of global GDP.

A discount rate is a factor that converts anticipated returns from an investment project in different time periods to their present value. Our results are based on a discount rate of 3%, which is in the middle of the range used in the literature to discount climate effects.[31–33] As a sensitivity test, we also used values of

0% and 6% (appendix). The differences between these rates in terms of the shares of costs borne by the different regions are quite small. The 6% rate means future costs and benefits are both given a lower value. As relatively fast-growing countries in terms of GDP and population, such as India and China have higher co-benefits and potentially higher costs in the future, these are given a small weight with a higher discount rate, making their share of net costs lower at a 6% rate than at a 3% rate. The reverse holds for the USA. The EU is somewhere in between, but the difference between the discount rates in terms of shares is only 1–2%.

Figure 3 shows the monetised health co-benefits and mitigation costs for each scenario. Health co-benefits are the difference between the monetised health damage of each policy scenario and those in the baseline scenario.

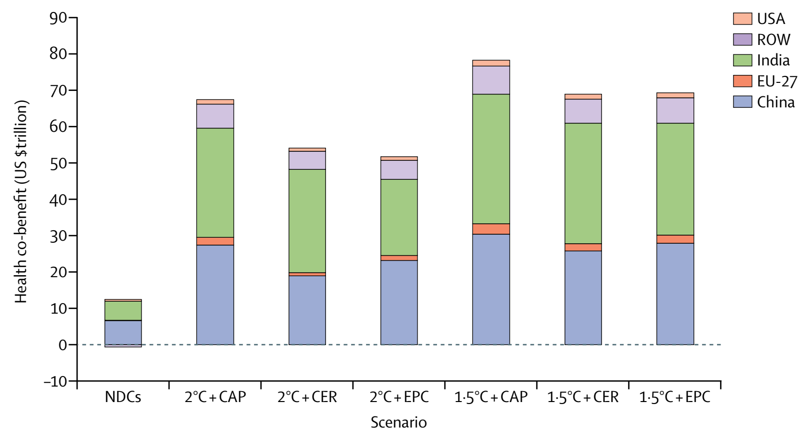


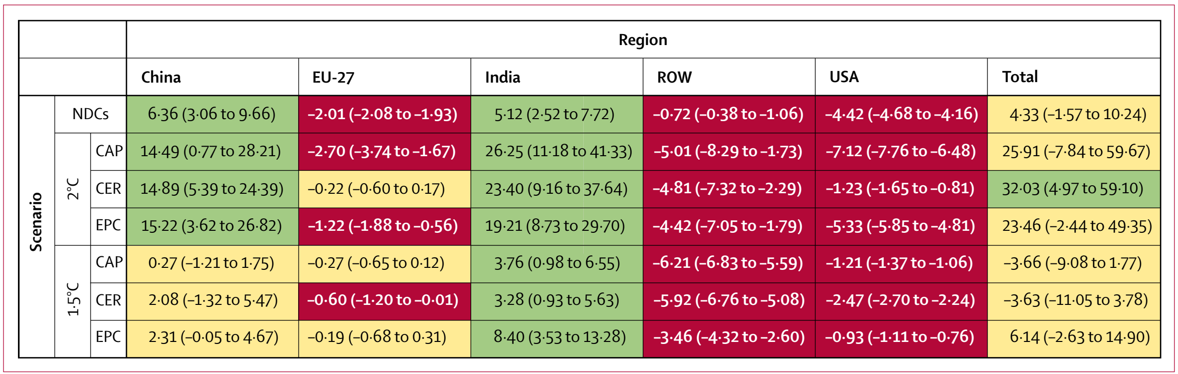
Figure 4: **Cumulative health co-benefit per region and scenario, 2020–50**
The discount rate used is 3%. NDCs=nationally determined contributions. CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. EU-27=the 27 countries of the European Union in 2007–13. ROW=the rest of the world.

