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Local air pollution and global climate change: A combined cost-benefit analysis

Johannes Bollen [a,*], Bob van der Zwaan [b,c], Corjan Brink [a], Hans Eerens [a]

[a] PBL, Netherlands Environmental Assessment Agency, P.O. Box 303, 3720 AH, Bilthoven, The Netherlands
[b] ECN, Energy Research Centre of the Netherlands, Policy Studies Department, P.O. Box 56890, 1040 AW, Amsterdam, The Netherlands
[c] Columbia University, Lenfest Center for Sustainable Energy, Earth Institute, NY, USA

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ABSTRACT

This article presents the findings of a combined cost-benefit analysis of local air pollution and global climate change, two subjects that are usually studied separately. Yet these distinct environmental problems are closely related, since they are both driven by the nature of present energy production and consumption patterns. Our study demonstrates the mutual relevance of, and interaction between, policies designed to address these two environmental challenges individually. Given the many dimensions air pollution control and climate change management have in common, it is surprising that they have only little been analyzed in combination so far. We attempt to cover at least part of the existing gap in the literature by assessing how costs and benefits of technologies and strategies that jointly tackle these two environmental problems can best be balanced. By using specific technological options that cut down local air pollution, e.g. related to particulate emissions, one may concurrently reduce CO_2 emissions and thus contribute to diminishing global climate change. Inversely, some of the long-term climate change strategies simultaneously improve the quality of air in the short run. We have extended the well-established MERGE model by including emissions of particulate matter, and show that integrated environmental policies generate net global welfare benefits. We also demonstrate that the discounted benefits of local air pollution reduction significantly outweigh those of global climate change mitigation, at least by a factor of 2, but in most cases of our sensitivity analysis much more. Still, we do not argue to only restrict energy policy today to what should be our first priority, local air pollution control, and wait with

* Corresponding author.
E-mail address: Johannes.Bollen@pbl.nl (J. Bollen).

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the reduction of greenhouse gas emissions. Instead, we propose to design policies that simultaneously address these issues, as their combination creates an additional climate change bonus. As such, climate change mitigation proves an ancillary benefit of air pollution reduction, rather than the other way around.

1. Introduction

Two interrelated environmental policy problems are global climate change (GCC) and local air pollution (LAP). Both are discussed in the political arena: the first notably in the United Nations Framework Convention on Climate Change (UNFCCC) and the second in, e.g. the United Nations Economic Commission for Europe's task-force on Long-Range Transboundary Air Pollution (UNECE-LRTAP). Emissions from the combustion of fossil fuels contribute to both GCC and LAP. Options to mitigate these problems are typically chosen to address each exclusively. For example, to reduce the emissions of SO_2, NO_x, or particulates, one often uses end-of-pipe abatement techniques specifically dedicated to these respective effluents, but not to CO_2. Their application thus only contributes to diminishing LAP, not GCC. Alternatively, one of the ways to cut down emissions of CO_2 is to equip fossil-fired power plants with CO_2 Capture and Storage (CCS) technology, which in principle only addresses this greenhouse gas, and not the emissions of air pollutants. CCS equipment installed in isolation therefore alleviates GCC, not LAP. Still, options exist capable of simultaneously addressing both environmental problems, such as the substitution of fossil fuels by various types of renewables or nuclear energy. This paper investigates, through an integrated cost-benefit analysis of GCC and LAP, to what extent synergies between solutions for these environmental challenges can be created by using technologies that are beneficial to both at once.

Nordhaus became one of the early protagonists in the cost-benefit analysis of GCC by deriving an analytical solution to a simple climate change maximization problem (Nordhaus, 1977, 1982). The answer to the problem involved an optimal time-profile for the concentration of CO_2 in the atmosphere. Nordhaus later developed a numerical model (DICE) that simulated a rudimentary world climate–economy system (Nordhaus, 1993). Estimates for climate change damage costs, however, fundamentally determined his modeling results, like those of others who meanwhile had undertaken similar research (see, for example, Fankhauser, 1995; Manne and Richels, 1995; Tol, 1999; Rabl et al., 2005). The reason was a very incomplete scientific understanding of potential climate change impacts, resulting in large cost uncertainties. Another shortcoming of this type of work was, and still is, that none of the GCC cost-benefit analyses cover the LAP problem, even while these two issues are closely linked. Indeed, they are both much driven by current energy production and consumption patterns. This paper attempts to correct for this, by presenting a single model that includes detailed descriptions of the costs and benefits of both GCC and LAP control strategies.

In 1999, the EU adopted the *Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone*. This protocol set emission ceilings for the year 2010 for SO_2, NO_x, NH_3, and VOC (volatile organic components). A few years later, the EU developed the *National Emission Ceiling Directive* that stipulated more stringent targets for these pollutants. The multi-national negotiations, leading to the agreement of these targets, used insights from scientific assessments and estimates for the economic costs of pollutant abatement options obtained with the LAP model RAINS (Amann et al., 2004a,b). Recently, results from RAINS have been used for restricted cost-benefit analyses of LAP, notably to serve the Clean Air For Europe program (CAFE, see Holland et al., 2005). Other studies of costs and benefits of air pollution policy packages have been performed that focused on isolated environmental problems or single pollutants (such as RIVM, 2000). All these analyses conclude that the monetary benefits of air pollution policies can be much larger than their costs. They all imply that the benefits are dominated by the avoided number of premature deaths from the chronic exposure of the population to concentrations of particulate matter (PM). A few studies merely signal potential LAP benefits resulting from GCC policies (Criqui et al., 2003; van Vuuren et al., 2006). They typically fix the carbon price, however, and restrict their analysis to Europe and the year 2010. These analyses therefore disregard the potential benefits of other and more costly options that simultaneously avoid GCC and LAP. Burtraw et al. (2003), in a similar study, also fix the carbon price and restrict themselves to the electricity sector in the United States for the year 2010. They find ancillary benefits from a decline in SO_2 and NO_x emissions, as well as avoided compliance costs under existing or anticipated emission caps. The authors also conclude that the initial carbon prices are significantly lowered because of these ancillary benefits. However, their analysis does not consider longer term or non-electric energy options. Thus, they give little guidance on how to design optimal strategies for addressing global warming and local air pollution. To our knowledge no multi-region model exists, that (1) covers the world and has a long time horizon, (2) jointly analyzes optimal greenhouse gas and PM emission reductions, and (3) allows balancing the costs of abatement with the benefits of avoided damages for both GCC and LAP. Our study aims to fill this gap.

To be able to analyze the dual GCC-LAP problem, we judged it best to employ a global top-down model, but with a sufficiently large number of bottom-up technology features. For this purpose, we adapted the climate change model MERGE (Model for Evaluating the Regional and Global Effects of greenhouse gas reduction policies) as developed by Manne and Richels (1995). We employed MERGE in its cost-benefit mode, rather than in its cost-effectiveness format, which allows for an investigation of the balancing between the costs of abatement technologies and the benefits reaped from avoiding environmental damages. Hence, we did not impose a climate constraint under which total costs are minimized, as done in some of the other energy-environment models (such as DEMETER, see van der Zwaan et al., 2002; Gerlagh and van der Zwaan, 2006). We expanded MERGE with a module dedicated to LAP including mathematical expressions for:

- emissions of primary PM from energy use in electricity and non-electricity sectors;
- chronic exposure of the population to increased PM concentrations;
- number of people prematurely dying from chronic PM exposure;
- monetary estimates for the damages resulting from premature PM deaths.

We calibrated the LAP module to estimates from studies by the World Health Organization (WHO, 2002, 2004) and the RAINS consortium (Amann et al., 2004a), as well as several other sources (Pope et al., 2002; Holland et al., 2004). Since GCC and LAP damage cost estimates, as well as most of our other modeling assumptions, are subject to uncertainties, we performed an extensive sensitivity analysis with respect to all these elements. To mention just a few: our discounting assumptions, the climate sensitivity parameter, the costs of implementing CO_2 and PM abatement options, the willingness-to-pay (WTP) for avoiding GCC damages, the number of premature LAP-related deaths, and the monetary valuation of these deaths.

Reaping the welfare benefits from avoiding LAP-related damages constitutes the main mechanism at work in our new version of MERGE. LAP damages result from emissions of PM. Abatement of these emissions implies costs incurred by the implementation of end-of-pipe measures or switches from fossil fuels to the use of cleaner forms of energy. When benefits exceed costs for certain regions, an incentive is created for lowering the emissions of PM. A similar and synchronous balancing between costs and benefits occurs for CO_2 emission reductions. At the same time the new model allows for balancing the incentives to act on LAP and GCC, while interactions and spill-overs between these two add to the overall optimization process.

