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Co-Benefits of Climate Change Mitigation Policies: Literature Review and New Results

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ABSTRACT/RÉSUMÉ

Co-benefits of climate change mitigation policies: literature review and new results

There are local air pollution benefits from pursuing greenhouse gases emissions mitigation policies, which lower the net costs of emission reductions and thereby may strengthen the incentives to participate in a global climate change mitigation agreement. The main purpose of this paper is to assess the extent to which local air pollution co-benefits can lower the cost of climate change mitigation policies in OECD and non-OECD countries and can offer economic incentives for developing countries to participate in a post-2012 global agreement. The paper sets out an analytical framework to answer these questions. After a literature review on the estimates of the co-benefits, new estimates, which are obtained within a general equilibrium, dynamic, multi-regional framework, are presented. The main conclusion is that the co-benefits from climate change mitigation in terms of reduced outdoor local air pollution might cover a significant part of the cost of action. Nonetheless, they alone may not provide sufficient participation incentives to large developing countries. This is partly because direct local air pollution control policies appear to be typically cheaper than indirect action *via* greenhouse gases emissions mitigation.

JEL classification: I10; Q53; Q54.
Keywords: co-benefits; local air pollution; climate change; mitigation policy; health.

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Les bénéfices connexes des politiques d'atténuation du changement climatique : revue de la littérature et nouveaux résultats

Les politiques de réduction des émissions de gaz à effet de serres ont des bénéfices en termes de pollution atmosphérique locale, ce qui diminue le coût net de ces politiques et ainsi renforce les incitations à participer à un accord mondial d'atténuation du changement climatique. Le principal objectif de ce document est d'évaluer dans quelle mesure les bénéfices connexes sur la pollution atmosphérique locale peuvent, d'une part réduire le coût des politiques d'atténuation du changement climatique dans les pays de l'OCDE et dans les pays en dehors de l'OCDE et d'autre part fournir des incitations économiques aux pays en développement à participer à un accord mondial pour l'après 2012. Le document établit un cadre d'analyse pour répondre à ces questions. Après une revue de la littérature des estimations des bénéfices connexes, de nouvelles estimations, obtenues dans un cadre d'équilibre général dynamique couvrant l'ensemble des régions du monde, sont présentées. La principale conclusion est que les bénéfices connexes de l'action climatique en termes de réduction de la pollution atmosphérique locale couvriraient une part importante du coût des politiques. Néanmoins, à eux seuls, ils seraient insuffisants pour amener les grands pays en développement à participer. Cela tient en partie au fait que l'application de mesures visant directement la pollution atmosphérique locale est généralement meilleur marché qu'une action indirecte via la réduction des émissions de gaz à effet de serres.

Classification JEL : I10 ; Q53; Q54.
Mots-Clés : bénéfices connexes ; pollution atmosphérique locale ; changement climatique ; politiques d'atténuation ; santé.

TABLE OF CONTENTS

Tables

Figures

CO-BENEFITS OF CLIMATE CHANGE MITIGATION POLICIES: LITERATURE REVIEW AND NEW RESULTS

By

Johannes Bollen, Bruno Guay, Stéphanie Jamet and Jan Corfee-Morlot[1]

1. Introduction and main findings

1. There is a potentially large and diverse range of collateral benefits that can be associated with climate change mitigation policies in addition to the direct avoided climate impact benefits. Depending on the context, mitigation actions targeting clean energy technologies or energy efficiency, for example, are likely to include large near-term improvements in local or in indoor air quality which in turn limit risks to human health and improve local environments. These collateral benefits are referred to here as "co-benefits" of climate change mitigation policies.

2. Through both a literature review and an empirical analysis using a macro-economic modelling framework, a number of policy questions are explored in this paper:

- To what extent will co-benefits vary with the scale of mitigation effort?
- To what extent do co-benefits lower the cost of mitigation policies in OECD and non-OECD countries?
- To what extent do co-benefits of climate mitigation policies offer economic incentives for developing countries to participate in a post-2012 global agreement?

3. The paper starts by setting out an analytical framework to guide the literature review and the empirical work. The review of the literature on co-benefits focuses on the magnitude of co-benefits across different scales of greenhouse gas (GHG) mitigation efforts, and their distribution across developed and developing countries. The main conclusions that can be drawn from this review are the following:

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- Since co-benefits of climate change policies in terms of local pollution control accrue in the near term while benefits from climate change mitigation come over the longer run, co-benefits provide some incentives to participate into a climate change mitigation agreement by offsetting some share of GHG mitigation costs in the short term.

- However the magnitude of the incentives depends on several issues that have not been fully addressed by the existing literature. In particular, the incentives provided by co-benefits depend on the avoided cost of achieving the same co-benefits by direct policies, which represents an opportunity benefit.

- There are synergies between climate change and local air pollution (LAP) policies that have been only partially investigated. For instance, a reduction of Methane (a GHG mainly arising from the agriculture sector) would lead to both a reduction in overall GHG concentration and a decrease in the background tropospheric ozone concentrations, which also have an important warming effect in addition to detrimental impacts on human health and crop yields. The potential "double dividend" of policies to limit GHG emissions that have benefits for both climate and local pollution has also been rarely assessed.

- There are also important trade-offs between climate change and LAP policies, which depend on the technologies and policies that are implemented to achieve targets. A first example of these trade-offs is the implication for global climate of a reduction in certain local pollutants that have a "cooling" effect, and the trade-offs between less temperature increases and less local air pollutants. Another example is the possible co-costs stemming from GHG mitigation policies, in particular those related to indoor air pollution in developing countries. This is because a global carbon price may provide perverse incentives to use non-commercial fuels biomass for heating and cooking, with detrimental effect on health. In principle, it is possible to design mitigation policies that yield maximum benefits in both climate change and LAP areas. Such an approach would need to be coordinated on a global scale and to take into account interactions among the full range of GHG and local pollutants.

4. In order to address some of the shortcomings of the literature, an empirical analysis of co-benefits within a global macro-economic framework is undertaken in this paper. The purpose of this analysis is to assess the magnitude of the co-benefits of mitigation policies in terms of reduction in local air pollution and its implications for human health as well as the incentives that the co-benefits can give to countries to participate in an international climate change mitigation agreement. Although there are various uncertainties surrounding the analysis, several main findings can be mentioned:

- Reductions in GHG emissions are found to induce large reductions in LAP emissions, with potentially significant positive impacts on human health. For instance, in a scenario where GHG emissions are cut by 50% relative to 2005 levels in 2050, the number of premature deaths caused by air pollution could be lowered by 20% to 40% in 2050-depending on regions- relative to a business as usual scenario.

- Over the medium run and/or for less stringent long-run emission-reduction objectives, these co-benefits may be lower in developing countries than in the OECD area, as the cheapest GHG abatement opportunities in developing countries are initially found in the electricity sector, where the human health benefits from emission cuts appear to be smaller. However, for stringent emissions cuts and/or over longer horizons, co-benefits ultimately become higher in many non-OECD countries than in their OECD counterparts as abatement gets larger in the transport and household energy consumption sectors.

- The monetary value that can be attached to these human health co-benefits depends on a crucial yet controversial parameter, namely the value of statistical life (VSL). With a reference VSL of $US1 million (2000$US) for the European Union, consistent with values that have been adopted in several programmes on local air pollution, the co-benefits could range between 0.7% of GDP in the European Union to 4.5% in China in 2050 under a 50% GHG emissions cut scenario.

- In the medium run, the only benefits of GHG mitigation policies are the co-benefits, since the direct benefits of GHG mitigation policies in terms of avoided damage from climate change are expected to occur in the longer run. Nonetheless, co-benefits alone may not provide sufficient participation incentives to large developing countries, not least because direct local air pollution control policies appear to be typically cheaper than indirect action *via* GHG emissions mitigation. However, they are found to provide a larger participation incentive to developing countries than to developed ones.

- Even if countries did not join in an international climate change mitigation agreement, they may still reduce significantly GHG emissions indirectly by adopting country specific measures to control LAP, at least provided that relatively stringent LAP targets were adopted. This is illustrated here through a scenario where all countries are assumed to simultaneously implement drastic actions to reduce local air pollution.

2. A framework for analysis

5. From an economic perspective, an assessment of whether co-benefits provide an incentive to participate in a GHG mitigation agreement requires consideration of the opportunity costs of mitigation action. That is, the costs and impacts of policies to address conventional pollutants will need to be explicitly accounted for.

6. In such a framework (Figure 1, “Window 1”[2]), the decision to invest 1$ in climate mitigation policies instead of other policies to limit local pollutants depends on the global net return:

Net return = (*Impact1+ Additional Impact1 – Cost1*) - (*Impact2 + Additional Impact2 - Cost2*),

With “Impact 1” and “Additional Impact 1” being the impact of climate change mitigation policy in terms of, respectively, reduced GHG emissions and reduced LAP, “Cost 1” the cost of this policy, “Impact 2” and “Additional Impact 2” being the impact of LAP control policy in terms of, respectively, reduced LAP and reduced GHG emissions, and “Cost 2” the cost of this policy.

[Figure 1.Three windows in the analysis of co-benefits]

7. For a positive net return, there is a net benefit to use 1$ in climate mitigation policies instead of allocating it to other policies to limit local pollutants while for a negative net return, there is a net cost. Thus in order to evaluate incentives provided by co-benefits, the additional co-benefit impact should be compared not only to the cost of climate change policy but also to the opportunity cost, which is the net loss of investing the dollar in climate policies instead of other policies (*Impact 2 + Ad. Impact 2-Cost2*).

8. Some of the literature tries to take into account the avoided regulatory cost for reductions achieved in other (non-CO_2) pollutants (Van Vuuren 2006; Van Harmelen 2002), however these studies have focused uniquely on developed countries. Furthermore, since some countries have already started to

2 . “Window 1” considers the costs and benefits of climate change mitigation policy.

introduce policies to control LAP, it is also important to assess the impacts on GHG emissions of these policies (Window 2[3]).

9. Given the interactions between GHG and local pollutant mitigation policies, the preferred methodological approach would be an integrated approach that internalises both climate change and local pollutant externalities, which permits exploration of the optimal solution.[4] Assessing this optimal policy could be useful as a benchmark to evaluate GHG and LAP mitigation policies that are discussed at an international level. A few recent studies permit such an integrated analysis (Bollen *et al.* 2007; Reilly *et al.* 2007).

3. A literature review

3.1 Local Pollutants, Channels and Impacts

10. Local pollutants are responsible for well known environmental problems such as smog, acid rain and indoor air pollution which in turn have a wide range of effects on human health, ecosystems, building, crops as well as climate. It is important to understand the inter-linkages between local and global pollutants as well as their end impacts on the environment and ultimately on human welfare. The relative size of the co-benefits of climate change policies in terms of local pollutants and vice versa depends upon the synergies and trade-offs that occur across these channels and the end points in affected sectors. These pollutants are mainly but not exclusively local air pollutants originating from a number of human activities that are also responsible for GHG emissions. Several local air pollutants also affect radiative forcing in the atmosphere thus adding or detracting from global warming.

11. Among local air pollutants the most important class is particulate matter (PM). PM travel through the air suspended in a gaseous form, where the particles and the suspending gas together are referred to as an aerosol. It is widely recognised that small PM (under 10 micrometers, also referred to as PM10) can cause heart and lung disease. Recent research identifies even smaller particles (under 2.5 micrometers or PM2.5) as the most detrimental for human health (Pope, Arden *et al.* 2002).

12. In developing countries, indoor air pollution in the form of PM is estimated to be a more significant problem for human health than is ambient outdoor air pollution (WHO 2004).[5] This is because in developing countries, roughly 2.5 billion people depend on traditional biomass such as fuel wood and charcoal as their primary fuel for cooking and heating because it is a cheap source of fuel (Stern 2006). Women and children are most severely affected because they spend most time in the home doing domestic tasks. Despite their rapid development in recent years, India and China suffer a large number of premature deaths from indoor air pollution because of their dependence on charcoal and wood for cooking and heating. As economies catch up, traditional biomass is expected to be gradually replaced by modern, cleaner cooking fuels, which would reduce both GHG emissions and health problems, while transportation would become a more significant problem.

3 . "Window 2" considers the costs and benefits of LAP control policy.

4 . The integrated approach combining climate change mitigation policy and LAP control policy is labelled "Window 3".

5 . WHO (2004a) states that in the year 2000 global mortality due to indoor air pollution from solid fuels is more than 1.6 million, compared to 0.8 million for urban air pollution. This two-fold difference in mortality is not just a result of higher populations in developing countries, but is due to differing gross incidence rates. Urban (outdoor) air pollution mortality is 12 per 100 000 in developed countries compared to 14 per 100 000 in developing countries. Indoor air pollution mortality is 2 per 100 000 in developed countries compared to 34 per 100 000 in developing countries

13. Another major form of air pollution with detrimental health effects is tropospheric ozone. When found in high concentrations it is both detrimental to human health causing death and morbidity (WHO 2003) and to crop, pasture and forestry yields causing plant senescence (Wang and Mauzerall 2004).

14. Some local pollutants exert a negative climate forcing (cooling effect) while others exert a warming effect, but overall, aerosols are estimated to have a cooling effect. Most noteworthy is ozone, which is the third most important greenhouse gas (Prather *et al.* 2001).[6] The climate forcing of aerosols varies depending on the type of aerosol with some important associated uncertainties. For example, black carbon exerts important positive forcing effects while sulphates exert important cooling effects. The overall trend however suggests that the cumulative effect of all aerosols is a negative forcing which is mainly the result of sunlight dispersion or "dimming" and increased cloud formation effects (IPCC 2007). There is thus a complex set of combined effects: actions that reduce greenhouse gas reduction through cleaner energy use may also directly reduce other local pollutants (such as PM or ozone) and in turn lead to indirect effects on radiative forcing.