Notably, at the global level, the value of the health co-benefits is greater than the cost of achieving the mitigation target for all the scenarios. Indeed, there is one mitigation strategy, 2°C+CER, for which the co-benefits are more than double the mitigation costs. The ratio of health co-benefits to mitigation costs ranges from 1·4 (1·5°C+CAP) to 2·45 (2°C+CER). The sensitivity analysis shown by the uncertainty range suggests that, even when taking the lower bound of VSL, the health co-benefits are very close to the mitigation cost, covering between 70–91% of that cost. For the non-equitable 2°C+CER scenario, even the lowest estimate of the health co-benefits is higher than the mitigation cost. It is notable that the generally higher value of the co-benefits in the CAP scenarios do not outweigh the larger policy costs, resulting in lower ratios of co-benefit to cost.

Figure 4 shows the regional distribution of these co-benefits, with most of the co-benefits located both in China and India. In the NDC scenario, China accounts for 55% of these co-benefits and India for 43%, respectively. In the 2°C and 1·5°C mitigation scenarios, they represent similar shares.

To compare co-benefits and mitigation costs for the different mitigation pathways, it is very useful to see what proportion of the additional effort of setting a more stringent target is compensated by the additional health co-benefits. This is especially important for addressing the objectives of the Paris Agreement to pursue efforts to reduce emissions to limit the temperature increase to 1·5°C.

It is key to analyse the policies step by step—ie, first, identify the effect of achieving the NDCs or the 2°C target (following the different defined criteria for distribution of mitigation efforts) compared with the baseline (no climate policy) scenario; then calculate, the effect of achieving the extra effort of the 1·5°C target instead of the 2°C target.



			Region					
			China	**EU-27**	**India**	**ROW**	**USA**	**Total**
Scenario	NDCs		6·36 (3·06 to 9·66)	–2·01 (–2·08 to –1·93)	5·12 (2·52 to 7·72)	–0·72 (–0·38 to –1·06)	–4·42 (–4·68 to –4·16)	4·33 (–1·57 to 10·24)
	2°C	CAP	14·49 (0·77 to 28·21)	–2·70 (–3·74 to –1·67)	26·25 (11·18 to 41·33)	–5·01 (–8·29 to –1·73)	–7·12 (–7·76 to –6·48)	25·91 (–7·84 to 59·67)
		CER	14·89 (5·39 to 24·39)	–0·22 (–0·60 to 0·17)	23·40 (9·16 to 37·64)	–4·81 (–7·32 to –2·29)	–1·23 (–1·65 to –0·81)	32·03 (4·97 to 59·10)
		EPC	15·22 (3·62 to 26·82)	–1·22 (–1·88 to –0·56)	19·21 (8·73 to 29·70)	–4·42 (–7·05 to –1·79)	–5·33 (–5·85 to –4·81)	23·46 (–2·44 to 49·35)
	1·5°C	CAP	0·27 (–1·21 to 1·75)	–0·27 (–0·65 to 0·12)	3·76 (0·98 to 6·55)	–6·21 (–6·83 to –5·59)	–1·21 (–1·37 to –1·06)	–3·66 (–9·08 to 1·77)
		CER	2·08 (–1·32 to 5·47)	–0·60 (–1·20 to –0·01)	3·28 (0·93 to 5·63)	–5·92 (–6·76 to –5·08)	–2·47 (–2·70 to –2·24)	–3·63 (–11·05 to 3·78)
		EPC	2·31 (–0·05 to 4·67)	–0·19 (–0·68 to 0·31)	8·40 (3·53 to 13·28)	–3·46 (–4·32 to –2·60)	–0·93 (–1·11 to –0·76)	6·14 (–2·63 to 14·90)

Figure 5: **Net incremental benefits by region and scenario**
Data are in US$ trillion. The discount rate used is 3%. The values in parentheses are the range of results based on the lower and the upper bounds of the VSL. The first rows represent the net incremental results of adopting the NDCs or the 2°C stabilisation target against a baseline of no climate policy. The last rows give the net incremental benefits of setting the 1·5°C policy compared with the (already stablished) 2°C target. A green cell shows that, irrespective of the VSL value, the incremental health co-benefit is greater than the incremental mitigation cost; a yellowcell shows that whether the health co-benefits exceed the extra mitigation cost depends on the VSL value; and a red cell shows that the additional health co-benefits are never sufficient to cover the additional mitigation cost. VSL=value of statistical life. NDCs=nationally determined contributions. CAP=capability scenario. CER=constant emission ratios scenario. EPC=equal per capita scenario. EU-27=the 27 countries of the European Union in 2007–13. ROW=the rest of the world.