The analysis in this paper involves a stylized version of LAP, since it is restricted to one pollutant only (primary PM) and disregards other pollutants (e.g. secondary formed aerosols). We thus employ several abstractions:

- We focus on emissions from fossil-fuel combustion, in both the electricity and non-electricity sectors, as these have an impact on (mainly) urban exposure to PM, but are also the main source of greenhouse gas emissions, and constitute as such the principal driver of both GCC and LAP.
- While recognizing that LAP also includes pollution such as acidification, we restrict ourselves to PM only, as the monetary health benefits from PM emission reductions are much larger than those for other pollutants.

- Mostly fine PM is responsible for deaths resulting from particulates in the ambient air, that is, PM with a diameter smaller than 2.5 μm (henceforth labeled as $PM_{2.5}$), so that in principle we will only focus on this category of PM.
- We disregard the contribution to PM concentrations from secondary aerosols, as the corresponding related health impacts are more uncertain than for primary PM. The impact of secondary aerosols on mortality may even turn out to be very limited (see WHO, 2006, p. 242).
- Another reason for disregarding secondary aerosols is that their inclusion would necessitate addressing their interregional diffusion, and thus require an in-depth version of an air-transport model, which is beyond the scope of this paper.
- Whereas theoretically PM can travel thousands of kilometers before being deposited, the major contribution to local PM concentrations comes from emissions that remain close to their source. Indeed, the high concentrations of primary PM in cities and densely populated urban areas mostly result from local transportation systems and power plants in their direct vicinity. We therefore make the assumption that regional PM emission reductions contribute to a decrease in PM concentrations within the region under consideration only.

Among our other approximations are:

- We have purposefully modeled LAP at a highly aggregated level, since this enables us to integrate LAP and GCC into a single modeling framework. The drawback hereof is that the PM emissions problem is modeled in a more rudimentary fashion than in, e.g. RAINS, as we simplify its detailed bottom-up abatement cost information for EU countries to only a few sectors and regions. The advantage, however, is that with this approach we are able to also introduce more economic realism than available in RAINS, as our simplification allows for an enrichment in terms of the simulation of time-dependent abatement technology costs.
- The RAINS PM emissions information we use only covers Europe. Since few reliable data are available on PM emissions and activities for countries outside Europe, we have ourselves derived emission coefficients for all other world regions, based on those for Europe.
- The concentration of $PM_{2.5}$ has a larger mortality impact in comparison to PM_{10}, but data on the former are generally scarce, while amply available for the latter. We therefore use PM_{10} data as proxy for $PM_{2.5}$ data, as done in (WHO, 2006).
- At an intermediate level of PM emissions a linear relationship exists between emissions and concentrations. PM concentrations, however, depend not only on regionally produced air pollution, but also on local factors such as meteorology. As a result, it proves that at low PM emission levels an increase hardly alters the PM concentration, the latter mainly being determined by regional PM background values. For our calculations we nevertheless restrict ourselves to a linear dose–response relationship.
- The valuation of premature deaths from chronic exposure to PM concentrations is a contentious issue, since there are basically two ways to value health impacts, either through a ‘Value of a Statistical Life’ (VSL) or a ‘Value Of a Life Year lost’ (VOLY) method. In the first, one values a premature death against the VSL, while in the second, one estimates the number of ‘Years Of Life Lost’ (YOLL) and multiplies these with the VOLY. The European Commission decided for the CAFE program to adopt the precautionary principle, and thus employed the higher damage estimates from the VSL approach, also because they argue it to be more statistically reliable than the VOLY method. In this paper we also choose to follow the VSL approach, and test the robustness of our major conclusions through a detailed uncertainty analysis.

Modeling a stylized version of LAP and restricting our analysis to one but dominant LAP-related substance – primary PM from fossil energy, with a very local character – allows us to explore and test the potential significance of the synergy aspects between policies mitigating LAP and GCC in an integrated cost-benefit framework. This framework enables us to derive optimal pathways for CO_2 and PM emissions, under varying parameter values and modeling assumptions, on the basis of a trade-off between costs associated with mitigation efforts and benefits obtained from avoiding mid-term air pollution and long-term climate change damages. Section 2 of this article gives an overview of our adapted version of MERGE, and explains in detail how we extended the original MERGE model with a module covering air pollution. We highlight our most important results in Section 3, in terms of simulated CO_2 emission levels and calculated costs and benefits of GCC and LAP policy. In Section 4 we present our uncertainty analysis, while reserving Section 5 for our main conclusions and recommendations.

2. Methodology

Climate change is mostly driven by CO_2 emitted from fossil-fuel combustion processes. Also air pollution is predominantly fossil-fuel induced, but the range of relevant pollutants is much wider (Amann et al., 2004a). The public health impacts as a result of air pollution mostly stem from the inhalation of and exposure to PM, with short-term consequences like eye irritation and chronic bronchitis or asthma. The long-term effects include restricted activity days, cancers, and premature deaths (Cohen et al., 2004). In terms of monetary damages, the health problem brought about by LAP is dominated by mortality rather than morbidity (Holland et al., 2005). We have thus expanded MERGE with the mortality impacts from PM emissions as proxy for LAP, so that the new model version can balance benefits and costs of two energy-related environmental problems.

2.1. MERGE

MERGE allows for estimating in detail the costs of greenhouse gas reduction policies (Manne and Richels, 2004). The domestic economy of each of the nine simulated regions is represented by a Ramsey-Solow model of optimal long-term economic growth, in which inter-temporal choices are made on the basis of a utility discount rate.[1] Response behaviour to price changes is introduced through an overall economy-wide production function, and output of the generic consumption good depends, like in other top-down models, on the inputs of capital, labour, and energy. One of the major contributors to climate change is CO_2, which originates from energy use in a bottom-up perspective. Separate technologies are defined for each main electric and non-electric energy option. In addition to emissions of CO_2, the model governs mathematical expressions simulating the development of energy-related emissions of other greenhouse gases as well as non-energy-related greenhouse gases. The amount of greenhouse gases emitted in each simulation period feeds into the global atmospheric greenhouse gas concentration. Every concentration increase matches a corresponding global temperature increment. In its cost-benefit mode, MERGE calculates an emissions time path that maximizes the discounted utility of consumption. The production and consumption opportunities of the geopolitical regions are negatively affected by damages (or disutility) generated by GCC and LAP. The cases analyzed and solutions obtained with MERGE assume Pareto-efficiency, that is, only states of the world in which no region can be made better off without making another region worse off are considered. Abatement of greenhouse gases and PM can be optimally allocated with respect to the dimensions time (when), space (where), and nature of pollutants (what). Abatement technologies can address either GCC or LAP, or alternatively both at once. Energy savings for example, one of the more expensive means to mitigate climate change, simultaneously reduce the intensity of PM.

We have modified the original MERGE model, as described in Manne and Richels (1995, 2004) and Manne et al. (1995), by adding the link of LAP to energy production. We thus obtain a model that simulates the costs and benefits from both GCC and LAP policies in a dynamic and multi-regional context. In each year and region an allocation of resources now includes investments in end-of-pipe PM abatement according to the relation:

$$Y_{t,r} = C_{t,r} + I_{t,r} + J_{t,r} + K_{t,r} + D_{t,r} + X_{t,r}, \tag{1}$$

in which Y represents output or GDP aggregated in a single good or *numéraire*, C consumption of this good, I the production reserved for new capital investments in the next time step, J the costs of energy,

[1] The nine regions modeled in MERGE are: USA, Western Europe, Japan, Canada/Australia/New Zealand, Eastern Europe and the former Soviet Union, China, India, Mexico and OPEC countries, and the rest of the world. It employs a time horizon up to 2150 with time steps of ten years.

K the costs of PM abatement, D the output required to compensate for GCC-related damages, and X the net export of the numéraire. Subscripts t and r refer to time and region, respectively. The complete set of tradables includes such products as oil, natural gas, and energy-intensive goods. Solving the cost-benefit problem implies reaching agreement on an international control system that leads to the temperature limit and avoided premature deaths that together minimize the discounted present value of the sum of abatement and damage costs.[2] Disutility is associated with the damages from GCC and LAP, as can be seen from the objective function (or maximand) of the total problem, i.e. the Negishi-weighted discounted sum of utility:

$$\sum_r n_r \sum_t u_{t,r} \log(E_{t,r}[C_{t,r} - F_{t,r}]), \tag{2}$$

with n the Negishi weights, u the utility discount factor, E the disutility factor associated with GCC as percentage of consumption, and F the absolute damages associated with LAP measured in 2000 US$. As in MERGE, the loss factor E is expressed by:

$$E(\Delta T) = \left(1 - \left(\frac{\Delta T}{\Delta T_{cat}}\right)^2\right)^h \tag{3}$$

in which ΔT is the temperature rise with respect to its 2000 level, and ΔT_{cat} the catastrophic temperature at which the entire economic production would be wiped out. The t-dependence of the problem is reflected in the temperature increase reached at a particular point in time. The r-dependence is covered by the 'hockey stick' parameter h, which is assumed to be 1 for high-income regions and takes values below unity for low-income ones. Since we have left the GCC part of MERGE unchanged with respect to its original form, below we only focus on our MERGE expansion, which accounts for (A) the relation between PM emissions and ambient PM concentrations, (B) the link between increased PM concentrations and incurred premature deaths, and (C) the meaning of these deaths in terms of their monetary value.