15. Figure 2 summarises the channels through which local pollutants affect ecosystems, crop yields and human health. Indoor air pollutants and especially black carbon have strong negative impacts on human health. SO_x has negative impacts on human health (*via* sulfate PM) and causes material damage to buildings as well as acidification of ecosystems. NO_x emissions are responsible for ozone (which in turn has direct health impacts) and nitrate PM impacts upon human health (*e.g.* respiratory diseases, cancer), decreased agricultural productivity due to ozone, ecosystem acidification and eutrophication.[7]

[Figure 2. Summary of the pollutant channels]

3.2 Review of Studies

16. Table 1 summarises the key findings of the studies reviewed going through the three windows of analysis depicted in Figure 1. The majority of the literature focuses on the interactions between climate change mitigation and local air pollution (LAP) policies and most of these are centred on the human health impacts. There is also a small but emerging literature on crop impacts of LAP and the interactions with climate change policies. The main finding from this review of available estimates is that co-benefits are expected to cover a significant part of climate change mitigation costs (Figure 3).

[Table 1. Scenario and results of studies reviewed]

[Figure 3. Review of existing regional estimates of the co-benefits in 2010 at different GHG emission prices]

Human health impacts

17. Starting with analyses that are climate change centred, a number of studies conclude that co-benefits (in the form of "Additional impact1") are positive and large. These include Bussolo and O'Connor (2001), showing that in India, 334 lives are saved per million tonnes of carbon abated for a 15% reduction from the CO_2 reference baseline in 2010. This compares to 298 and 210 lives saved for China estimated by

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6 . Despite its radiative properties, ozone is not included in the Kyoto Protocol perhaps because it is an indirect pollutant, formed in the atmosphere through a chemical reaction with other direct pollutants.

7 Acidification of plants and soils derives from SOx and NOx deposition and leads to forest and plant dieback while eutrophication occurs in freshwater environments due to nitrogen loading – it is also known as algal bloom disrupting the normal functioning of these ecosystems and possibly also water treatment for drinking water supplies.

Garbaccio *et al.* (2000) and O'Connor *et al.* (2003) respectively. The numbers for previous studies conducted in Chile and the United States are considerably lower. The relative magnitudes of the marginal mortality reductions are consistent with the hypothesis advanced in O'Connor (2000) that developing countries with few initial local pollution controls (hence, little decoupling of CO_2 emissions from other pollutants) are likely to benefit relatively more in lives saved from climate policy than developed countries where such decoupling is far more advanced. Another factor in the cases of China and India is the high urban population densities, hence, large exposed populations relative to Chile and the United States.

18. In the short to medium term, indoor pollution (cooking smoke) from biomass (including fuel wood but also crop residue and dung cakes) weighs in more heavily than outdoor pollution in the health burden in developing countries[8] and climate change mitigation policies may increase indoor pollution in developing countries.[9] The basis for this argument is that if CO_2 abatement policies in developing countries leads to higher electricity or modern fuel prices, this could reduce the use of electricity and kerosene, delay electrification and increase the use of biomass and thus indoor air pollution in households. Data availability and quality for commercial and non-commercial fuels are incomparable and hence the transition from one to the other is difficult to characterize (Mazzi and Dowlatabadi 2005). Studies examining the impact of fuel prices on consumption generally show low cross-price elasticities between biomass, kerosene and electricity (Gundimeda 2003; Kebede *et al.* 2002; Sudhakara Reddy 1995). However, they also suggest an asymmetry: given the limited access to electricity in many developing countries, people are constrained in their capacity to substitute from solid fuel to electricity, but not from electricity to solid fuel, with larger detrimental effect on human health (Gundimeda 2003; Kebede *et al.*2002). This effect could significantly limit co-benefits of climate change policies in terms of reduced indoor pollution in some contexts and is generally ignored in economic studies reviewed above (O'Connor 2003; Bussolo and O'Connor 2001 studies; Bollen 2007). However, the effect of GHG mitigation policies on indoor air pollution will depend on policy design. Well-designed policies (e.g. that increase biomass fuel stove efficiency and lead to switch to more efficient fuels) can yield benefits in terms of both GHG emission and indoor air pollution reduction.

19. In the longer-run, the co-benefits and the synergies between climate change and LAP policies are likely to decline over time as local air pollution is expected to decrease with economic catching-up, following a Kuznets curve, while GHG emissions are projected to continue rising. The main thrust in local pollution control is improved fuel quality resulting in lower ash and sulfur content, stricter enforcement of emission regulations, deeper penetration of flue gas desulfurisation (FGD) technology in stationary facilities, and energy efficiency improvements, of which only the latter significantly contribute to GHG mitigation. These policy developments are already visible in India and are likely to be strengthened in the future (Garg *et al.* 2003).

Avoided Costs

20. A number of studies have tried to estimate the avoided cost of meeting a cap in LAP that can be obtained through climate change mitigation policies. These studies focus on the European context and they do not take into account the impacts of such LAP policies (human health, crop yields, ecosystems, etc.).

21. Van Harmelen *et al.* (2002) model the avoided costs of reaching LAP mitigation targets in Europe when climate change mitigation policies are also included. They show that the costs of SO_2 and NO_x mitigation by direct policies (end-of-pipe technology) in a world without climate policy are comparable or in some periods even higher than the costs of an integrated mitigation of SO_2, NO_x and CO_2

8 . Smith, 1993; Stern 2006; Aunan *et al.* 2006.

9 . See Mazzi and Dowlatabadi (2005) for the case of India.

emissions. They assume a cap on LAP is set by the targets in the Gothenburg Protocol[10] followed by reduction rate increases after 2010 a logistic function up to a maximum value (95% for SO_2 and 85% for NO_x). For mitigation of SO_x and NO_x to these levels, assuming reductions are achieved through end-of-pipe control technologies, average pollution control costs over the century can be reduced by 50–70% for SO_2 and around 50% for NO_x when climate mitigation measures are introduced.

22. Van Vuyren *et al.* (2004) model the avoided costs of reaching the Gothenburg Protocol and the EU National Emission Ceilings Directive for local air pollution for different Kyoto implementation strategies that vary by whether or not emission trading is used and the extent of trading. Three different scenarios on Kyoto implementation were found to reduce European CO_2 emissions by 4-7% while also reducing European emissions of SO_2 by 5–14% compared with a no Kyoto policies case. The magnitude of co-benefits depends on how emission trading mechanisms and surplus emission allowances (*i.e.* in the case of Russian allowances which significantly exceed actual emissions) are used in to meet the Kyoto targets (see Table 1). Use of emission trading reduces emissions of air pollutants for Europe as a whole even further than domestic implementation because it allows pursuit of deeper emission reductions in central and eastern Europe where synergies between air pollution and greenhouse gas mitigation objectives are greater than in western Europe (*e.g.* 10-14% versus 5% for SO_2 emissions in the case of emission trading versus unilateral domestic implementation). The total cost savings compared to implementing current policies for regional air pollution without the Kyoto Protocol amount to around half the costs of the climate policy.

Agriculture and forestry impacts

23. A small but growing literature is examining the synergies and trade-offs between climate change and LAP policies in the agricultural and land use sectors where a central issue is the interaction between CO_2 fertilisation on the one hand and methane (a potent GHG) and tropospheric ozone pollutant pathways on the other. When considered in isolation, CO_2 fertilisation is predicted to exert a positive impact on global crop yields up to moderate levels of climate change (*i.e.* 2-3 Celsius above 1990 levels) (IPCC 2007b; Tubiello *et al.* 2006).[11] But, tropospheric ozone concentrations are expected to have significant negative effects on crop yields and these are likely to increase dramatically over the next 50 years due to a widespread increase in threshold concentration events for ozone (Reilly *et al.* 2007, Wang and Mauzerall 2004).

24. Early literature on climate change effects on the agriculture and forestry sectors ignored interactions with troposheric ozone. Reilly *et al.* (2007) is the exception; the authors demonstrate that both ozone and climate change effects –and policies to address them- need to be considered in an integrated framework. Their analysis suggests that the co-benefit of climate change mitigation policy in the agriculture sector can be weak, or can even turn into co-costs. This is because, although capping GHG yields reductions in tropospheric ozone through various pollutant pathways, these benefits are offset on a global scale by the loss of beneficial CO_2 fertilisation effects. Capping local pollution alone yields large positive effects on crop production. Capping GHG and local pollutants in an integrated manner yields results that are roughly equivalent to capping local pollutants alone in the long-term. The regional

10 . The Gothenburg Protocol sets emission ceilings for 2010 for four local air pollutants (sulphur, NOx, VOCs and ammonia) in European countries and North America.

11 . There are some uncertainties about the magnitude of the fertilisation effect and about the threshold beyond which it holds, which is thought to vary by soil conditions among other local factors. Also the distribution of these effects is expected to be uneven, with more positive effects in cooler regions and less so in tropics (Reilly *et al.* 2007; IPCC 2007b).

distribution of impacts depends on the size of the agriculture sector[12] and on trade effects, with countries less affected by LAP being able to export agricultural products to other regions. The Reilly *et al.* analysis also points to the need to adopt a general equilibrium framework to assess the impact of climate change and climate change policies on agriculture, which has rarely been the case in the early literature. While the impacts on crop yield can be large, the economy-wide impact is mitigated by adaptation and re-allocation of resources towards other sectors of the economy.

Conclusions

25. Current studies do not have a comprehensive treatment of co-benefits. The opportunity cost of investing in climate change mitigation policies rather than in LAP control policies has not been fully incorporated in existing studies. Furthermore, the interactions between pollutants in the atmosphere are important for assessing the co-benefits since the local air pollution reduction associated with climate change mitigation policies also has some implications for temperatures. Finally, the co-benefits have been seldom assessed within a general equilibrium framework. The purpose of the following empirical work is to assess the LAP co-benefits of climate change mitigation policies, including their opportunity cost, within a general equilibrium framework that incorporates the interactions between pollutants.

4. New simulations on the co-benefits of climate change mitigation policies

26. The purpose of this analysis is to assess the size of the co-benefits of mitigation policies in terms of reduction in local air pollution and its implications for human health within a general equilibrium framework. The analysis also estimates the potential incentives that co-benefits could give countries to participate into an international climate change mitigation agreement following the framework presented in section 2. As with most of the studies reviewed in the previous section, this analysis does not incorporate the impact of mitigation policies on indoor pollution.

4.1 Methodology and baseline

Main features of the model

27. The analysis is based on an extended version of the Model for Evaluating the Regional and Global Effects of GHG reduction policies (MERGE), which was initially developed by Manne and Richels (2004). This model is a dynamic general equilibrium model with a detailed energy sector and a global coverage, covering nine separate geographical regions.[13] The domestic economy of each region is represented by a Ramsey-Solow model of optimal long-term economic growth, in which inter-temporal choices are made. The social discount rate is assumed to be 4% in 2000 and to decline linearly to 2% in 2100 following Weitzman's (2001) recommendations. Output depends on the inputs of capital, labour and energy through an economy-wide production function. Separate technologies are defined for each main electric and non-electric energy option. A climate module translates CO_2 emissions from fossil-fuel consumption into world CO_2 concentration and temperature dynamics.

28. The MERGE model was extended to simulate the impacts of climate change mitigation policies on outdoor local air pollution (Bollen *et al.* 2007), as well as to include a broader range of local pollutants. The analysis covers the main pollutants with impacts on health, namely particulate matter (PM2.5) from

12 . Agriculture represents about 20% of developing country output compared to only about 2% in developed countries.

13 . Regions in MERGE are the United States, Western Europe, Japan, Canada/Australia/New Zealand, Eastern Europe and Russia, China, India, OPEC and Mexico, and the rest of the world. The model has a time horizon of 150 years (up to 2150) with time steps of ten years.

the combustion of solid or liquid fuels in both rural and urban areas, which account for a large amount of the health damages of outdoor LAP, as well as secondary aerosols (SO_2, NOx) from the combustion of oil and coal, and NH3 from agriculture. The impact of ozone on health is not treated as a co-benefit but is included in the damages from climate change.

29. The social global welfare function is:

$$\sum_r n_r \sum_t u_{t,r} \log\left(E_{t,r} F_{t,r} C_{t,r}\right) \qquad (1)$$

with *n* representing the so-called Negishi weights[14], *u* the utility discount factor, the economic loss factors associated with global climate change (*E*) and with LAP (*F*), and *C* consumption. The global climate change loss factor *E* is:

$$E = (1 - (\Delta T / \Delta T_{cat})^2)^h \qquad (2)$$

in which ΔT is the temperature rise relative to its 2000 level, and ΔT_{cat} the catastrophic temperature at which the entire economic production would be wiped out. Losses depend on the time at which temperature increase is reached and on regions through a parameter *h*, which is assumed to be 1 for high-income regions, and below unity for low-income regions.