Figure 5 compares the incremental health co-benefits with the incremental mitigation cost for a range of values of VSL for each of the intermediate steps. For China and India, the mitigation costs are compensated by the co-benefits for a 2°C target, irrespective of the burden sharing approach. The extra cost of going from the 2°C to the 1·5°C target is also always fully compensated for India, whereas for China it depends on the VSL chosen. The results in the other regions suggest that the incremental mitigation cost is often higher than the incremental co-benefit. Globally, the incremental health co-benefits outweigh the incremental mitigation cost of a 2°C target, depending on the VSL value, except for CER where this is the case for all VSL values.

Updated emission trajectories have been used in more recently published GCAM scenarios,[34] so we did a sensitivity analysis to investigate whether these changes affected our results. We found that the changes did not affect the overall conclusions of the paper, as shown in the appendix. Although there is emerging work investigating different future air pollution policy pathways,[35] these will be analysed in future research. The impact of alternative socioeconomic pathways on emission trajectories is shown in the appendix.

Discussion

Climate change and air pollution are important, interrelated problems. Our study is a comprehensive assessment of the global and regional implications of climate change mitigation in terms of (ambient) air pollution in the coming decades. The results show that, in all the scenarios, global health co-benefits are greater than the mitigation cost of achieving the target. The ratio of health co-benefit to mitigation cost ranges between 1·4 and 2·45. The staged approach, CER, is the most efficient burden sharing approach in terms of net cost.

Because of uncertainty over VSL values, we did a sensitivity analysis. The result of this analysis showed that, even with the lower bound of the VSL, the value of the health co-benefits would cover 70–91% of the mitigation costs, depending on the chosen scenario. There was one strategy, 2°C + CER, for which, the health co-benefits remained greater than the costs, even with the lower bound for VSL.

To better understand which target might be favourable for each region and under what burden sharing criteria, we did a incremental analysis, comparing the additional benefits of going from no target to an NDC-based target, from no target to a 2°C target, and from a 2°C target to a 1·5°C target. The results showed that in China and India, the cost of setting any additional policy could be compensated just with the health benefits in most cases. Other regions could not compensate the costs with the co-benefits alone, but the co-benefits would make a valuable contribution towards covering the mitigation costs, from 7% to 84% in the EU-27 countries and from 10% to 41% in the USA. In all cases it is important to remember that attaining the 2°C target comes with considerable benefits from reduced climate change impact benefits for all regions, including health benefits, and attaining a 1·5°C target has even greater climate benefits.

The study has various limitations, which we elaborate on in the appendix. For example, we could not include all of the published strategies because of modelling limitations (GCAM does not allow negative emissions to be set as regional climate targets) and we only focused on health damage without taking into consideration other potential types of damage (ie, agricultural damage due to ozone concentration). In particular, we wish to draw attention to two points. First, population projections by grid cell do not allow for changes when the cell currently has a zero population, so we have to assume that no urban expansion will occur on land that is currently completely uninhabited. Second, the policy instrument we use with GCAM for the GHG reductions is a regional carbon tax (one per defined region), so further work will be needed to consider more fragmented instruments.

Contributors

AM and JS designed the study and prepared the methods. RVD contributed with the FASST model calculations. SJS helped with the GCAM model and the model linking process. CP-I, IA, and MG-E contributed to background and analysis. All authors contributed to the writing of this Article.

Declaration of interests

We declare no competing interests.

Acknowledgments

This study received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement number 642260 (TRANSrisk project). MG-E, IA, and JS acknowledge financial support from the Ministry of Economy and Competitiveness of Spain (ECO2015-68023). MG-E and JS acknowledge financial support from the Basque Government (IT-799-13 and PRE_2017_02_0139).

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