2.2. From deaths to damages

Starting at the back-end of the impact pathway chain, how should we monetize the premature deaths resulting from chronic PM exposure? Holland et al. (2004) recommend using both the VSL and VOLY methods to value mortality incurred from PM exposure. Table 1 lists the respective numbers as used in our analysis. The difference between the two approaches is smaller than the figures in this table may suggest. Indeed, much of their apparent divergence disappears when the VOLY numbers are multiplied by the actual number of life years lost. Typically one may assume for Europe an average of 10 life years lost under current PM exposure levels, in which case at median estimates the VOLY approach results in a valuation of death approximately 50% lower than in the VSL approach. In this article we take the median estimate of the VSL approach in 2000 as our benchmark case.

Since for the base year 2000 in Europe VSL equals about 1.06 million US$(2000), we get as equation for the monetized damages F from LAP:

$$F_{t,r} = N_{t,r} 1.06 \left(\frac{Y_{t,r}/P_{t,r}}{Y_{2000,weur}/P_{2000,weur}}\right), \tag{4}$$

in which N is the number of people prematurely dying from the chronic exposure to PM. For regions other than Europe we obtain the VSL by multiplying the VSL for Western Europe (WEUR) with an additional factor, in which P is the exogenous number of people in a region. This factor consists of the ratio of the GDP per capita of the region under consideration and that of Europe. For future years and for all regions the VSL is assumed to rise according to the growth rate of per capita GDP, as expressed by Eq. (4).

[2] Output Y is equal to the sum of production of a new vintage and the old one. For the new vintage, a 'putty-clay' constant-elasticity-of-substitution relation applies with inputs new capital, labour, electric and non-electric energy. For the old vintage there is no substitution between inputs.

Table 1
Valuation of PM deaths in Europe in million US$(2000). Source: Holland et al. (2004).

	VSL	VOLY
Median	1.061	0.056
Mean	2.165	0.130

Note: VSL and VOLY are reported in €(2000) and converted to US$(2000) by € = 0.92$.

2.3. *From concentrations to deaths*

For the range of average ambient PM concentrations that we simulate, we assume that mortality due to LAP increases linearly with the PM concentration. While the full relation between these variables is not linear (see Eq. (5)), for their values in our model linearity proves a good approximation. Under this assumption we estimate the number of deaths *N* that result from energy-related primary PM emissions. We hereby follow the same method used in WHO studies that estimate the total number of deaths, and years of life lost, from public PM exposure (WHO, 2002, 2004). Hence we use only one risk coefficient, which depends on the PM concentration. It is derived from a large cohort study of adults in the USA (Pope et al., 2002). We multiply this coefficient with the population of a given region at a given point in time to obtain the total number of deaths in that region. By using this coefficient we implicitly focus on $PM_{2.5}$ only. The equation we added to MERGE (in the format customarily used in health risk assessments) reads:

$$N_{t,r} = \frac{(1.059 - 1)G_{t,r}}{(1.059 - 1)G_{t,r} + 1} P_{t,r} c_{t,r} \tag{5}$$

in which *G* is the $PM_{2.5}$ concentration in units of 10 $\mu g/m^3$, *P* the population of a region, and *c* the crude death rate (Pope et al., 2002). We follow Holland et al. (2005) by estimating all deaths above the nil-effect of 0 $\mu g/m^3$.[3,4] The values we adopt for the regional crude death rates are based on Hilderink (2003) and account for the fact that ageing societies experience relatively more PM-related deaths and should thus be represented by higher values of *c*. As expressed by Eq. (5), with increasing levels for *c* the number of premature deaths from PM increases at any given concentration level.

2.4. *From emissions to concentrations*

Because of a lack of detailed knowledge on air pollution concentration levels in many parts of the world, the World Bank (2007) developed an econometric model to estimate PM concentrations in urban residential areas and rural non-residential pollution hotspots based on data from the WHO (2002). The World Bank estimates only focus, however, on emissions of relatively large particulates with a diameter $<10\ \mu m$, PM_{10}. Another study by WHO (2004) translates PM_{10} concentrations to $PM_{2.5}$ concentrations through information available on geographic variations of their ratio. This allows estimating the mortality impacts from ambient air pollution. The study lacks, however, impacts in rural areas. We combine the two approaches by applying scaling factors, characteristic for each region, which enables us to derive rural $PM_{2.5}$ concentrations from urban PM_{10} levels. Fig. 1 schematically illustrates where we applied these scaling factors, and how we accordingly derived total (urban plus rural) $PM_{2.5}$ concentrations from urban PM_{10} concentrations, per region, for the base year 2000.

Our purpose is to study the potential synergies between GCC and LAP policies, so that we need to know both CO_2 and PM emissions related to energy use. Fig. 1 therefore also illustrates how we

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[3] As opposed to WHO (2004), which only measures the number of deaths above a threshold concentration level of 7.5 $\mu g/m^3$. On the other hand, we implicitly apply an upper bound concentration by restricting our analysis to the number of premature deaths from primary PM.

[4] We assume a linear function as opposed to a log-linear one, because we think that changes in average regional PM concentrations are relatively small in comparison to the case with more pollutants and secondary aerosol formation. These other pollutants are beyond the scope of this paper. Our choice is also justified on the grounds that close to the optimum a linear relationship proves a good approximation of the non-linear case.

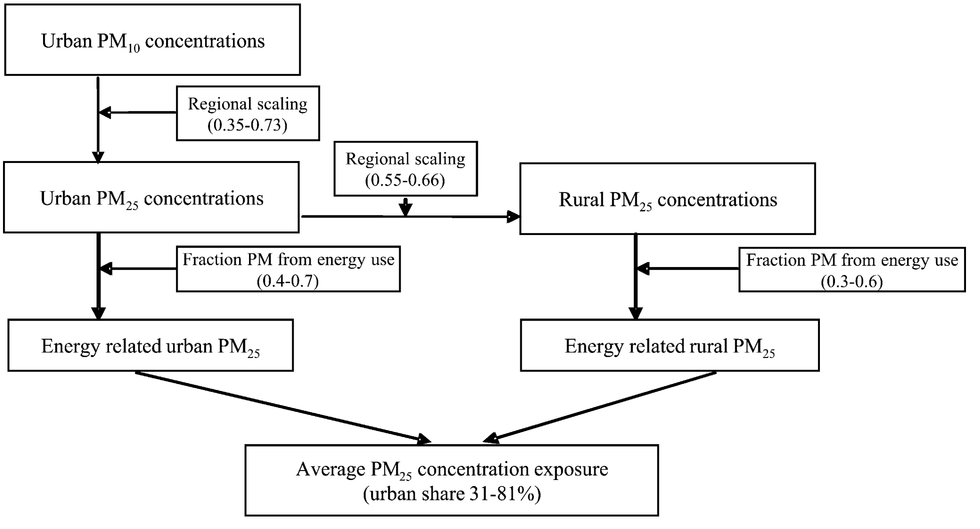

Fig. 1. Flow scheme for our calculation of regional (urban plus rural) $PM_{2.5}$ concentrations (scaling factors between brackets).

subtracted background PM concentrations from their total to obtain energy-related PM levels. We again use a set of scaling factors to lower total PM concentrations and get concentrations that stem from energy use only. In MERGE we employ a region-specific linear relationship between the $PM_{2.5}$ concentration level G and the PM_{10} emission level H:

$$G_{t,r} = \alpha_r H_{t,r}, \qquad (6)$$

in which α expresses this linear region-specific relationship and incorporates the ratio between concentrations of PM_{10} and $PM_{2.5}$. Eq. (6) implies that emissions remain within a region and do not affect concentrations in other regions. We think it is justified to make this simplifying assumption because the regions modeled in MERGE are large, and the concentrations employed are averages of urban and rural areas (see Fig. 1). Hence, air quality of border locations (which may in principle be affected by emissions of another region) has little impact on the average PM concentration in an entire region. Moreover, primary PM, the pollutant modeled in this paper, mainly affects local air quality (see OECD, 2008).[5] We tested this approximation by making the alternative assumption that accounts for transboundary aspects of PM pollution in two regions (OECD Europe and Eastern Europe plus the former Soviet Union), which proved to generate negligible impact on the optimal emission pathways for greenhouse gases and PM.[6] We did not link $PM_{2.5}$ concentrations directly to $PM_{2.5}$ emissions, as the latter are mostly derived from PM_{10} emission data inventories anyway.