30. In each year (t) and region (r), the constraint is to allocate GDP between consumption (*C*), investment (*I*), energy (*J*), expenditure to reduce LAP (*K*), expenditure to compensate for climate change-related damages (*D*), and net-exports (*X*).

$$Y_{t,r} = C_{t,r} + I_{t,r} + J_{t,r} + K_{t,r} + D_{t,r} + X_{t,r} \qquad (3)$$

31. The model can be run in a "cost-benefit mode", in which the problem is to find, consumption, LAP and damages from climate change that maximise the global objective function under the allocation of resources constraint. The target is itself endogenously chosen so as to balance the costs and benefits of policies. The model can also be run in a "cost effectiveness mode", with least cost policies to meet some imposed climate and/or LAP targets being determined by the model.

Technologies

32. The MERGE model includes a portfolio of energy technologies, which are gradually implemented as soon as they become profitable with the rise of the carbon price. This technology portfolio is based on assumptions on the dates of availability and costs of these technologies (Table 2). Emission coefficients are also attributed to these technologies. LAP emission coefficients are not related to the GHG emission coefficients, which means that technologies emitting less GHG may or may not lead to more LAP. For instance, the Integrated Gasification Combined Cycle is a technology that produces electricity from coal with less GHG emissions but more NO_x emissions, compared with some cheaper technologies.

[Table 2. Characteristics of the portfolio of technologies available in the MERGE model]

14 . The welfare weights are obtained following Negishi (1972) and ensure the correspondence between a competitive equilibrium and a maximum point of a social welfare function which is a linear combination of regional utility functions. They are determined iteratively so that each region will satisfy an intertemporal foreign trade constraint.

Model extension to incorporate the physical impacts of local air pollution

33. Emissions of local air pollution are converted into their contribution to particulate matter ($PM_{2.5}$) concentration assuming a linear function between emissions and concentrations[15]:

- Concentration in each region is derived from the substance-specific contribution of emissions to ambient concentration. Equation (4) summarises the relationship between average yearly $PM_{2.5}$ concentration in year *t* and region *r* (*G*) and substance-specific contributions (*H*), with *s* the substance index (*s* = SO_2, NO_x, PM_{10}, and NH_3):

$$G_{t,r} = \sum_{s \in S} H_{s,t,r} \qquad (4)$$

- The substance-specific contribution to the regional yearly $PM_{2.5}$ concentration is based on the weighted mean of urban and rural concentrations, which is derived by converting emissions into concentration with a substance-specific coefficient (α) for urban (urb) and rural (rur) areas:

$$H_{s,t,r} = \Delta e_{s,t,r} \left(u_{t,r} \alpha_{s,r,urb} + \alpha_{s,r,rur} \right) \qquad (5)$$

with *u* the exogenous time series of the proportion of people living in urban areas in year t in region *r*, and $\Delta e_{s,t,r}$ the growth of emissions of substance *s* at time *t* compared with the year 2000.

34. The number of deaths *N* caused by local air pollutants is estimated by assuming that the risk of death increases log-linearly with the concentration of $PM_{2.5}$ following the World Health Organisation methodology (see WHO, 2002 and 2004). The risk coefficient (equal to 1.059) is derived from a large cohort study of adults in the United States (Pope *et al.* 2002) and concerns fine PM of a diameter smaller than 2.5 micrometers (or $PM_{2.5}$):

$$N_{t,r} = \frac{(1.059-1)G_{t,r}}{(1.059-1)G_{t,r}+1} P_{t,r} c_{t,r} \qquad (6)$$

in which *G* is the anthropogenic[16] $PM_{2.5}$ concentration, *P* the region's population of the region, and *c* the crude death rate. The values of regional crude death rates are based on Hilderink (2003), and incorporate ageing so as to reflect that, for a given PM concentration level, the number of deaths increases with ageing. As a result, the crude death rate is assumed to increase by 12% on average and by 8% in OECD regions in 2050 relative to 2000 in the baseline scenario. The number of deaths for a given level of concentration also increases as a consequence of urbanisation, which is assumed to develop with income growth according to an exogenous path. On the whole, in the baseline scenario, the impacts of population growth, ageing, and urbanisation are assumed to increase the number of deaths in 2050 by at least 30% within OECD and by over 60% in non-OECD regions.

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15 The model is linear in emission changes for each region, which implies that transboundary air pollution, the pollutants that are generated in one region and felt in others, is not incorporated. This restriction is expected to have only limited impacts on results, however.

16 For the calculations on premature deaths, the WHO recommends to subtract 7.5 ug/m3 from the observed concentration level as a proxy for natural background concentration. The simulated concentration levels restrict to anthropogenic sources and subtraction of natural sources is not required.

Attributing a value to physical health impacts

35. In order to convert physical impacts expressed in terms of the number of premature deaths into monetary units, an estimate of the value of statistical life (VSL) is needed. Usual estimates that come from the labour market literature cannot directly be used in the context of local air pollution. This is because the elderly benefit disproportionately from air quality policies that reduce particulate matter emissions and older individuals should be willing to pay less for reduced mortality risk because they are purchasing fewer additional years of life expectancy (see Jamet and Corfee-Morlot, 2009 and Viscusi and Aldy, 2003 and 2007). The reference estimate of the VSL used here (1.061 million 2000$US - for European countries) is the median of a range of estimates adopted in the context of environmental issues and is consistent with values recommended by Holland *et al.* (2004) for the Clean Air for Europe Programme (CAFE) at the European Commission (Krupnick *et al.* 2004).

36. The VSL is assumed to increase with income, as recommended by Viscusi and Aldy (2003). The monetised damage from LAP (*F*) is obtained by multiplying the number of premature deaths from chronic exposure (*N*) by the VSL reference estimate (*VSLref*) and adjusting this monetised impact for the GDP per capita (*Y/P*) gap of the region considered with respect to Europe:

$$F_{t,r} = 1 - \frac{VSLref * N_{t,r}}{C_{t,r}} \left(\frac{Y_{t,r} / P_{t,r}}{Y_{2000,weur} / P_{2000,weur}} \right) \quad (4)$$

As a result of this formulation, the gap between OECD and other countries introduced by the adjusted-for-income VSL decreases over the projection period, as their GDP per capita gap of non-OECD countries closes.

Main features of the baseline scenario

37. Economic and population projections that drive GHG emissions are similar to those developed for ENV-Linkages projections (see Duval and de la Maisonneuve, 2009; Burniaux *et al.* 2008). The regional time profiles of LAP substances follow the OECD Environmental Outlook (OECD, 2008) for SO_2, NO_x and NH_3, and Bollen *et al.* (2007) for $PM_{2.5}$. It is assumed that existing regulations to control LAP will be maintained and will increase over time with increasing income, which partly explains the somewhat flat projected profile of most of these emissions (Figure 4).

[Figure 4. GHG and local air pollutants emissions in the baseline scenario]

4.2 The co-benefits of mitigation policies

38. Policies to mitigate GHG emissions will induce some reductions in local air pollutants. These cuts are expected to provide local benefits in terms of human health improvement to countries that mitigate their GHG emissions, regardless of other countries' actions. The purpose of this section is to assess the size of co-benefits in terms of reduced LAP, as well as the incentive they can provide for countries to participate in an international agreement to mitigate climate change. In order to estimate these co-benefits and the extent to which they vary with mitigation targets, three scenarios are considered where a global carbon price policy is assumed to be implemented to cut global GHG emissions in 2050 by 25%, 35% and 50% relative to their 2005 levels respectively.

GHG and LAP emissions reductions

39. With GHG abatement opportunities being cheaper in most non-OECD countries than in their OECD counterparts, GHG emission reductions in China and India are higher – although somewhat delayed - than in the OECD regions in the three scenarios. The allocation of these reductions across sectors is crucial for co-benefits, and depends on where the abatement opportunities are. In both absolute and relative terms, emissions reductions are highest in the power generation sector (Figure 5). In OECD countries, reductions in the transport sector start at the beginning of the period and are significant, while in non-OECD countries these reductions typically start after 2020. Emission reductions from household heat generation are relatively low in all countries.

[Figure 5. GHG emissions reductions by sector for a selected number of regions]

40. GHG emission cuts are found to induce reductions in LAP emissions (Figure 6). Reflecting the time pattern of GHG emission reductions, reductions in LAP emissions come later in most non-OECD countries than in their OECD counterparts. The delay in non-OECD countries also comes from the fact that, in these countries, cheapest GHG abatement opportunities are first in sectors with little influence on local pollutants, *i.e.* typically the electricity sector rather than the transport and household heating sectors (Figure 5). In particular, SO_2 emission cuts, which can be achieved through reduced oil combustion in the transport and household heating sectors, are relatively high in the OECD in the first 20 years but they are limited in non-OECD countries. By contrast, reductions in particulate matter are larger in India and China than in OECD countries, where PM emissions are low in the baseline as a result of the air quality policies that have been taken in the past.

[Figure 6. Reduction in air pollutant emissions induced by cuts in GHG emissions]

Co-benefits in terms of reduced numbers of premature deaths

41. Mitigation policies are found to reduce the number of premature deaths relative to the baseline scenario (Figure 7). For moderate reductions in global emissions (such as a 25% cut) and/or over relatively short horizons (such as up to 2020), the physical co-benefit of GHG mitigation policies is estimated to be smaller in China and India than in OECD (Figure 7, upper Panel). The time profile and size of physical co-benefits reflect those of local pollutant emission reductions (Figure 8). As already mentioned, co-benefits are lower in most non-OECD countries because GHG abatement first takes place in the electricity sector in these countries, with less implication for local air pollutants. Furthermore, LAP in OECD countries is mainly driven by the demand for transport services, whereas outside the OECD a major driving force is coal burning by households, which is expensive to reduce. Thus, the resulting GHG emission reductions have more impact on LAP in the former than in the latter group of countries. Finally, exposure to LAP is usually higher when pollution results from many small sources in transport and domestic sources than from large-scale power plants.

[Figure 7. Avoided premature deaths from reduced local air pollution through GHG mitigation policies]

[Figure 8. GHG emission reduction paths and avoided premature deaths]

42. However, for stringent emission cuts and/or over longer horizons, the physical co-benefits of mitigation action ultimately become higher in many non-OECD countries than in their OECD counterparts (Figure 7, middle and bottom Panels). As cheaper CO_2 abatement opportunities in the electricity sector in non-OECD countries get exhausted and OECD countries run out of options to reduce LAP through GHG mitigation policies, not least in the transport sector, abatements become significant in the transport and household energy consumption sectors in non-OECD countries and their co-benefits become larger.

Furthermore, while at the beginning of the period, the OECD population is comparatively older and more vulnerable to LAP than the population of India and China, this effect vanishes by the end of the period and beyond 2050 with population ageing in non-OECD countries.

Monetary co-benefits of climate change mitigation policies

43. Co-benefits in monetary units are first expressed per ton of CO_2eq to show their size independently of the amount of emission reductions. While the average co-benefit per ton of carbon cannot be directly compared to the carbon price - which is the marginal cost of abatement and as such exceeds the average cost - the analysis suggests that co-benefits could cover a sizeable part of mitigation costs in OECD countries (Figure 9). The monetised co-benefits of mitigation policies per ton of carbon are lower in non-OECD countries than in their OECD counterparts. This is both because physical impacts are lower in non-OECD countries for moderate GHG emission cuts and/or over shorter horizons, and because their VSL is lower especially at the beginning of the period. Co-benefits in non-OECD countries are projected to increase somewhat over time reflecting larger physical impacts with income growth and urbanisation, as well as higher VSL as GDP per capita in these countries progressively converges towards OECD levels.

[Figure 9. Co-benefits per ton of CO_2 equivalent and GHG emission prices]

44. Under a uniform carbon price scenario, GHG emissions reductions would be larger in non-OECD countries than in their OECD counterparts, and as a result overall co-benefits expressed as a percentage of GDP rapidly become larger in non-OECD countries in the 50% GHG emissions cut scenario (Figure 10).

[Figure 10. Co-benefits of reducing GHG emissions by 25% and 50% in 2050]

Avoided cost versus air pollution benefit

45. LAP co-benefits of climate mitigation policies provide some economic incentives for countries to participate in a global agreement to mitigate GHG emissions (''Window 1'' in Figure 1). In the coming decades, the benefits of climate change mitigation policies would be essentially the co-benefits since the direct benefits of mitigation policies are expected to occur in the longer run. More precisely, with the direct benefits of GHG mitigation policies being close to zero in the next few decades (up to 2050), the "size" of the co-benefits of mitigation policies can be expressed as follows with co-benefits valued in terms of avoided premature deaths:

Co-benefits size = GHG mitigation benefits + LAP co-benefits – GHG mitigation cost

≈ LAP co-benefits – GHG mitigation cost

46. The extent to which co-benefits can offset mitigation costs depends on the allocation of costs across countries and on the features of a global agreement, including in particular the world allocation of permits or, equivalently, emission reduction commitments. With a global carbon tax – or equivalently under full auctioning of emission permits, mitigation costs would be unevenly distributed, with most non-OECD countries facing the largest costs. As a result, even if the co-benefits are expected to be larger in most non-OECD countries for a stringent target in 2050, they would offset mitigation costs to a lesser extent than in OECD countries (Figure 11). With a different distribution of the cost of action, co-benefits could offset a much larger share of mitigation costs in non-OECD countries, and, they could possibly exceed them.[17]

17 . Co-benefits expressed in % of GDP are also very sensitive to the assumed VSL. With a VSL divided by two for instance, co-benefits would also be divided by two.

[Figure 11. Share of the GHG mitigation cost covered by local air pollution reduction co-benefits in 2050]

47. However, since many countries can be expected to pursue policies to reduce LAP anyway, the extent to which the co-benefits can convey incentives for GHG mitigation not only depends on the share of the mitigation cost that could be offset by the co-benefits but also on the cost of achieving the same level of reduction in LAP through direct policies, which represents an "opportunity benefit" (see Section 2). Therefore, instead of valuing LAP co-benefits in terms of premature deaths avoided, they could be valued in terms of the avoided cost of air pollution policies. Under such an approach, the size of co-benefits no longer depends on the VSL assumption, which is a controversial issue. Rather:

Co-benefits incentives = GHG mitigation benefits + LAP mitigation cost – GHG mitigation cost

≈ LAP mitigation cost – GHG mitigation cost,

with LAP and GHG mitigation costs corresponding to policies leading to the same level of reduction in local air pollution.

48. In order to determine the avoided cost of air pollution policies attached to co-benefits, model simulations are run to calculate the minimum cost of achieving the same reduction in health damage as in GHG mitigation scenarios through direct LAP policies. These illustrative simulations assume that all countries undertake simultaneous (but independent) action to restrict LAP.[18] In all regions, the avoided costs of LAP policies are much lower than the benefits of reduced air pollution. Therefore, although co-benefits are found to offset a significant share of GHG mitigation costs, they alone are unlikely to provide sufficient incentives to participate into a global GHG mitigation agreement in the next decades (Figure 12).[19] This is because there are alternative mitigation options to achieve the same level of reduction in air pollution at a much lower cost. In general, premature deaths can be reduced by relatively cheap end-of-pipe control technologies that have the potential to lower emissions of SO_2, NO_x, NH_3 and PM. However, co-benefits are found to provide a larger incentive to participate to developing countries than to developed ones.

[Figure 12. GDP impact of participating in a global climate change agreement to reduce GHG emissions by 50% in 2050]

4.3 Interactions between local air pollution and climate change mitigation policies

49. The analysis undertaken so far suggests that direct policies to address local air pollution can lead to the same LAP benefits as GHG mitigation policies but at a much lower cost. Since many countries have already started, or are planning to implement LAP control policies, one important question is whether and to what extent these policies may incidentally affect GHG emissions (''Window 2'' in Figure 1). If LAP control policies also have impacts on GHG emissions, then the issue of the optimal mix between LAP and GHG mitigation policies needs to be addressed (''Window 3'' in Figure 1). This section gives some results on the interactions between local air pollution and climate change mitigation policies.

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18 . Another option would have been to calculate the cost for each country to control LAP while other countries do not reduce LAP relative to baseline. The alternative assumption made here is likely to lower the cost of direct policies to control LAP because global action against LAP tends to lower oil demand and price and thereby to reduce the cost of these policies.

19 . However, over a longer horizon (2100), the gains from GHG mitigation policies are expected to be large and to outpace mitigation costs.

The impacts of LAP policies on GHG emissions

50. In order to assess the impacts of LAP policies on GHG emissions, a scenario with a 25% reduction in the world number of premature deaths in 2050 relative to 2005.[20] Because this target is very stringent and does not result from economic optimisation, the scenario should be seen as illustrative. It implies large reductions in all local air pollutants. In all regions, emission reductions are the highest in the electricity sector, but reductions in the transport sector are also significant, in particular in India and to a lesser extent in China.

51. This illustrative scenario where all countries take joint (but independent) actions to drastically reduce local air pollution shows that LAP policies have the potential to substantially lower GHG emissions (Table 3). Even if countries did not join in an international climate change mitigation agreement, they might still reduce GHG emissions largely as a side effect of their LAP control policies, provided that relatively stringent LAP targets were adopted. This is because large reductions in LAP cannot be achieved only through end-of-pipe measures which have no effect on GHG emissions. Improvements in energy efficiency would also be needed, leading to significant reductions in GHG emissions.[21] The largest GHG reductions are found in India and China.[22]

[Table 3. Local air pollutants and GHG emissions reductions relative to baseline levels in a local air pollutants mitigation scenario]

Synergies between LAP policies on GHG emissions

52. Since both GHG and LAP mitigation policies have externalities in terms of LAP and GHG emissions respectively, a combined policy is likely to be optimal. In order to assess the optimal mix between LAP and GHG mitigation policies, the model is run in the "cost-benefit mode" (see Section 4.1). The externalities from both policies are fully internalised by agents (regions), and the mix of policies is endogenously determined by taking into account their benefits and costs. The optimal policy mix is achieved when the marginal discounted consumption loss from GHG and LAP mitigation are equal to the marginal discounted avoided damage from LAP and climate change.

53. The optimal policy mix is found to entail less GHG emission reductions than in the scenario where these are cut by 50% in 2050 (relative to 2005 levels), but more reductions in LAP than those induced by this scenario (Figure 13). As a result, this optimal policy mix leads to more LAP benefits and less climate benefits because GHG emissions are cut by less than 50%.[23] However, it should be acknowledged that this finding is highly sensitive to VSL as well as to discount rate assumptions since LAP benefits are expected to be felt earlier than climate benefits.

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20 . This corresponds to a reduction by 70% in 2050 relative to BAU level.

21 . Similar results are found by Reilly *et al.* (2007) who analyse the impact on crop production of controlling GHG and/or LAP, including tropospheric ozone and find that once LAP is capped, benefits to cap GHG emissions in addition are small because the positive effect of an increase in levels of atmospheric carbon dioxide on plants through stimulated photosynthesis (the fertilisation effect) would then be lost, although there are uncertainties on this effect.

22 . The impact on temperatures of these GHG emissions cuts would be somewhat offset by the fact that, in order to achieve the LAP reduction target, it is optimal to lower SO2 emissions, which has a cooling effect on temperatures. The partial loss of this cooling effect is found to be significant, thereby lowering the impact of global LAP policies on climate change mitigation.

23 . It is also because of larger reductions in SO_2 emissions in this scenario, which have a cooling effect, offsetting part of the climate benefit achieved through GHG emissions cuts.

[Figure 13. GHG and local air pollutants emissions in an optimal policy mix scenario compared with a GHG mitigation scenario]

54. The allocation of GHG emission reductions across regions also depends on whether the externality associated with the co-benefits of GHG mitigation policies is fully internalized or not. This is because regions with least cost opportunities to lower GHG emissions – *i.e.* mainly non-OECD countries – are not those where co-benefits are expected to be highest, at least for moderate target and/or on a medium-run horizon (see above). Therefore, an optimal policy mix will tend to imply relatively larger GHG emission reductions in OECD countries in part due to larger co-benefits, compared to a situation where the co-benefit externality is not internalised. As a result, mitigation costs would be larger but these will be more than offset by larger benefits.

5. Limits to the empirical analysis and conclusion

55. The findings in this paper should be interpreted with care given the various uncertainties surrounding the analysis. Uncertainties come not only from the main modelling assumptions but also from existing restrictions to the analysis. For the uncertainties concerning parameters of the model, a sensitivity analysis was undertaken to understand the impacts of alternative assumptions on results. The main uncertainties considered are the following:

- The value of statistical life used to assign a monetary value to avoided premature deaths is an uncertain and controversial parameter (see Jamet and Corfee-Morlot, 2009). It strongly determines the size of the co-benefits. The co-benefits expressed in $US per ton of carbon or in percentage of GDP linearly depend on this value. The value used here is the median value across a range of estimates used in the context of environmental studies. Estimates obtained in the labour market literature are higher and would lead to accordingly higher estimates of co-benefits. However, the incentives attached to co-benefits do not depend on the VSL since co-benefits are valued in terms of avoided costs of policies to control LAP and not in terms of avoided premature deaths.

- The results are also sensitive to the income elasticity of VSL, which is assumed here to be equal to one but could be lower (Viscusi and Aldy, 2003 and 2007). A lower value (0.5) would imply a higher VSL for non-OECD countries at the beginning of the period with the VSL being increased by a factor of 2.5 to 4 but the gap would lower over time.

- The social discount rate plays a crucial role when present discounted values of impacts are calculated and/or when optimal policy mixes are explored. In order to mitigate the impact of this parameter, results are either presented in a particular year (2050), or the whole path of co-benefits is shown. However, results on the optimal policy mix between LAP and GHG mitigation policies are influenced by the social discount rate. In particular, a higher discount rate would lower the weight of climate change mitigation benefits relative to those from LAP control policies, thereby leading to lower GHG emission reductions and larger LAP cuts.

- While the analysis uses the only existing model that incorporates LAP and its impacts on health within a dynamic general equilibrium framework, the LAP extension of the model is not very detailed and relies on some simplistic assumptions. LAP is modelled at a fairly aggregate level and the sectoral characteristics of local air pollutants are not fully incorporated.[24]

24 . For instance the LAP extension of the model is much less detailed than in the RAINS model (Amann *et al.* 2002), which however does not have a general equilibrium structure.

- The impacts expressed in terms of avoided premature deaths strongly depend on the coefficient that attributes a particular risk of premature deaths to a given level of LAP concentration. This parameter is calibrated based on the relatively low concentration levels of PM2.5 found in the United States (see Pope *et al.* 2002). Insofar as it turns out to be smaller (higher) for higher concentration levels, the size of the co-benefits estimated here would be biased upwards (downwards).

- The relationship between PM emissions and health is assumed to be linear. However, low emission levels are likely to have little influence on health. Assuming a linear relationship may lead to an overestimate of premature deaths and, hence, of monetary impacts.

56. In addition to uncertainties on model parameters, there are several restrictions to the analysis. The analysis focuses on the co-benefits of mitigation policies in terms of reduced LAP and does not include other co-benefits. As in the rest of the literature, the estimates omit the possible co-effects of GHG mitigation on indoor air pollution (cooking smoke) from biomass and coal, which might turn out to be a co-cost, at least in the short to medium term. Furthermore, the modelling analysis does not include ozone, which is a local pollutant with possibly large impacts on health (and agriculture), and which would be lowered by GHG mitigation policies since some GHG are ozone precursors. On the whole, the net effect of these uncertainties and restrictions on simulations results and their implications for policy are not clear.

57. Nonetheless, the paper's findings point to the need of a comprehensive treatment of co-benefits in terms of health, ecosystems, crop yields and climate impacts in the long-term. Macroeconomic assessment of co-benefits could be improved through:

- *Integrated strategy assessments in a general equilibrium framework*. The interactions between pollutants in the atmosphere call for studies that look at the co-benefits for climate and for local pollution that can be derived from a multi-gas mitigation policy taking into account such interactions. The scientific literature has paved the way for such assessments but co-benefits assessments using CGE modelling have yet to include all of the known effects. This would make it possible to compare the net return from GHG mitigation with the net return from local pollutant mitigation thus opening the way towards the integrated policy solutions (Window 3).

- *Inclusion of other pollutants (e.g. ozone) and indoor as well as outdoor air pollution*. For example, modelling the relation between climate change policies (*i.e.* carbon prices) and indoor air pollution would provide a significant improvement in the scope of the co-effects covered and greatly improve a co-benefits assessment. This will require more micro scale analysis of indoor environments and non-commercial cooking fuel choices (mostly biomass).

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Table 1. Scenario and Results of Studies Reviewed

Study	Scope	Modelling	Scenarios	Average co-benefits $/tC	GHGs and Pollutants	Major Effects
Bollen *et al.* 2007	Global to 2100	Computable general equilibrium model (CGE) MERGE Model– adapted for Local Air Pollution	Cost-benefit optimization of global climate change mitigation as well as Local Air Pollutants mitigation	Results expressed in terms of the percentage change of the total discounted stream of consumption. Benefits of local air pollution reduction may outweigh those of global climate change mitigation. Simultaneous inclusion of both CC and LAP externalities results in an additional energy-related CO2 emission reduction (more than the sum of the application of either policy alone) of 15 % in Western Europe and 20 % in China.	PM2.5 from: - Old power plants (coal and oil) -Non-electric applications -Transport -Chemical products -Total primary energy	Mortality from Air Pollution (Number of people prematurely dying from chronic PM exposure)
Bussollo and O'Connor 2001	India to 2010	CGE, Indian economy ten years forward to 2010	Carbon tax scenarios 66$ yielding 15% CO2 reduction by 2010. No policies are implemented for air pollution. Existing standards not enforced.	**$58/tC** (at 1995 exchange rate). No regret (*i.e.* where marginal benefits equal marginal costs) is around 17-18% GHG emission below baseline. With a 15% reduction in emissions from baseline, 334 lives are saved per Mt of reduction.	PMs caused by SO_2 NOx from fossil fuels. (biomass is excluded)	Mortality and morbidity from Air Pollution
O'Connor *et al* 2003	China to 2010	CGE model of the Chinese economy to 2010.With a focus on differentiating Guangdong from the rest of China	Carbon tax scenarios 5-65$ (7$ tax yielding 5% emission reductions by 2010; 24$ tax yielding a 15% CO2 reduction by 2010).	**9$/tC (1997 exchange rate)** = 210 lives per MtC reduction. Co- benefits from reduced crop damage are nearly as large. Without crop: 5 % “no regrets” abatement rate of baseline emissions in 2010. Under the with-crop scenario, “no regrets” 15% to 20% reduction from 2010 baseline emissions.	PMs and O_3 caused by SO_2 and NOx from fossil fuels	Mortality and morbidity from Air Pollution Agricultural productivity effects

Table 1. Scenarios and results of studies reviewed (*continued*)