As with PM concentrations, in many regions of the world data available on the levels of energy-related PM_{10} emissions are incomplete. Europe is one of the exceptions, as large databases have been constructed over the past decades to feed the highly publicized policy debate on air pollution. This debate resulted in a multi-gas and multi-effect protocol that put stringent limits on the emissions of a series of air pollutants. The results of the integrated assessment of a range of air pollutant abatement options, obtained with the RAINS model, were important inputs to the public deliberations that led to the protocol (Amann et al., 2004a). We connect to the RAINS model by mapping technologies simulated in MERGE to sectors analyzed in RAINS. Table 2 lists energy-related PM_{10} emissions in 2000 from a set of different sources as obtained from the RAINS database, which we transformed for usage as input in our extended version of MERGE.

[5] For more details, see Chapter 6 of the OECD Environmental Outlook.
[6] We performed this test as part of our uncertainty analysis, the details of which can be obtained from the corresponding author.

Table 2
Energy-related PM_{10} emissions (Mt) in 2000 in OECD Europe as modeled in MERGE based on data from RAINS.

RAINS sector	MERGE technology	Acronym	Emissions of PM_{10} (Mt)
Coal			
Existing power plants	Old power plants	CR	0.100
Direct use	Non-electric applications	CN	0.498
Oil			
Existing power plants	Old power plants	OR	0.014
Direct use	Transport	OT	0.535
Derived products	Chemical products	ON	0.021
Other			
Primary to secondary energy	Total primary energy	TP	0.131
Total			1.299

Note: The last entry (TP) refers to PM_{10} emissions from refineries and transport of energy.

The equations we added to MERGE to cover emissions H of PM_{10}, in year t and region r, read:

$$H_{p,t,r} = s_{p,t,r} A_{p,t,r} \left(1 - \sum_x q_{x,p,t,r}\right), \tag{7}$$

and

$$H_{t,r} = \sum_p H_{p,t,r} \tag{8}$$

in which p is the index referring to elements in the total set of MERGE technologies or activities, the most important ones of which are listed in Table 2. The variable A measures the level of a specific activity (in EJ), s is the activity-specific emissions factor (in Mt/EJ), and $0 < q < 1$ represents the abatement intensity of a specific activity. The latter is equal to the marginal fraction of emissions reduced per abatement effort from a set of specific end-of-pipe (EOP) measures (see also Eq. (9)).[7] In Eq. (8) the emissions in year t and region r are summed over the emissions from all activities p. Running MERGE involves choosing the optimal levels for A and q.

There are two additional technology options not mentioned in Table 2, which are optional from 2020 onwards: 'clean' coal-fired power stations in the electricity sector and renewables in the transport sector. The former are power plants that produce zero emissions of PM_{10}, but still emit the usual levels of CO_2. An example of the latter is bio-diesel for use as transport fuel, the combustion of which does not generate net emissions of CO_2 but does emit PM_{10}. These two types of technologies play a peculiar role in our model, as they may be relevant for either GCC or LAP policy, but not both. Each type has the characteristic of being stimulated under one policy, while simultaneously being discredited under the other one. Which of these two stimuli dominates cannot be predicted *a priori*, but can only be derived *a posteriori* through factual model runs. For the base year, the emission factors s are assumed to be uniform across regions for each activity. Of course, especially for activities in low-income regions, like India and China, this assumption may seem rather unrealistic. But since we transform our calibrated PM_{10} emissions to *actual* concentrations of $PM_{2.5}$, and because MERGE is based on a comparison between emission reduction costs and the impact of emission abatement on PM concentrations and corresponding change in the monetized damages incurred, the induced error on optimal mitigation behaviour is much smaller than our approximation may suggest. For the base year 2000 and reference region Europe, s is defined as the ratio between PM emissions (as in RAINS)

[7] The index x represents a discrete number of steps ranging from {1, . . ., 11}. Each step is associated with a fixed uniform marginal cost level for all activities within a region. As x increases, also the cost level increases. For example, in Europe at $x = 1$ the marginal cost level is fixed at 379 \$/t PM_{10} (=350 €/t PM_{10}), at $x = 2$ the marginal cost level is fixed at 1623 \$/t PM_{10} (1500 €/t PM_{10}), and at $x = 11$ the marginal costs lie above 155,000 \$/t PM_{10} (144,000 €/t PM_{10}). The 11 steps with fixed marginal cost levels and the incremental abatement intensities q (in % emission reduction) together reproduce the Marginal Abatement Cost Curves (MACCs) for Europe, based on RAINS.

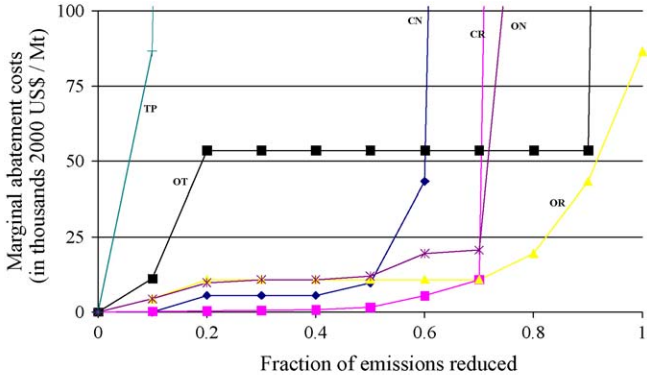

Fig. 2. Marginal abatement cost curves for the six PM_{10}-emitting activities of Table 2 as adopted from RAINS, as applicable to the year 2000 in Western Europe.

and the output of PM-emitting activities (as in MERGE). The emission factors are assumed to decrease over the coming decade and are kept at their 2020 values thereafter, based on the baseline scenario reported in Amann et al. (2004b).[8] For our uncertainty analysis regarding emission factor values we compared SO_2 emission coefficients for Europe (see Amann et al., 2004a) with those for China (see Foell et al., 1995). We used the percentage difference between the SO_2 emission factors of these two regions as proxy for PM emission coefficient differences between developed and developing countries.

2.5. EOP-abatement costs of PM

The alternative to experiencing damages as a result of PM emissions is avoiding them. EOP-measures exist that significantly lower energy-related PM_{10} emissions. The RAINS model simulates such abatement technologies for Europe, and includes data for their costs in each sector. Because abatement options can be ordered according to increasing deployment costs, RAINS adopts distinct Marginal Abatement Cost Curves (MACCs) for different PM_{10} emission activities. MACCs constitute the graphical representation of emission reduction costs for the ranked set of available abatement technologies. MERGE does not simulate explicit PM abatement technologies. We nevertheless implicitly adopt the same MACCs as used in RAINS, based on the mapping of energy technologies between RAINS and MERGE as listed in Table 2. Like in RAINS, we assume that not all abatement options can immediately enter the market. It takes time to develop abatement technologies, even if the required know-how to implement them is already available. For 2020, we allow MERGE to deploy PM abatement measures up to 50% of the total feasible reduction potential. For 2030, this threshold is raised to 75%, and beyond 2040 the full range of options is implementable. Fig. 2 plots the MACCs for the six main PM-emitting activities in Europe.

As can be seen from Fig. 2, abatement costs remain below 5000 $/tPM_{10}$ for most activities (except TP) when PM_{10} emissions are reduced by only 10%. When emission reduction levels reach 70%, abatement costs increase to at least 10,000 $/tPM_{10}$, and in most cases significantly higher. For the short run, we employ essentially the same European MACCs as used in RAINS for EOP PM abatement technologies. For future years, however, we lower these cost curves to account for an autonomous reduction in abatement costs within a sector.[9] On the other hand, income will rise over time, as a result of which the costs of producing abatement technologies will increase, since higher wages will push production costs upwards. In particular, we assume that abatement costs will increase according to this phenomenon at 20% of the GDP per capita growth rate. Both the cost-reducing and

[8] Information on all further modeling details may be obtained from the corresponding author.

[9] Up to 2040, the abatement costs follow assumptions in RAINS, but beyond 2040 these costs decrease exogenously at a constant rate of 0.5%/yr. *De facto* little technological progress materializes in our simulations, however, as LAP is mostly resolved by 2060.

cost-incrementing tendencies are simulated in our version of MERGE. MACCs similar to the ones of Fig. 2 are applied to all world regions, but typically with a stretched y-axis, so that the same abatement options become cheaper in, e.g. China in comparison to those in Europe. For the time dependence of MACCs in other regions similar adjustments are made. A side-effect of our approach is that "low-hanging fruit" as implemented in Europe twenty years ago is not simulated in our analysis, since the MACCs we use are based on options available today. As a result, we over-estimate the costs of the options currently available in China. This is admittedly a shortcoming of our approach. The total PM_{10} abatement costs K for each region r and year t, as appeared in Eq. (1), are now:

$$K_{t,r} = \sum_{p}\left[s_{p,t,r}A_{p,t,r}\sum_{x}q_{x,p,t,r}Q_{x,p,t,r}\right], \tag{9}$$

with Q the marginal costs associated with the reduction of PM_{10} emissions through EOP-abatement techniques (y-axis of Fig. 2), indexed for each activity p and marginal abatement effort x. Again, q is the marginal fraction of emissions reduced, which is the incremental value of the fraction of reduced emissions as plotted on the x-axis of Fig. 2. As mentioned, we also assume PM emissions from the use of renewable energy. Although the corresponding emission coefficients are lower than those for oil, the abatement costs (in absolute terms) of renewables-induced PM emissions exceed those from oil combustion (by about 33%).