Study	Scope	Modelling	Scenarios	Average co-benefit $/tC	GHG and Pollutants	Major Effects
West *et al.* (2006)	Global to 2030	No CGE modeling	Reducing global anthropogenic Methane (CH_4) emissions cut by 20% starting in 2010. Results in 2030	12 US$/tCO2eq. or $44/tC CH_4 cut by 20% prevents 30,000 premature all-cause mortalities globally in 2030, and approximately 370,000 between 2010 and 2030.	O_3 caused by Methane	Premature human mortality that can be attributed to lower surface ozone concentrations.
West & Fiore (2005)	Global to reductions to 2010 (2030 results or effects)	No CGE modelling	Global reduction in 2010 of 59 Mton CH_4 /yr (range 49-72 Mton CH_4 /yr, using IEA data).* Results in 2030 This corresponds to a "no regret" strategy (where marginal benefit equals marginal cost), achieving about a 17% (15-21%) reduction of current annual anthropogenic CH_4 emissions	3.9 US$/tCO2 eq. (range of $2.3-5.5) or 14 US$/tCeq (range of $8.3-20), 5% per yr real discount rate. .	O_3 caused by Methane	agriculture, forestry, and only non-mortality ozone benefits on human health (reduced morbidity)
Reilly et al 2007	Global to 2100	MIT IGSM integrated model (including a developed climatic model, a local air pollution model and an economic model)	GHG reduction scenarios (550ppm in 2100) and local pollutant reduction scenarios	Crop yield effects in 2100 relative to 2000: -40 to - 60% in a baseline in which GHG and LAP emissions are not capped. Close to -20% if GHG emissions are capped +20% if LAP emissions are capped alone and if GHG and LAP emissions are capped simultaneously	All GHG, Tropospheric Ozone from all pathways (Knox, NMVOC, CO, and CH_4)	Global Crop Yields Forestry Yields and Pasture Yields

Table 1. Scenarios and results of studies reviewed (*continued*)

Study	**Scope**	**Modelling**	**Scenarios**	**Average co-benefits $/tC**	**GHGs and Pollutants**	**Major Effects**
Shresta et. al 2002 (one of many Studies using AIM Framework)	Vietnam to 2020	AIM Integrated Assessment model (CGE)	BAU scenario is compared to CO2 emission reduction targets of 5%, 10% and 15% by 2020	SO_2 emission in the 5%, 10% and 15% CO2 reduction cases would decrease by 13%, 22% and 33% respectively as compared with that in reference scenario. Tax instrument to reach target: 5% :$9.2/ tCO_2 10%:25.7tCO_2$ 15%:58.3tCO_2$	CO_2, SO_2, NO_2	Emission reduction in physical terms
Van Harmelen et al 2002	Europe with European part of USSR to 2100	TIMER energy model (no general equilibrium effect) extended to SO_2 and NOx. Bottom up features for add-on technologies	GHG reduction scenario: Special Report on Emission Scenarios (SRES) IPCC 2001 scenario A1 and B1. (year 2100) Air Pollution Baseline: 1)Gothenburg protocol 2) Reduction rate increases after 2010 following a logistic function up to a maximum value (95% for SO_2 and 85% for NOx).	LAP control costs averaged over the century can be reduced by climate mitigation measures by 50–70% for SO_2 and around 50% for NOx. The costs of SO_2 and NOx mitigation by add-on technology are comparable or in some periods even higher than the costs of an integrated mitigation of SO_2, NOx and CO_2 emissions. Avoided costs of SO_2 and NOx can outweigh the costs of these climate measures.	CO_2, SO_2 ,NOx	Avoided costs of implementation in monetary terms

Table 1. Scenarios and results of studies reviewed (*continued*)

Study	Scope	Modelling	Scenarios	Average co-benefits $/tC	GHGs and Pollutants	Major Effects
Van Vuuren *et al.*2004	Europe (Kyoto period)	Integrated model -climate policy model (FAIR) -energy model (TIMER) -regional air pollution model (RAINS)	Three different Kyoto implementation strategies to cut GHGs: Domestic Action (unilateral achievement of targets), Restricted Trade (without use of surplus allowances from countries with economies in transition), Normal Trade (full use of emission trading) Air pollution: achievement of Gothenburg Protocol and the EU National Emission Ceilings Directive.	European CO_2 emissions cut by 4–7% leads to a decrease in European emissions of SO_2 by 5–14% compared with a no Kyoto policies case. Total cost savings for implementing current policies for regional air pollution of the Kyoto Protocol are of an order of 2.5–7 billion Euros. In all cases, this is in the order of half the costs of the climate policy (4–12 billion Euros). Using emission trading mechanism reduces emissions of air pollutants for Europe as a whole even further than domestic implementation (*e.g.* 10–14% versus 5% for SO_2 emissions)	CO_2, SO_2, NOx, VOC, PM	Avoided costs of implementation in monetary terms

Table 2. Characteristics of the portfolio of technologies available in the MERGE model

Non-Electricity sector						
			Emission coefficients			
Date of availability	**Technology**	**Cost in 2000** $/GJ	**Carbon** t/GJ	**SO2** t/GJ	**NOx** t/GJ	**PM** t/GJ
Available	Coal direct use	2.5	0.024	0.34	0.22	0.12
Available	oil production at alternative cost levels	3.0-5.3	0.02	0.15	0.035	0.017
Available	Coal production at alternative cost levels	2.0-4.3	0.014	0	0.35	0
Available	Renewable	6	0	0	0	0.011
	Carbon free technology	14, decreasing to 6	0	0	0	0
Electricity sector						
			Emission coefficients			
Date of availability	**Technology**	**Cost in 2000** Mills/kWh	**Carbon** Bn tons/TWH	**SO2** Mt/TWh	**NOx** Mt/TWh	**PM** Mt/TWh
Available	Hydroelectric and geothermal	40	0	0	0	0
Available	Existing nuclear	50	0	0	0	0
Available	Existing gas fired	36	0.14	0	0.26	0
Available	Existing oil fired	38	0.21	1.87	0.40	0.01
Available	Existing coal-fired	20	0.25	0.99	0.42	0.01
2010	New gas-fired	13	0.09	0	0.23	0
2020	Advanced gas-fired with CO_2 capture and sequestration	30	0	0	0	0
2010	New coal-fired	41	0.2	0	0.35	0
2050	Advanced coal-fired with CO_2 capture and sequestration	56	0.01	0.029	0.01	0
2030	Integrated gasification combined cycle with CO_2 capture and sequestration	62	0.02	0.04	0.23	0
2010	Carbon free technology	100 decreasing to 5	0	0	0	0

Source: Bollen *et al.* (2009)

Table 3. Local air pollutants and GHG emission reductions relative to baseline levels in a local air pollutants mitigation scenario

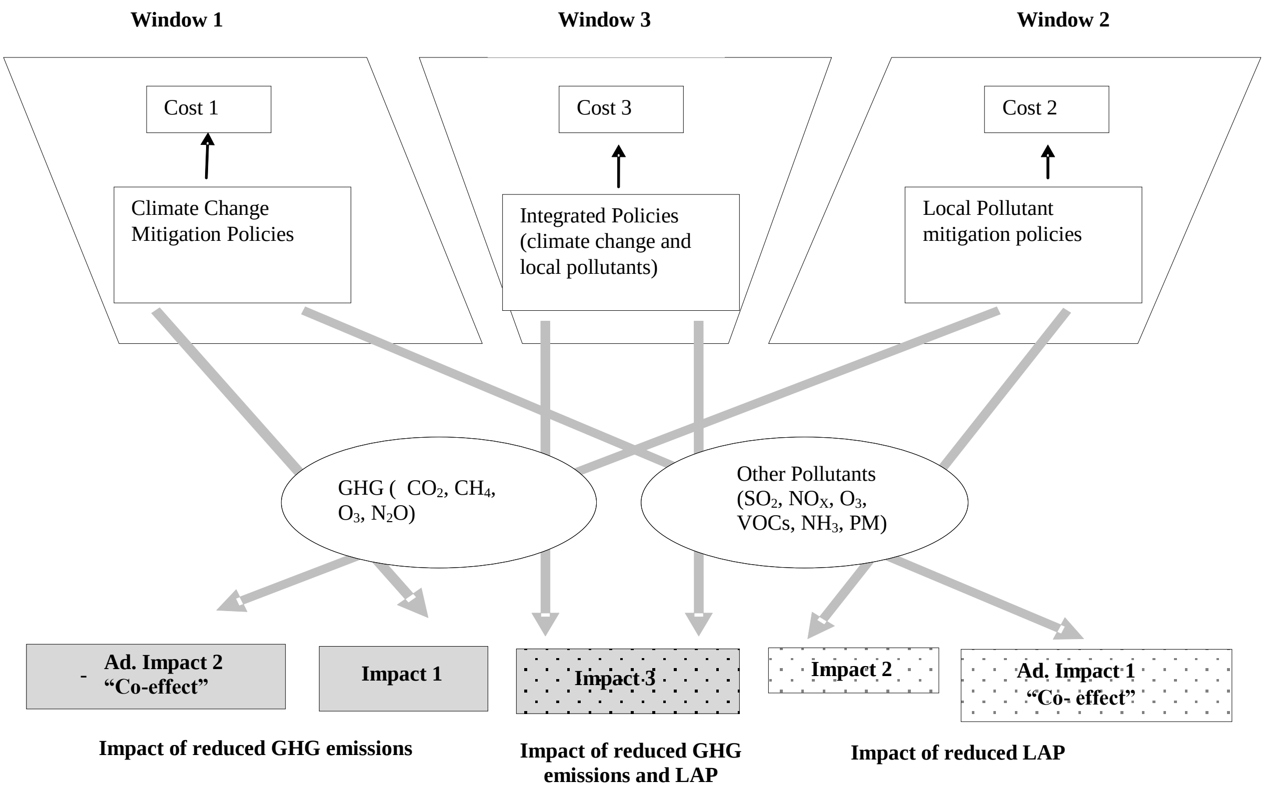
Achieved reductions relative to baseline levels when LAP is controlled to reduce premature deaths by 25% in 2050 relative to 2005 level (%)

	LAP emissions reduction by substance				Implied reduction in premature deaths
	SO_2	NO_x	NH_3	PM	
OECD	73	65	43	72	65
India	88	79	66	97	74
China	78	60	57	95	70

	LAP emissions reduction by sector				Implied GHG emissions reduction	
	Transport	Electricity	Household heating	Process	CO_2 eq.	CO_2
OECD	72	93	51	60	38	37
India	91	99	73	73	61	71
China	82	99	62	67	42	45

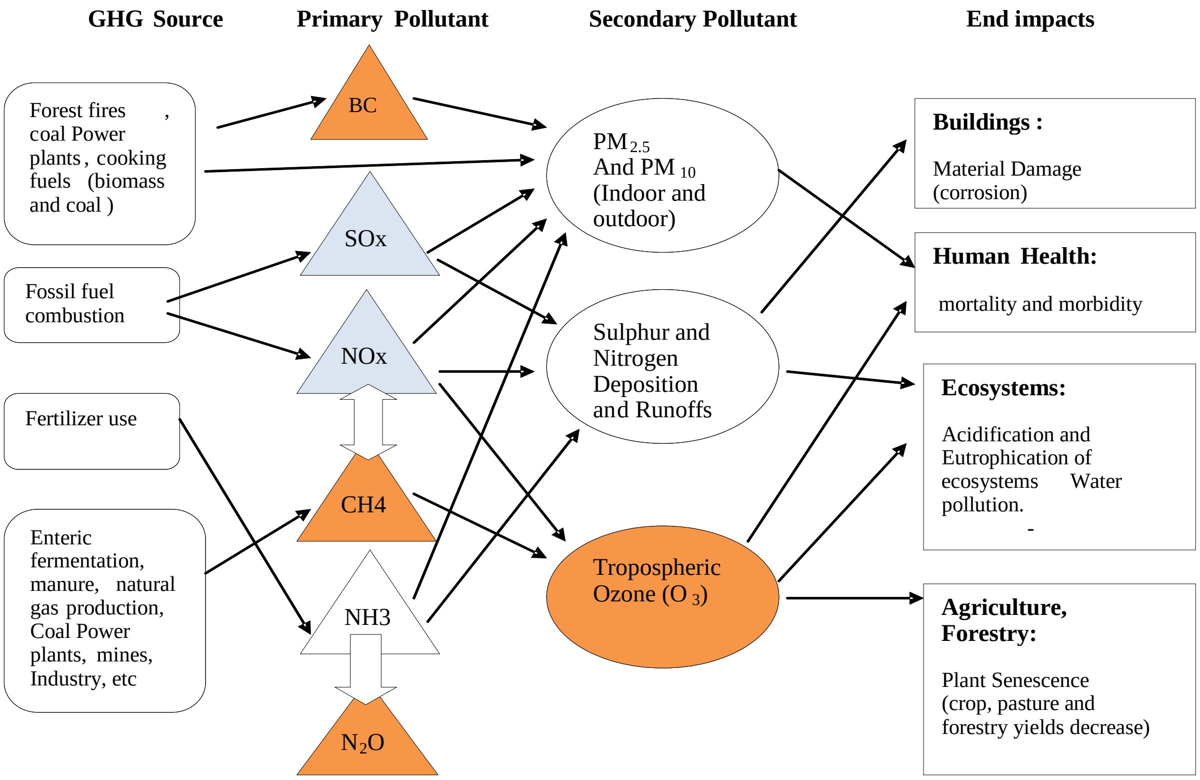
Source: Bollen *et al.* (2009)

Figure 1. Three windows in the analysis of co-benefits



Source: OECD

Figure 2. Summary of Pollutant Channels[1]

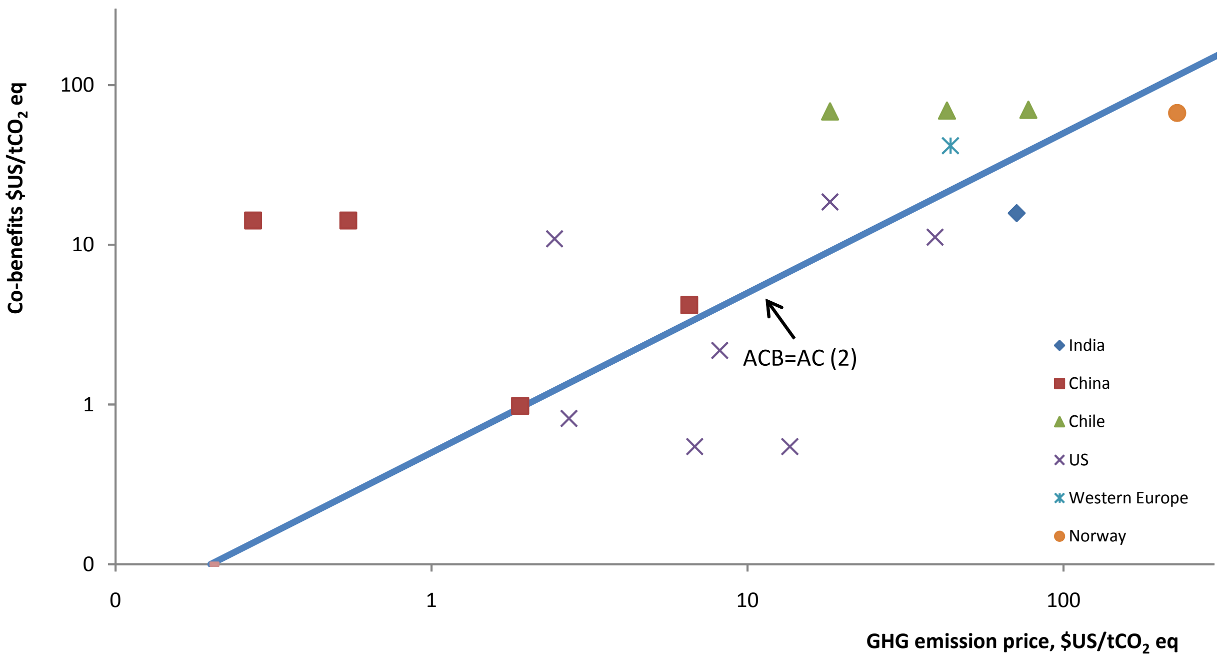


1. The gases shown in dark colour exert a positive effect on temperatures, while those in light colour negative effect. The white arrows mark the most important interactions between pollutants. Primary pollutants are directly injected in the atmosphere while secondary pollutants are formed in the atmosphere through chemical and photochemical reactions from the primary pollutants. BC denotes black carbon.

Source: OECD

Figure 3. Review of existing regional estimates of the co-benefits in 2010 at different GHG emission prices

($US/ton of CO_2 eq[1])

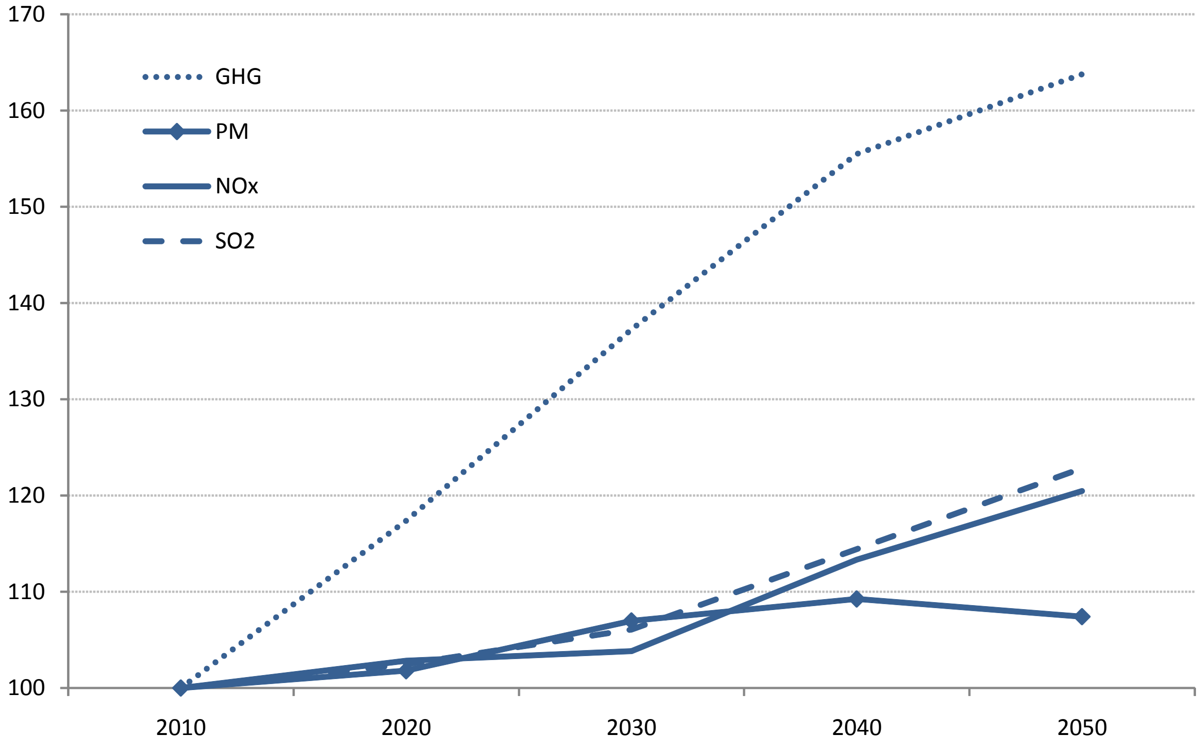


1. For each country, observations represent estimates from various studies and/or for various carbon prices. The base year for estimates is 1996 or the latest available year.

2. The line "ACB=AC" indicates a situation where the average co-benefit is equal to the average cost of abatement. It assumes that abatement costs are a square function of emission reductions; average costs can then be computed as one half of marginal costs (i.e the carbon price). Points above this line indicate situations where the average co-benefit is higher than the average cost.

Source: OECD.

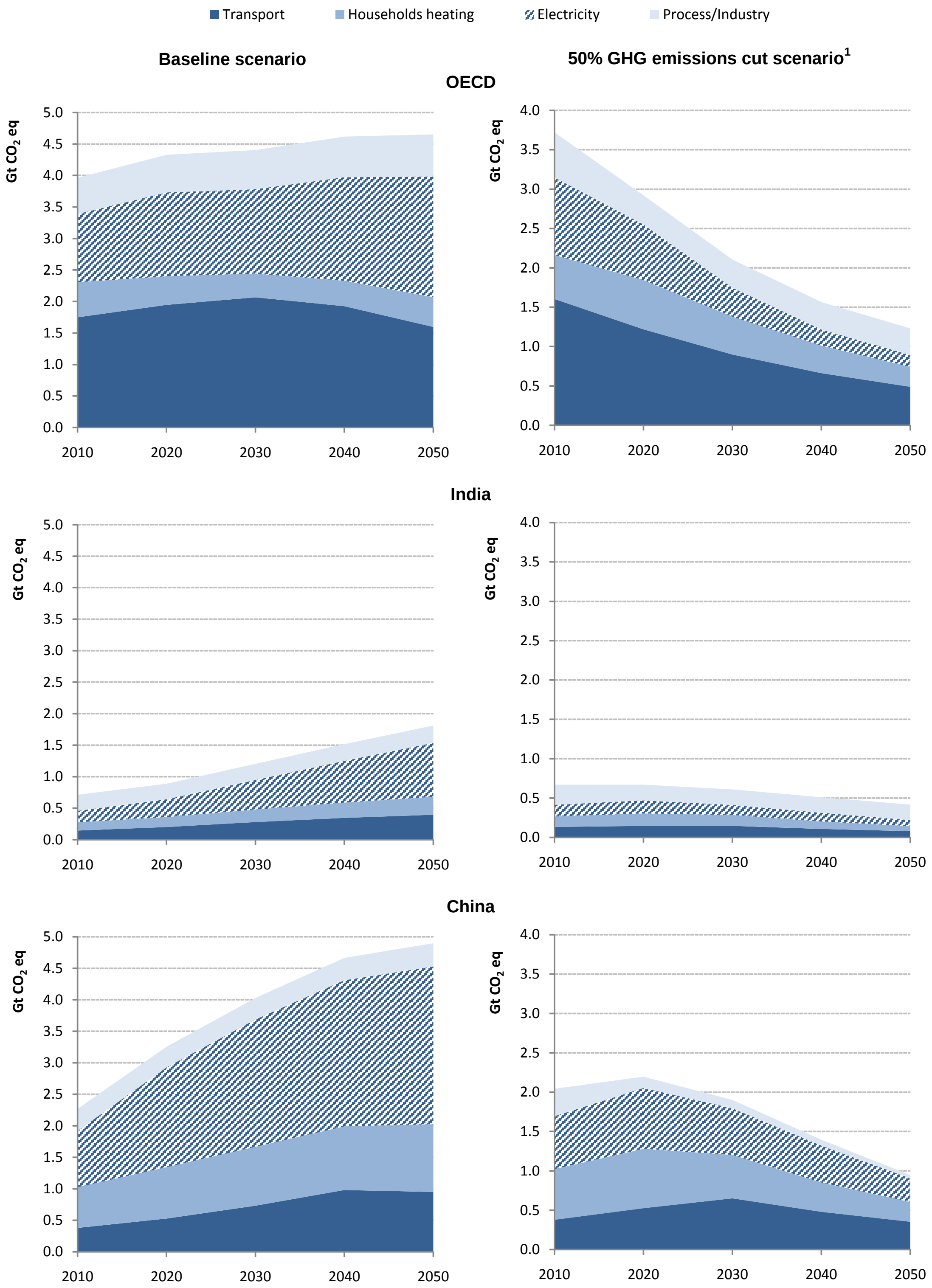
Figure 4. GHG and local air pollutant emissions in the baseline scenario
(Index 2010=100)



Source: Bollen *et al.* (2009).

Figure 5. GHG emission reductions by sector for a selected number of regions

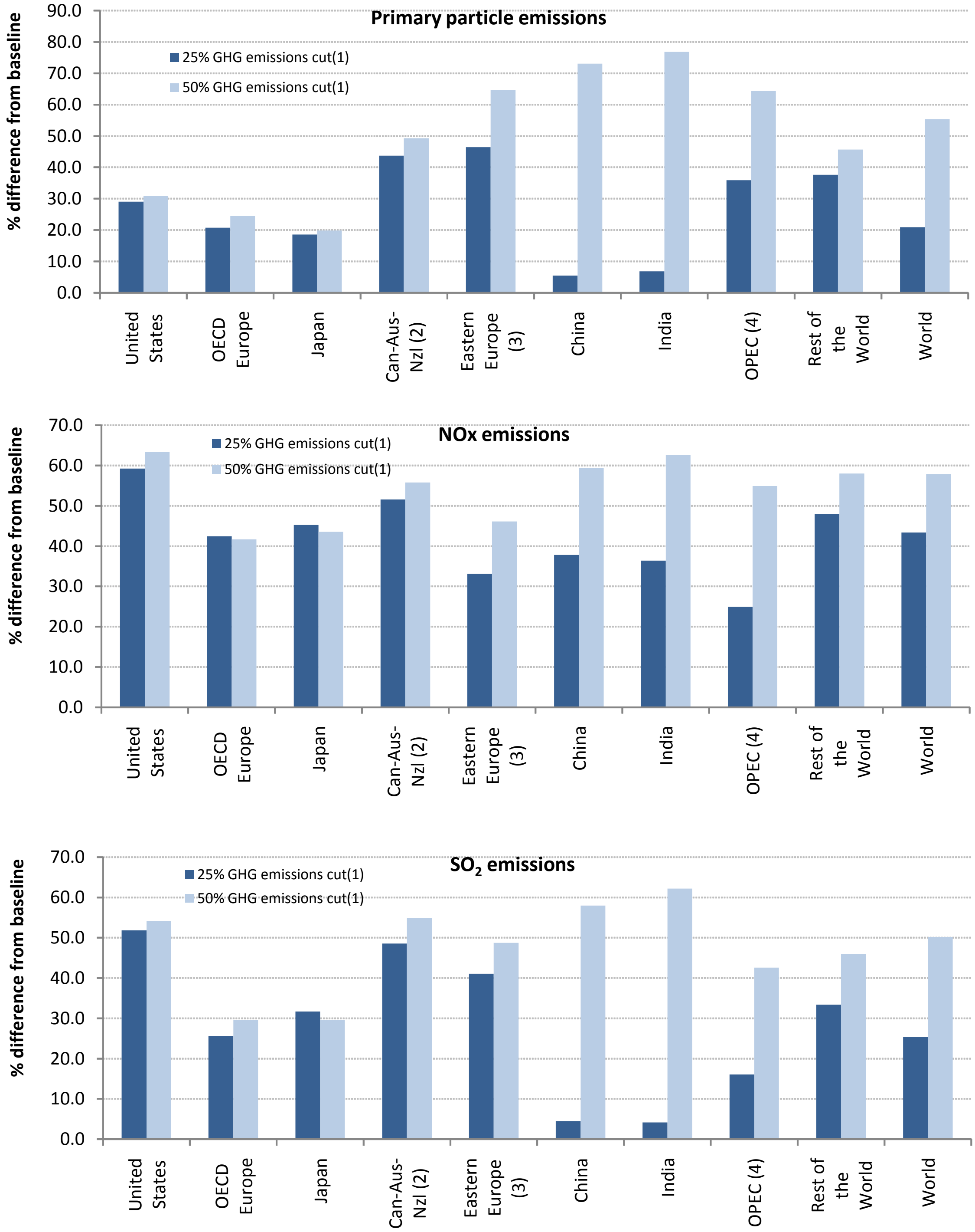
(GHG emissions in the baseline scenario and in a scenario where emissions are cut by 50% relative to 2005 levels in 2050)