There is an analogue between the PM_{10} EOP-abatement costs as we introduced in MERGE and the non-energy (and non-CO_2) abatement costs as implemented by Manne and Richels (2004). They report "For the abatement of non-energy emissions, MERGE is also based on EMF 21. EMF provided estimates of the abatement potential for each gas in each of the 11 cost categories in 2010. We incorporated these abatement cost curves directly within the model . . .". In our modified MERGE model we also incorporate additional exogenous information, that is, the feedback of EOP PM abatement expenditures through K in Eq. (1). Manne and Richels (2004) write ". . . abatement cost curves are extrapolated after 2010, following the baseline. We also built in an allowance for technical advances in abatement over time." In our MERGE version we assume an autonomous yearly increase of the potential incremental abatement effort for each marginal cost level, which is equivalent to an autonomous reduction of the marginal costs of a specific abatement technology.

Recall from Table 2 that the dominant sources of PM_{10} are the use of oil (in the transport sector) and of coal (for non-electric applications), which together account for almost 90% of Europe's emissions of this pollutant. Hence, total abatement costs are dominated by EOP measures related to these activities. For example, the oil sector represents a limited abatement potential, equal to 20%, if the marginal costs remain below 50,000 US$/Mt$PM_{10}$. But the abatement potential can be increased to more than 90% if the marginal costs are increased to more than 54,000 US$/Mt$PM_{10}$ (e.g. through the application of smoke filters on passenger cars).

3. Results

In order to analyze the effects of GCC and LAP control, we define three different policy scenarios for which we ran our expanded MERGE model. Externalities are internalized in these policy scenarios, that is, external costs (or environmental dual prices) are included in the prices for all energy services and consumer goods. In a baseline (Business-As-Usual or BAU) scenario these external costs are set to zero.[10] For all four scenarios we report our main findings in terms of CO_2 emission paths and the costs and benefits of policy intervention. Our first policy scenario (GCC) internalizes GCC damages: MERGE calculates the Pareto-optimal pathway for energy use based on the costs and benefits of CO_2 emission reductions in all regions. The second scenario (LAP) internalizes LAP damages: an energy system pathway is determined on the basis of the costs and benefits of PM abatement technology implementation. Our third scenario (GCC + LAP) internalizes both GCC and LAP damages, which yields

[10] Our baseline assumptions on the specific measures included in the MACCs and the exogenous costless decline of emission intensities are consistent with the assumptions on local environmental policies of the IPCC B2 scenario (see Nakićenović et al., 2000).

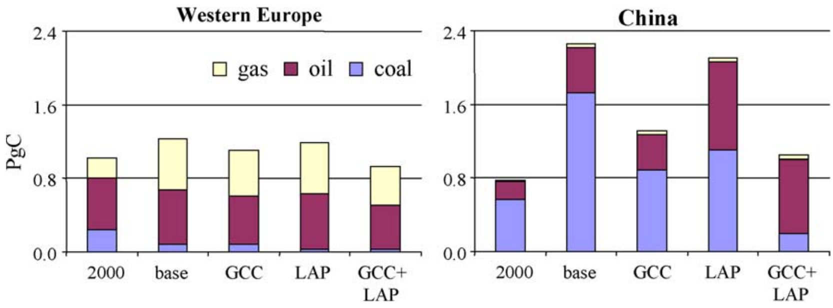

Fig. 3. Total energy-related CO_2 emissions in 2000 and for four scenarios in 2050 by source of production in Western Europe and China.

an energy technology diffusion path that accounts for costs and benefits of both CO_2 and PM reduction efforts.

3.1. CO_2 emissions

As a result of the internalization of LAP and GCC externalities, the emissions from all sources are subject to change. Fig. 3 depicts the total energy-related emissions of CO_2 generated in Western Europe and China in 2000 and 2050, specified by scenario and differentiated by source of production. For 2050 both the baseline and three policy scenarios are shown. A distinction is made between the three fossil fuels coal, oil, and natural gas, because their use behaves differently under the respective policies. We have purposefully chosen to show results for Western Europe and China. As for the former, Western Europe constitutes a representative and well-documented reference case, which is why we calibrated the emission coefficients for all regions to West-European data. As for the latter, China is likely to deliver the highest contribution to global energy demand and CO_2 emissions in 2050. The West-European share to global energy use (17% today) decreases in our BAU scenario to 9% by 2050, while China's share (9% in 2000) rises to 15% over this period. These BAU figures match the IPCC B2 scenario, as described in Nakićenović et al. (2000).

As can be seen from Fig. 3, CO_2 emissions in 2000 were larger in Western Europe than in China. While over the coming 40 years emissions in Western Europe are expected to only moderately increase, as shown by the baseline bar of Fig. 3, in China the level of these emissions almost triples and thereby largely surpasses that of Western Europe. The main reason is the large difference in prospected economic growth between these two regions. Also differences exist between Europe and China in terms of the present and future relative shares of the sources contributing to total CO_2 emissions. The use of coal, for example, plays a more prominent role in China than in Western Europe, in all scenarios, while the role of natural gas remains almost negligible in the former. Coal use in China is predominantly expanded in the fields of electricity generation by coal-fired power plants and heat production through the direct combustion of coal. Both these prospected increases in coal use greatly enhance China's CO_2 emissions, as simulated by our model. In Western Europe, the use of coal currently contributes significantly to total CO_2 emissions, but its share is expected to decrease over the coming decades. European use of natural gas, on the other hand, is becoming increasingly important.

The level and source of emissions are strongly dependent on the scenario simulated, especially for China. Internalizing GCC damages as disutility in consumption (cf. the baseline with the GCC scenario) reduces CO_2 emissions in both regions, but mostly in China. The reason is that China emits more and possesses cheaper CO_2 abatement options. The reduction of total CO_2 emissions in China is mainly driven by a decrease in the use of coal, whereas in Western Europe the (more modest) reduction in CO_2 emissions results mostly from a cut in the demand for oil. As we will see from Fig. 4, GCC policy also proves to have a significant beneficial effect in terms of avoided monetary damages from LAP.

When LAP policy is applied, more than 90% of global PM emissions are reduced. The inclusion of LAP externalities as disutility in consumption, however, proves to have little effect on the level of CO_2

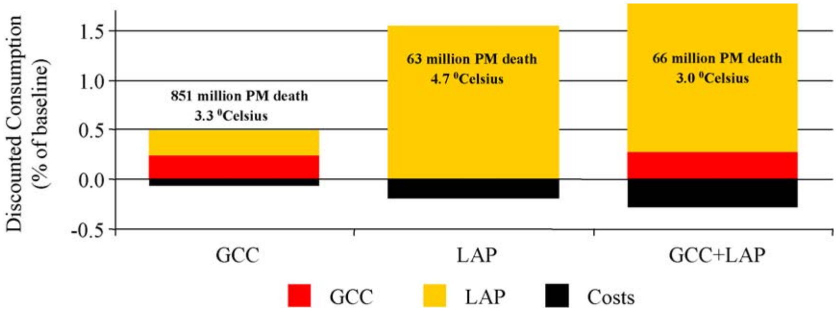

Fig. 4. Changes in costs, benefits, and global welfare for scenarios GCC, LAP, and GCC + LAP, expressed as % consumption change in comparison to the baseline.

emissions, both in Western Europe and China, as can be seen from Fig. 3. Most PM emissions are reduced through the implementation of EOP-abatement measures. For example, it is assumed that newly installed coal-fired power plants from 2020 onwards can be equipped with ‘clean-coal technology’, that is, do not generate PM emissions but continue to emit CO_2. Since the application of PM reduction technology under LAP policy is costly, we see that for Western Europe the use of coal and the corresponding CO_2 emissions decrease. In China the same can be observed, but another phenomenon is also at work: a trade-off emerges between different forms of energy. The use of oil instead of coal for heating purposes possesses a significant PM reduction potential, so that for China in the LAP scenario coal is partly replaced by oil. In China the impact of LAP policies on the origin of CO_2 emissions is thus larger than in Western Europe. We observe that oil remains a predominant energy source in all scenarios and regions, because limited opportunities exist to reduce oil demand in the transport sector, while its PM emissions can be duly addressed.