1. Relative to 2005 levels.
Source: Bollen *et al.* (2009).

Figure 6. Reduction in air pollutant emissions induced by cuts in GHG emissions

(% difference from baseline)



1. Relative to 2005 levels.

2. Canada, Australia and New Zealand are in the same geographical area in the MERGE model.

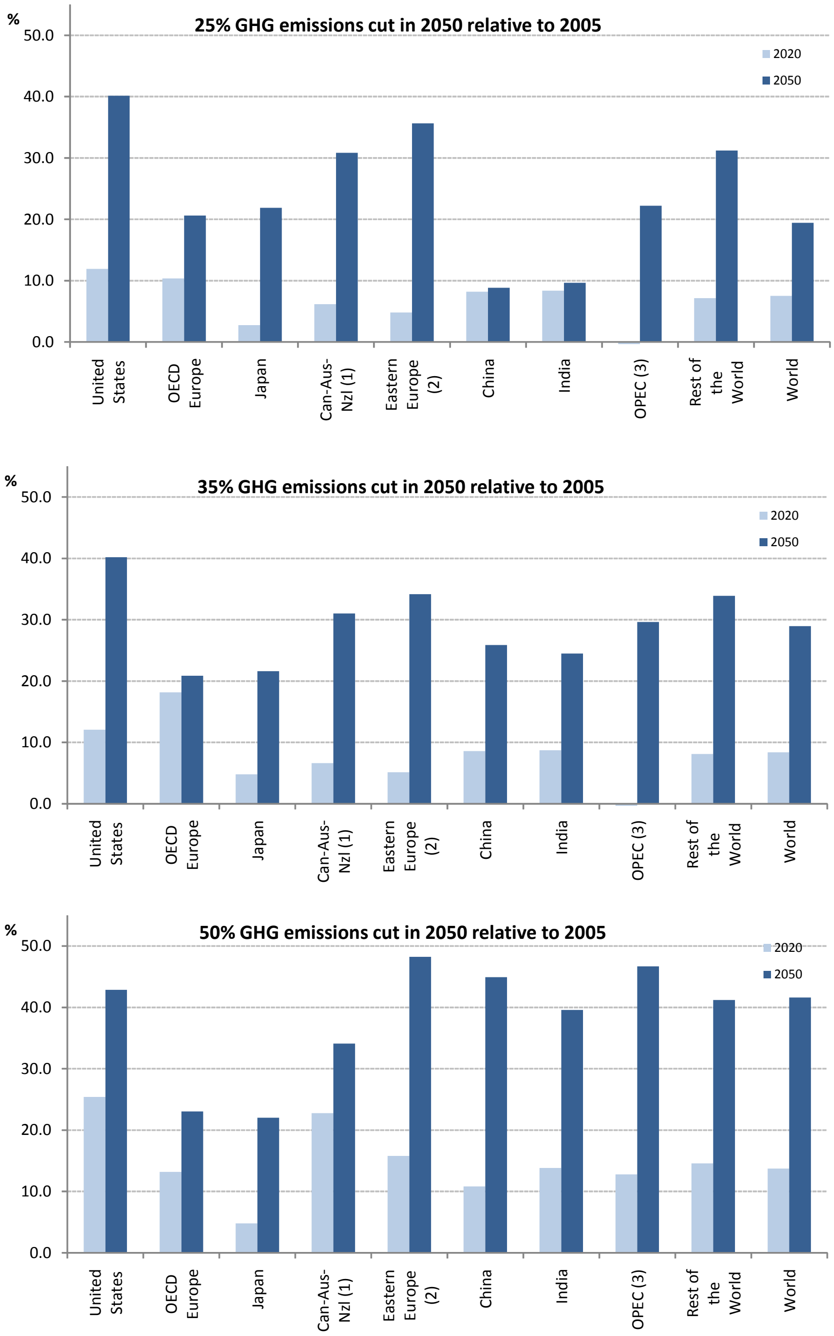
3. Including Russia.

4. Including Mexico.

Source: Bollen *et.al* (2009).

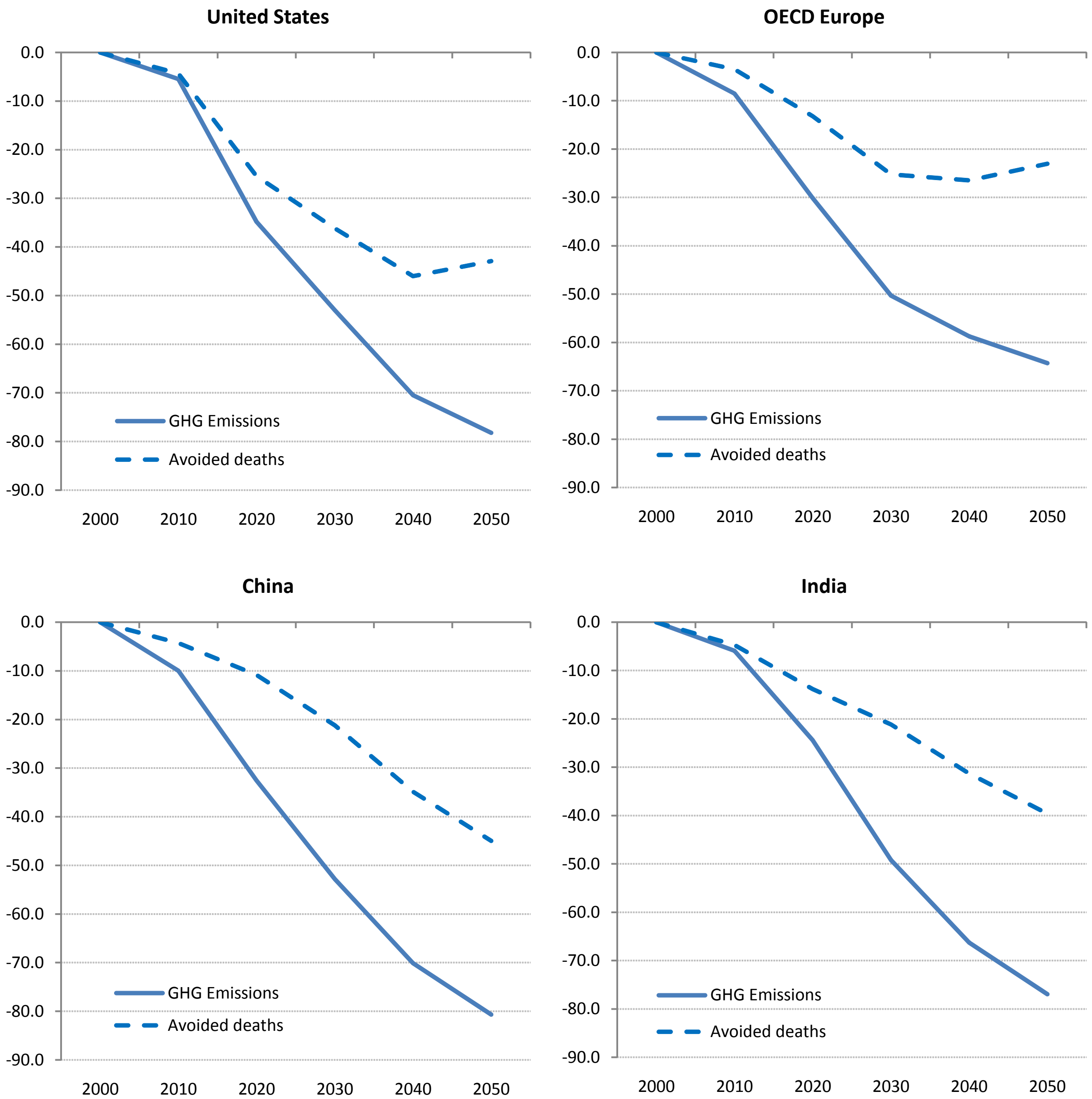
Figure 7. Avoided premature deaths from reduced local air pollution through GHG mitigation policies

(% differences from baseline)



1. Canada, Australia and New Zealand are in the same geographical area in the MERGE model.
2. Including Russia.
3. Including Mexico.
Source: Bollen *et al.* (2009).

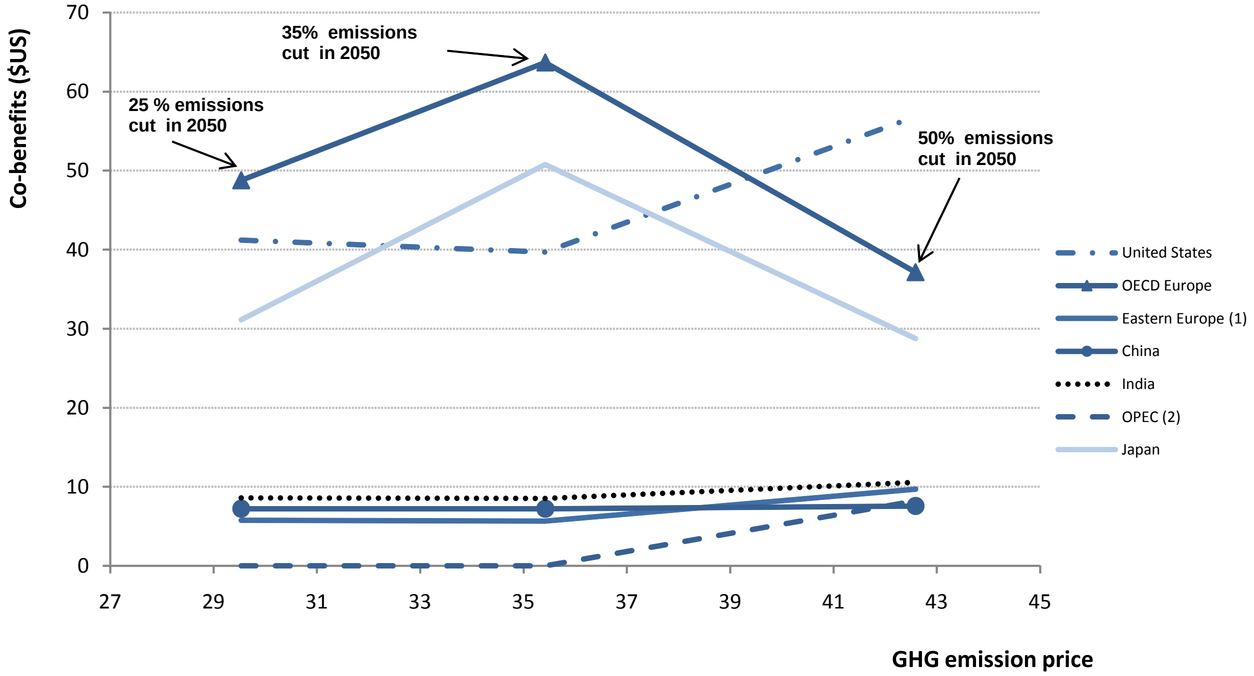
Figure 8. GHG emission reduction paths and avoided premature deaths[1]
(% differences from baseline)



1. "50% GHG emissions cut in 2050 relative to 2005" scenario.
Source: Bollen *et al.* (2009).

Figure 9. Co-benefits per ton of CO_2 equivalent and GHG emission prices

2020, $US per ton of CO_2 eq



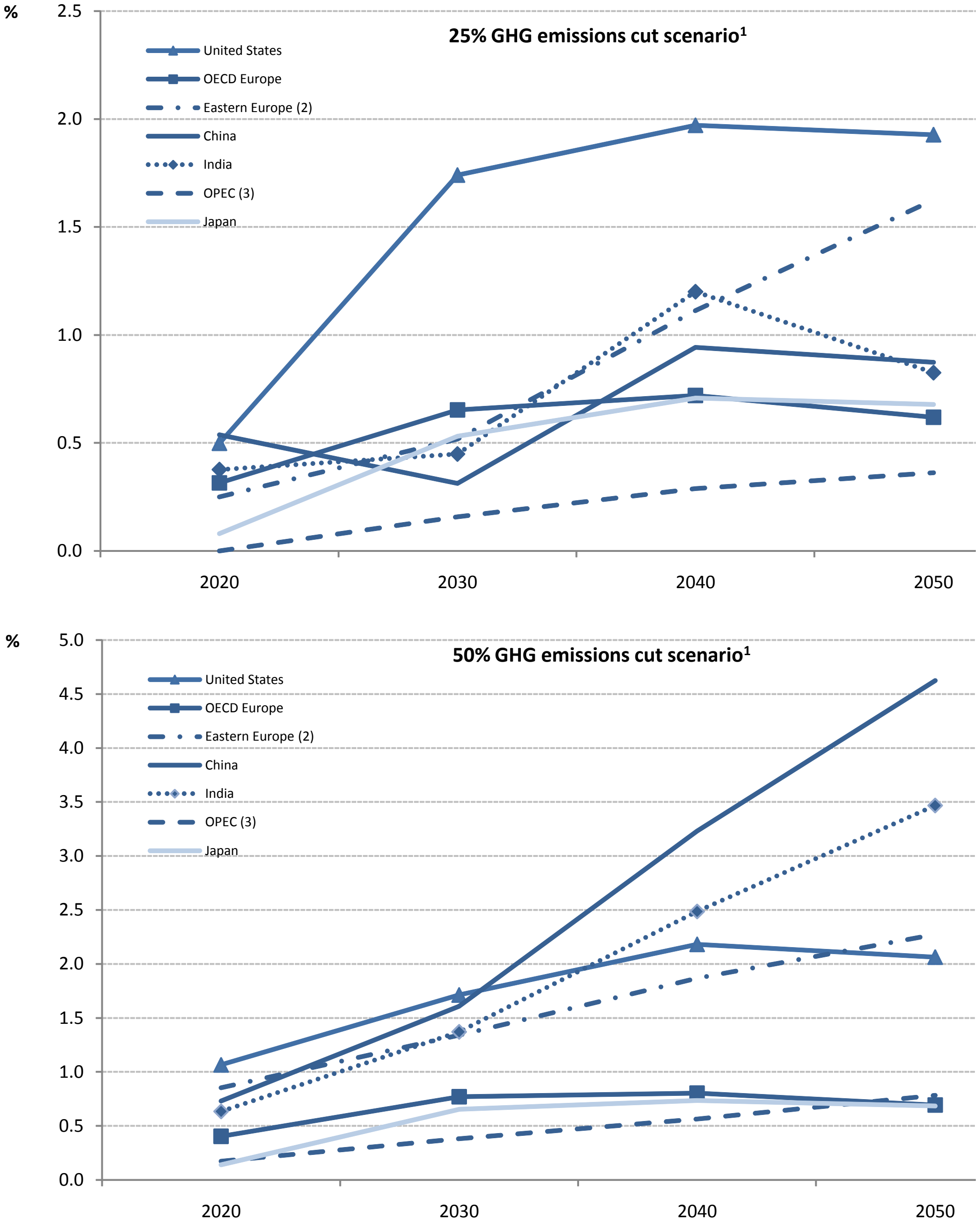
Note: Co-benefits per ton of CO_2 eq reflect an average co-benefit while the carbon price reflects the marginal cost of abatement, which exceeds the average cost. Therefore, their values are not directly comparable.

1. Including Russia.
2. Including Mexico.

Source: Bollen *et al.* (2009).

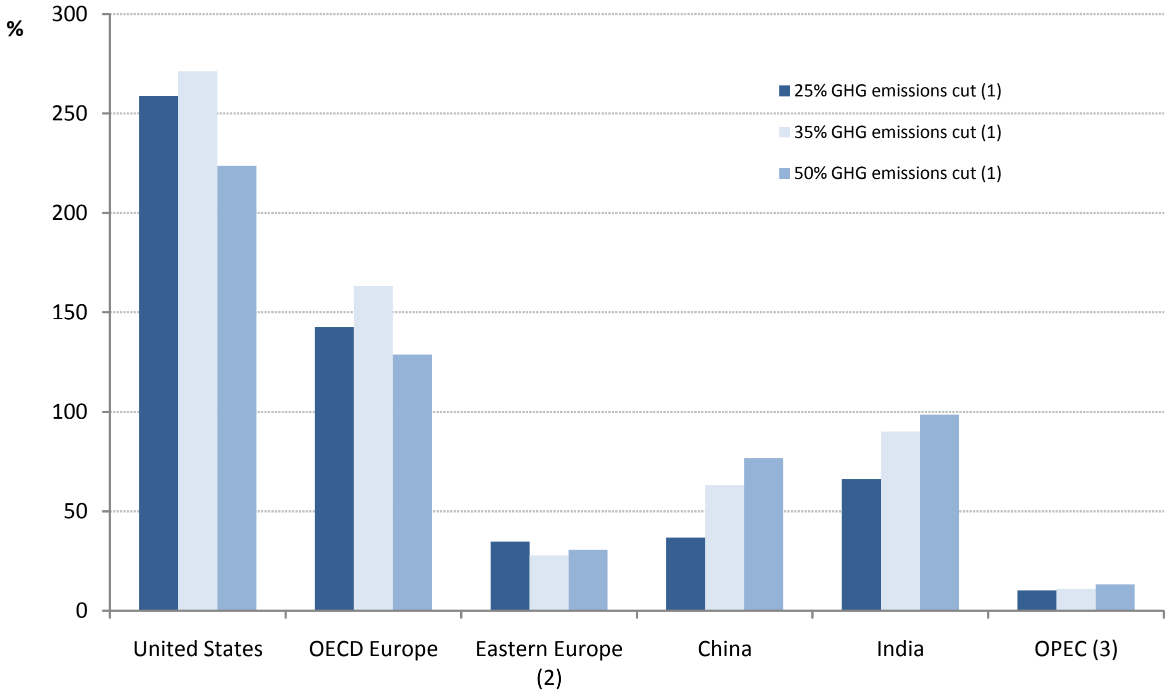
Figure 10. Co-benefits of reducing GHG emissions by 25% and 50% in 2050

(% of GDP)



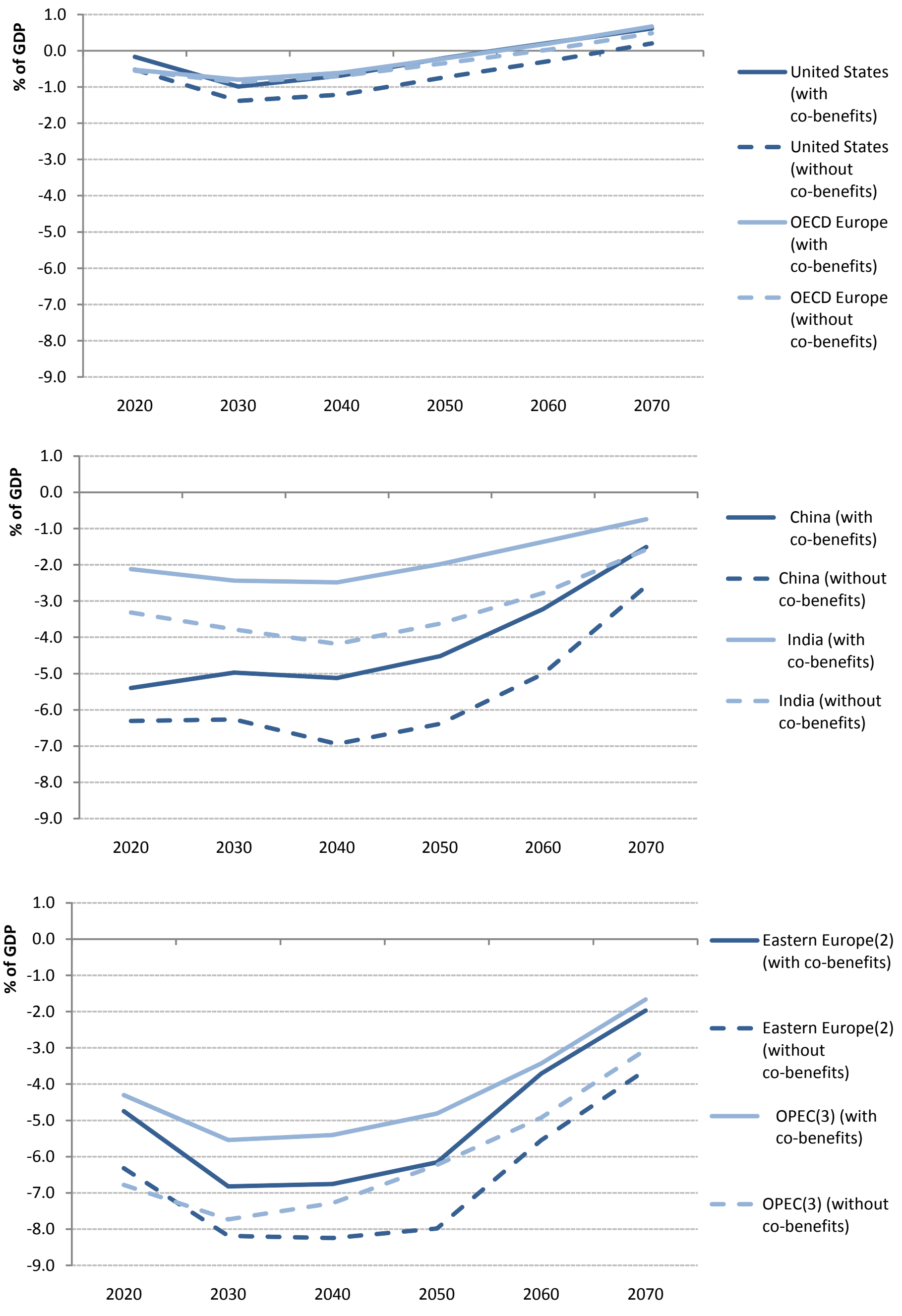
1. Relative to 2005.
2. Including Russia.
3. Including Mexico.
Source: Bollen *et al.* (2009).

Figure 11. Share of the GHG mitigation costs covered by local air pollution reduction co-benefits in 2050, in percentage



1. Relative to 2005 levels.
2. Including Russia.
3. Including Mexico.
Source: Bollen *et al.* (2009).

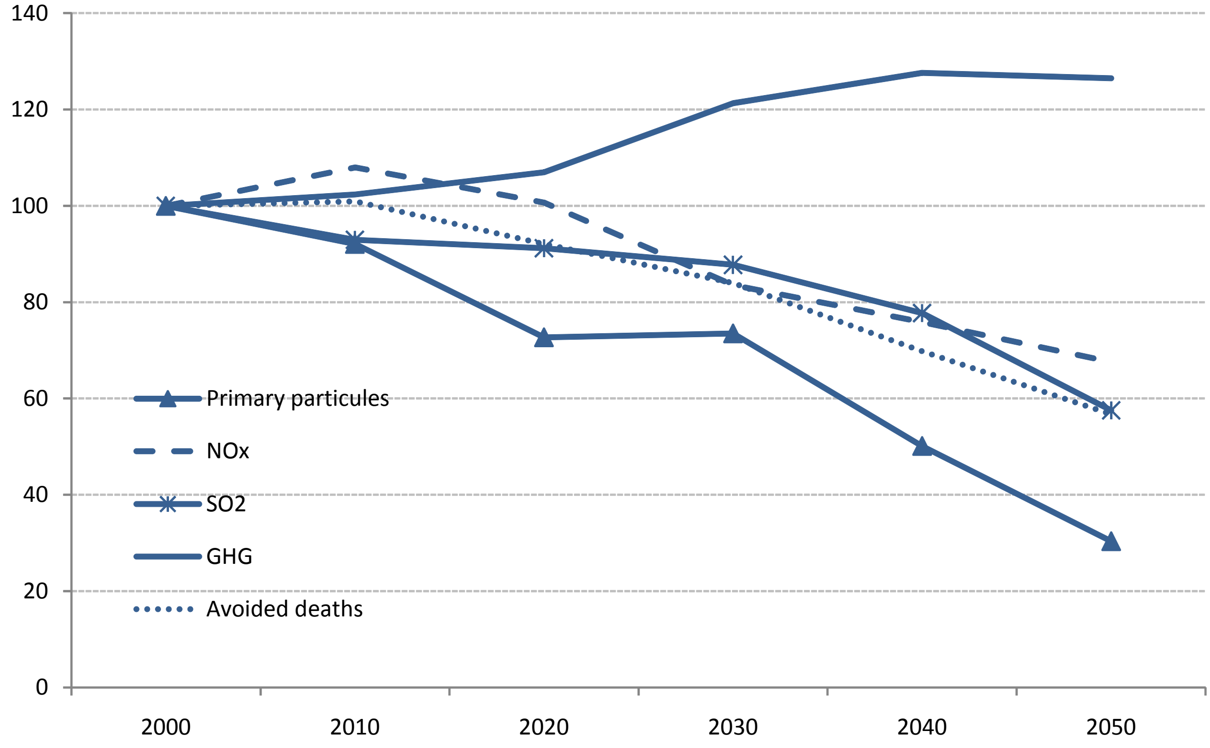
Figure 12. GDP impact of participating in a global climate change agreement to reduce GHG emissions by 50% in 2050[1]



1. "Without co-benefits" is the return from GHG mitigation policy when co-benefits are not included, or the difference between the benefits in terms of avoided global climate change and the cost of mitigation policy. "With co-benefits" is the return from GHG mitigation policy when co-benefits are included, *i.e* the difference between the benefit in terms of both avoided global climate change and local air pollution and the cost of mitigation policy to which the opportunity gain of not having to achieve the same level of LAP reduction through direct policies is then added.
2. Including Russia.
3. Including Mexico.
Source: Bollen *et al.* (2009).

Figure 13. GHG and local air pollutant emissions in an optimal policy mix scenario compared with a GHG mitigation scenario

(Index: scenario where GHG emissions are cut by 50% in 2050 relative to 2005 levels=100)



Source: Bollen *et al.* (2009).

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