If one combines GCC and LAP policy, there is little to gain in terms of additional reductions in PM emissions, since LAP policies alone already rid most of these emissions. For CO_2, however, Fig. 3 demonstrates that by combining GCC and LAP policy extra CO_2 emission reductions are achieved, that is, more than follows from the sum of the application of either policy alone. By comparing the GCC and GCC + LAP scenarios, we find that the synergy between GCC and LAP policy results in an additional energy-related CO_2 reduction of 15% in Western Europe and 20% in China. The explanation is that, by choosing technologies that simultaneously reduce CO_2 and PM emissions, one generates cost savings in EOP abatement that can be utilized to deploy more CO_2 abatement options. In other words, additional CO_2 emission reductions become economically feasible that previously were not. Also, learning dynamics justify higher energy costs for the mid-term, since these lead to lower costs for the long run. This process increases the emission abatement efficiency, as it generates supplementary cost decreases and corresponding savings, augments the CO_2-free technologies deployment potential, and thus yields deeper cuts in CO_2 emissions, achievable under the GCC + LAP scenario but not under the GCC or LAP policy case alone.

3.2. Costs and benefits

Fig. 4 shows the net impact on global welfare, resulting from both costs incurred and benefits obtained, expressed in terms of the percentage change (with respect to the baseline) of the total discounted sum of consumption up to 2150, for each of the three different policy scenarios. For simulating the baseline scenario the GCC loss factor E and the LAP loss term F in Eq. (2) are set to 1 and 0, respectively. For the GCC and LAP scenarios these parameters are ‘switched on’, to values <1 (E in Eq. (3)) when climate change damages are internalized, and >0 (F in Eq. (4)) when PM air pollution damages are internalized. For the GCC + LAP scenario both parameters are switched on. A comparison of the total discounted consumption stream corrected for values of E and F, between the baseline, on the one hand, and the respective scenarios, on the other hand, generates the benefits of GCC and/or LAP policy reported in Fig. 4. The first two bars represent the scenarios in which the external costs of respectively GCC and LAP are separately internalized in the prices of energy services and consumer goods. The third bar denotes the scenario in which both LAP and GCC external costs are simultaneously accounted for. The costs incurred by abatement activity are depicted below the *x*-axis. The avoided monetary damages, i.e. the benefits, resulting from GCC and/or LAP policy are plotted above the *x*-axis. The benefits are differentiated between those related to climate change mitigation (GCC, lower part in red) and PM emissions reduction (LAP, upper part in yellow). Also indicated for each scenario is the cumulative number of premature deaths due to $PM_{2.5}$ emissions and the long-term (2150) equilibrium temperature change with respect to its pre-industrial level as a result of greenhouse gas emissions. For BAU these observables amount to 1024 million and 4.8 °C, respectively, over the period 2000–2150.

A first and important finding from Fig. 4 is that GCC policy delivers benefits not only in terms of GCC but also for LAP, while purely LAP-oriented policy essentially only brings forward LAP benefits. Fig. 4 also demonstrates that in all three scenarios the benefits gained from environmental policies largely outweigh the costs of these policies. The explanation is that these policies lead to significant reductions in damaging CO_2 and PM_{10} emissions through relatively affordable means, achieved by a reallocation of financial resources to implement new energy technologies and EOP-abatement measures.

The first bar shows that internalizing GCC externalities in MERGE yields a clear net improvement in global welfare. The result that not only benefits materialize in terms of GCC, but also of LAP, can also be found in the co-benefit literature (see e.g. Criqui et al., 2003; van Vuuren et al., 2006). The avoided monetized damages of LAP appear to be in the same order of magnitude as the benefits of GCC. The reason is that carbon-free technologies such as renewables involve simultaneously lower PM_{10} emission intensities. The reduction of LAP damages occurs in the medium term, whereas GCC benefits only manifest themselves by the end of the century. The discounted avoided damages of LAP turn out to be about as large as the discounted benefits in terms of GCC.

The second bar shows that internalizing LAP damages yields a net global welfare improvement that is significantly larger than in the first case. Moreover, we find that internalizing LAP damages in MERGE leads to an optimal solution with environmental benefits at the global level, as a result of PM emissions abatement, that largely outweigh the climate benefits as calculated with the original MERGE model. The difference is as much as a factor of approximately 5. The LAP scenario, however, yields essentially zero GCC benefits.[11] The first reason is that LAP reduction is mostly achieved through the installation of EOP technologies that strongly abate the emissions of PM, but which only slightly reduce CO_2 emissions. Second, it proves that a switch in fuel-mix by the deployment of renewables, or a change in the nature of electric supply by solar, nuclear, and biomass energy, as means to reduce PM emissions, only start materializing in the long term, i.e. after 2040.[12] As a result, their significance in controlling the change in global atmospheric temperature remains small. In addition, it proves that much of the CO_2 emission reductions that are realized are partly offset by an expansion of the aforementioned clean-coal technologies, that is, coal-based technologies that are retrofitted with PM-abatement techniques (and as such receive an impetus from LAP policy, as they are generally cost-competitive) but remain potent CO_2 emitters. The impulse given to such clean-coal technologies is a perverse effect of LAP policy, as they are counter-productive for climate change control. Thus, overall the LAP scenario does little to reduce the global level of CO_2 emissions, and thus does not generate any real climate change benefits in terms of welfare improvements.

The third bar in Fig. 4 shows that there are synergies to be obtained from simultaneously internalizing LAP and GCC externalities in the production of energy and goods. As demonstrated, the costs and benefits of GCC + LAP policy are not merely the sum of those of the individual GCC and LAP scenarios. The total costs of the third scenario are slightly larger than the sum of those of the GCC and LAP policies individually. But the total benefits of the third scenario are clearly larger than the combination of those under the GCC and LAP policies. The increase in benefits is larger than the increase in costs, which implies an overall net welfare gain. Note that the LAP monetized benefits

[11] Under LAP an additional reduction of the temperature level of about 0.1 °C is achieved. The explanation is that policies avoiding LAP improve welfare. At a given temperature level, the willingness to avoid climate change will therefore increase as a result of this welfare improvement.

[12] These renewables prove mostly non-biomass in nature, because e.g. the production and use of ethanol derived from biomass generates PM emissions.

remain the same by going from the LAP to the GCC + LAP scenario, although the cumulative number of premature deaths increases slightly from 63 to 66 million.[13] The GCC benefits, however, clearly increase, as the stabilization temperature becomes 3.0 °C in the GCC + LAP scenario, rather than 3.3 °C in the GCC scenario. This 'bonus' is obtained through the long-term perspective of MERGE, in which a synergy between GCC and LAP policies can be created through a gradual transition of the energy system to one in which 'double-clean' technological options are deployed, i.e. that serve GCC mitigation and LAP reduction at once. The assumptions in MERGE regarding the way future technology cost reductions are achieved, for both new options like renewables and retrofit-ones like EOP-abatement applications, are instrumental herein. Note that the results presented in Fig. 4 are mainly driven by changes taking place in developing countries, as these are assumed to dominate the global economy in the long run.

4. Uncertainty analysis

Like other similar models, MERGE allows for calculating and comparing optimal time-dependent pathways for CO_2 and PM emissions, globally and per region, but can only do so under specific assumptions for the impacts of these emissions. In its cost-benefit mode MERGE generates monetary values for the environmental benefits of climate change mitigation and air pollution reduction, the results for which are dependent on these assumptions. Fig. 5 presents the findings of a detailed uncertainty analysis for the most relevant of these assumptions, in terms of globally aggregated discounted costs and benefits of the implemented policies. Our base case here is the GCC + LAP scenario specified in Fig. 4. Costs (the blue bars below the *x*-axis) and benefits (the red and yellow bars above the *x*-axis, differentiated between GCC and LAP) are expressed as percentage change of total discounted consumption with respect to BAU, for each of the different parameter variations. The numbers shown in the upper bars refer to the ratio of LAP to GCC benefits. For example, as indicated in the first bar, for the base case this ratio is about 5. The numbers above the figure are the calculated global mean temperature changes (3 °C in the base case) and those below the plot the numbers of premature deaths over the period 2000–2150 (66 million in the base case). All respective sensitivity variations are clarified in more detail in Sections 4.1–4.8.

4.1. Higher LAP emissions in developing regions

As explained, PM emission coefficients and abatement cost curves for all regions are derived from European data. Given the lack of appropriate data in many parts of the world, we think this is currently the best possible practice. With this approach, however, we are likely to underestimate the PM emission coefficients of developing countries, since our calibration does not reflect the significant implementation in Europe over the past few decades of EOP PM_{10} emission abatement technologies. As a result, in developing countries PM abatement options are also likely to be significantly cheaper than today in Europe. To account for the fact that developing countries have so far probably undertaken less stringent abatement activities than our calibration suggests, and are thus faced with lower marginal costs, we performed a joint sensitivity check. We uniformly increased the energy-related PM emission coefficients for non-Annex I (NAI) regions by a factor of 4, based on an analogous comparison of SO_2 emission intensities (see Foell et al., 1995; Amann et al., 2004a). In parallel we assumed that the first 75% of a given PM emission level can be reduced at the lowest possible marginal costs of abatement activity. These correspond to the marginal costs of the first incremental activity of the MACCs of the base case. We simultaneously lowered α (Eq. (6)) by a factor of 4 to simulate the same base year concentration level as in the benchmark case. The marginal cost of abatement of the remaining 25% of abatement potential is assumed to equal the base case MACC. As a result of these combined changes, the total costs of global PM abatement efforts decrease, while their environmental benefits increase. It proves that the LAP–GCC benefit ratio augments to 6 by this sensitivity test (second column of Fig. 5).

[13] Up to 2030 there are less premature deaths, while beyond 2030 the increase is higher than the deaths avoided before 2030. The discounted mid-term gains appear to compensate the long-term losses.

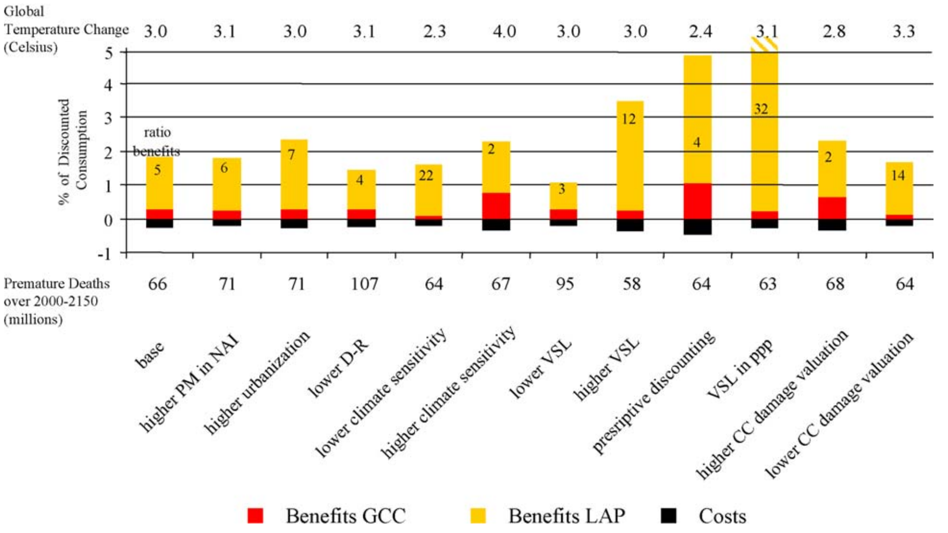

Fig. 5. Sensitivity of GCC and LAP policy costs and benefits, expressed as relative change of total consumption, for a range of important parameter variations.

4.2. Higher urbanization in developing regions

In the base case we assume that, under a growing world population, the ratio between the number of people living in urban versus rural areas remains constant. Especially in developing regions, however, people tend to migrate towards cities and densely inhabited areas. Since PM is mostly emitted in urban areas, the total population in these regions will consequently be more exposed to LAP. Regulating LAP is thus likely to generate more benefits. We have modeled a gradually increasing level of urbanization by letting α in Eq. (6) rise over time. This implies higher $PM_{2.5}$ concentration levels for given emission levels, an indirect way of expressing that more people are exposed to a fixed $PM_{2.5}$ concentration value. We assume that α increases by 0.5%/yr, up to a level of 40% higher than in the base case. The third column of Fig. 5 shows that the corresponding higher urbanization assumptions increase the ratio of LAP versus GCC benefits to 7. The effectiveness of LAP policy thus increases as a result of larger achievable long-term health benefits.

4.3. PM emissions–concentration relationship

What if the relationship between PM_{10} emissions and $PM_{2.5}$ concentrations of Eq. (6) proves to be a square root instead of a linear function? This would mean that we currently over-estimate the effect of emission abatement to reduce $PM_{2.5}$ concentrations. PM emission abatement efforts in reality thus preclude fewer premature deaths than we currently assume. We correspondingly adapted the dose–response (D–R) relation of Eq. (6) to perform a sensitivity exercise, which also involves an adjusted set of values for α in order to achieve the same concentration levels as in the base year of the benchmark case. The result is depicted by the fourth column in Fig. 5. Indeed, the benefits obtained from LAP policy decline, and the ratio of LAP to GCC benefits decreases to 4. Because of the reduced efficacy of LAP policy, the number of premature deaths increases significantly.

4.4. Lower and higher climate sensitivity

One of the most speculative parameters in analyzing GCC is the climate sensitivity, referring to the long-term global average temperature increase that corresponds to a doubling of the atmospheric CO_2 concentration with respect to pre-industrial levels. Under a given climate change control target, this parameter is among the main determinants of the required level of CO_2 emission reduction efforts (see, for example, van der Zwaan and Gerlagh, 2006). In our base case, the climate sensitivity is fixed at 2.5 °C. If the climate sensitivity is lower (higher), the damages incurred by CO_2 emissions will be lower (higher), and thus will call for less (more) climate mitigation efforts, and correspondingly yield less (more) benefits of GCC policy. Given the observed link between GCC and LAP policy, lower benefits of GCC policy involve (somewhat) lower benefits of LAP policy. We investigated the climate sensitivity values of 1.5 °C (low case) and 4 °C (high case), which resulted in a decrease, respectively increase, of the benefits of GCC policy, as demonstrated by the fifth and sixth columns in Fig. 5. The corresponding ratio of LAP versus GCC benefits proves to move up to 22, respectively down to 2. In the high climate sensitivity variant, which results in the lower bound of all LAP–GCC benefit ratios derived in our multiple sensitivity exercises, this ratio is still well above 1.

4.5. Lower and higher VSL

Assumptions with regards to VSL are key to cost-benefit analysis. In our base case we assume a VSL of 1.06 million US$, a value adopted in the CAFE program (Holland et al., 2005). The same reference reports a VOLY of 57,300 US$, which we multiply by the presumed value of 10 for YOLL as a result of chronic exposure to $PM_{2.5}$ in Europe (Pope et al., 2002). For our VSL sensitivity exercise, we adopt the resulting figure of 0.57 million US$ as lower bound. For the upper bound we assume a value of 2.1 million US$, which corresponds to the estimate for VSL in the USA (US-EPA, 1999).[14] With a lower (higher) value for VSL, there is reason to spend less (more) on PM emission abatement, so that less (more) LAP damages are avoided. The ratio of LAP–GCC benefits proves to decrease to 3, respectively increase to 12 (seventh and eighth columns of Fig. 5). The total costs of combined LAP and GCC policy are reduced by 30% when the value of VSL is reduced by 50%, and increase with 33% when the value of VSL is doubled. The total benefits are multiplied, respectively divided, by a factor of about 2 in these two cases.

4.6. Prescriptive versus descriptive discount rate

One of the main reasons that, in all our sensitivity scenarios, the avoided damages from GCC policy are found to be smaller than those from LAP policy is that GCC is intrinsically a long-term problem. Both climate damages and the effects of climate change mitigation only become manifest in the long run, and are thus discounted accordingly, with a rate determined by the present-day valuation of the impacts. We explored the consequences of two opposing views with respect to discounting. The utility discount factor, u in Eq. (2), equals the difference between the Marginal Productivity of Capital (MPC) and the per capita growth rate of GDP. In our base case, we adopt a descriptive view of discounting, with an MPC of 5% in 2000 that declines linearly to 3.5% in 2150 (see Manne, 1995). For our prescriptive case, we assume a value of 0 for MPC throughout the entire modeling horizon. Switching from a descriptive to a prescriptive approach enhances the importance of long-term GCC damages, and thus spurs climate change mitigation. The LAP–GCC benefits ratio therefore drops, to a value of 4 as shown by the ninth column in Fig. 5, and the optimal long-term temperature increase reduces to 2.4 °C.

4.7. VSL dependence on GDP expressed in MER or PPP

The value of VSL is region-specific, as low-income countries value premature deaths lower than wealthier ones. All regional VSL values in 2000 are obtained through normalization on the basis of GDP per capita relative to that in Western Europe. The latter, in turn, is measured in Market Exchange Rates (MER). Normalizing instead with GDP per capita expressed in terms of Purchasing Power Parity (PPP) would imply a higher VSL for developing regions, and thus a larger incentive to mitigate LAP in countries like China and India. To explore the relevance of this alternative assumption, in Eq. (4) we replaced GDP expressed in MER by GDP expressed in PPP. We did so by applying the rule (obtained

[14] We adopt the rule that the "environmental VSL" that we are interested in here equals 1/3 of the total VSL reported in that study, like in Holland et al. (2004).

through a linear regression, as in Manne and Richels, 2003):

$$\frac{PPP_{t,r}}{Y_{t,r}} = 1 + 1.25\left(\frac{P_{t,r}}{Y_{t,r}}\right) \tag{10}$$

in which Y is GDP expressed in MER, PPP is GDP expressed in PPP, and P is the size of the population.[15] Because this equation implies that for all developing regions VSL is increased considerably, the LAP–GCC benefit ratio at the global level increases, up to 32 (tenth column of Fig. 5). Obviously, under PPP assumptions a strongly increased incentive exists for stringent LAP policy in the developing part of the world, which reduces the total number of premature deaths down to 63 million. Meanwhile the optimal temperature change becomes slightly higher, by about 0.1 °C. The reason is that relatively cheap clean-coal-fired power stations are stimulated that prevent PM-related deaths but are not beneficial to mitigating global warming.

4.8. Higher and lower climate change damage valuation

For the valuation of non-market climate change damages the use of a WTP parameter proves crucial. Its value is speculative, however, and thus necessitates an uncertainty test. For our sensitivity analysis we investigate two variations, one involving a higher and the other a lower value for the WTP to prevent climate change damages. In our base case, at a 2.5 °C global temperature increase, we assume in the OECD a non-market GDP loss of 2%. In developing countries these losses are much lower but increase at higher income levels. For instance, when India achieves an income level of 25,000 US$ per capita, its WTP is assumed to increase to 1% of GDP. We doubled the central value for the non-market losses in our upper case, and halved it for the lower case. The former implies that for high-income countries the loss equals 4% of GDP under a 2.5 °C global temperature increase. Naturally, a higher (lower) WTP increases (decreases) the benefits of GCC policy. As a result of our upward and downward WTP variations, the ratio of LAP to GCC benefits reduces to 2, respectively increases to 14 (last two columns in Fig. 5).

5. Conclusions and recommendations

To our knowledge, this article is the first to present a cost-benefit analysis that combines the damages resulting from global climate change and local air pollution. We demonstrate that MERGE, originally a global welfare optimization model of the energy–economy–environment system capable of investigating climate change policies only, can be extended with pollutants other than greenhouse gases. With our adapted version of MERGE we perform an integrated assessment of the long-term conundrum of climate change mitigation and the short-term challenge of reducing local air pollution, including for each the associated costs and benefits. Since these environmental problems are both driven by present energy production and consumption patterns, they constitute an inseparable pair that should, as we have pointed out, ideally be studied together.

Our first main result is that the benefits of policies mitigating the emissions of CO_2 and PM_{10} largely outweigh the costs of these policies, even while they induce important reallocations of resources to new (e.g. renewable) energy technologies and end-of-pipe abatement techniques (rendering fossil-fuel usage clean). Our second finding is that, as expected, GCC policy significantly reduces CO_2 emissions and to some extent also PM emissions, while LAP policy induces radical PM emission reductions with negligible effect on the level of CO_2 emissions. Third, combining GCC and LAP policies generates little further PM emission reductions, but clearly achieves extra CO_2 emission reductions, that is, more than the sum of the reduction levels generated by either policy alone. Thus, a beneficial synergy between GCC and LAP policy can be created, with, as it proves, an additional energy-related CO_2 emission reduction of 15% in Western Europe and 20% in China. Fourth, we find that GCC policy also delivers a welfare co-benefit in terms of lower LAP, while LAP-directed policy only generates welfare gains in terms of LAP benefits. The explanation is that under GCC policy modest PM emission

[15] Hence, with lower income the difference between GDP expressed in MER respectively PPP becomes larger. Since this equation derives from a simple fitting procedure, no causality is implied. The constants are not dimensionless.

reductions are achieved as a result of the installation of new technologies like renewables that simultaneously reduce CO_2 and PM emissions. Fifth, we find that LAP policy leads to global environmental benefits that largely outweigh the benefits from GCC policy, by half an order of magnitude. Sixth, also in terms of costs and benefits we observe that a bonus can be created through a synergy of GCC and LAP policy, as the net welfare gain of combined GCC and LAP policy is higher than the sum of the gains of GCC and LAP policy alone. This welfare gain proves to be mostly employed to further mitigating climate change.

Our overall finding is that it is more urgent to address the problem of local air pollution than that of global climate change. The main reason is that the short-term benefits that may be obtained from air pollution control are much larger than the long-term benefits obtainable through strategic climate change measures, while the associated costs are in both of these policy cases much lower than the achievable benefits (even with very low discount rates, see also our sensitivity analysis). So, most environmental and human health policy today should be dedicated to local air pollution. We do certainly not suggest, however, that climate change policies should be neglected or postponed. Rather we advise to combine already today our first priority (LAP control) with our second (GCC mitigation), because there is a clear bonus to be gained in terms of climate change control by jointly implementing both policies. In this article we suggest that climate change mitigation is an ancillary benefit of air pollution policy, rather than the other way around: LAP control combined with GCC policy creates an extra early kick-off for the transition towards climate-friendly energy supply.

The benefits of climate change policy will be experienced much further in the future than those of air pollution policy, and thus are subject to more substantial discounting. This of course much contributes to our finding that the difference between the monetized benefits of avoided air pollution and precluded climate change is large. Given the importance of discounting assumptions for this principal result, we have modified our descriptive approach to one of a prescriptive nature in our sensitivity analysis (that is, replacing high discount rate values with low ones). But still we find essentially the same outcome. Since there are many other uncertainties involved in cost-benefit analysis, we have changed our assumptions regarding all main modeling parameters, which allows for an assessment of the robustness of our conclusions. We have reported in detail the specific variations applied to our assumptions concerning the principal driving forces behind our results. All of these confirm our conclusion that the benefits obtainable through LAP policy largely outweigh those of GCC policy, at least by a factor 2, and in most cases of our sensitivity study much more.

Our investigation has revealed the mutual relevance of policies designed to address the associated challenges of GCC and LAP. Strategies restricting to long-term climate change are likely to improve air quality, as emissions of both CO_2 and PM are often reduced at once. Alternatively, however, by only controlling local air pollution one only little helps to reducing emissions of CO_2 and hence to mitigating climate change. PM emission reductions are typically achieved through end-of-pipe applications that do not simultaneously affect emissions of CO_2. Yet even while the latter may be true, we have shown that a combined GCC plus LAP policy generates extra benefits in terms of climate change mitigation. Given this effect, we thus advise (1) policy makers to design and implement combined GCC and LAP strategies, and (2) analysts and scientists to correspondingly study these environmental challenges jointly. With this article we hope to have made an insightful first step.

An interesting corollary is a comparison of our results with those of Rabl et al. (2005). They report, like we do here, that uncertainties in damage costs distinctly affect cost-benefit analyses of environmental pollution. Still, they point out that, for a range of different pollutants, the social cost penalty is remarkably insensitive to errors in the assumed damage costs. Their main finding, namely that it is optimal to achieve significant emission reductions for all effluents analyzed, continues to hold under large variations of external environmental costs. The results presented here have also been subjected to an extensive robustness analysis regarding a range of possible uncertainties that relate to air pollution and climate change damage costs. Also our main finding, the predominance of LAP concerns above those for GCC, remains unaffected under a wide span of parameter values related to CO_2 and PM induced damages.

In this article we employed conservative estimates for the impact of ambient concentrations of $PM_{2.5}$ on mortality by neglecting some important contributing sources. Among these are the use of traditional fuel-wood in non-Annex I countries, the second-order formation of fine particulates through emissions of SO_x, NO_x, and NH_3, as well as (and in particular) process-related emissions. Still, even with these conservative estimates, our results point at LAP being the primary concern, and GCC the secondary. While we definitely do not want to discard the problem of GCC, LAP policy should be given clear priority. Furthermore, a GCC plus LAP policy can 'lock' the world deeper into climate change mitigation than GCC policy alone.

The two large developing countries, China and India, deserve a last remark, as they are likely to soon become dominant players in the global economy and will almost certainly increasingly become dependent on fossil fuels. They will without doubt continue their use of coal throughout much of the 21st century, also given their large domestic coal resources (see e.g. van der Zwaan, 2005). The sense of urgency to deal with local and regional pollution will be felt especially in these countries: already now their large cities are plagued by a severe deterioration of the ambient air. Several commercial end-of-pipe technologies exist that constitute clean complements to the traditional use of coal, which allows these nations in the short term to switch away from dirty coal combustion and benefit from the corresponding avoided air pollution damages. Still, they will not solely want to focus on LAP, but also need to start considering GCC, and thus contemplate the use of renewable energy resources like solar energy and wind power, or options like hydropower and nuclear energy, or the continued use of fossil fuels but complemented with CCS technology. This study shows that such climate mitigation options, however desirable and necessary, should first and foremost be carefully considered against the simultaneous benefits they engender in terms of their potential contribution to reducing local air pollution.

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