DISSERTATION

DEVELOPMENT AND ASSESSMENT OF FUTURE AIR POLLUTION PATHWAYS

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DECLARATION OF AUTHORSHIP

Unless otherwise indicated in the text or references, or acknowledged above, this dissertation is entirely the product of my own scholarly work. All direct or indirect sources used are acknowledged in the references. I am aware of the University's regulations concerning plagiarism, including those regulations concerning disciplinary actions that may result from plagiarism.

The PhD thesis presented here has not been submitted, either as a whole or in part, for a degree at this or any other university or institution. Furthermore, I certify that the printed version is equivalent to that submitted electronically.

Vienna, December 2016 Shilpa Rao

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“All the world’s a stage,

And all the men and women merely players:

They have their exits and their entrances;

And one man in his time plays many parts.”

—As You Like It, William Shakespeare

SUMMARY

This dissertation focuses on the development and analysis of long-term scenarios of air pollutants. The primary goal is to develop consistent and comprehensive global trajectories of a future air pollution emissions including a wide range of assumptions related to energy systems development, mitigation technologies, air quality legislations and institutional capacity. A secondary objective is to understand the achievement of short-term air quality and health related goals and the combination of policies that can facilitate that.

This dissertation describes the progressive advancements in the modeling and development of air pollution scenarios in integrated assessment models. The scenarios span a wide range of assumptions on technological development and extent and implementation of air pollution policies. They further include policies on climate change and energy access in an effort to understand the implications of multiple policies for air pollution and health outcomes.

The findings in this dissertation support the notion that scenarios generated by energy–economy–climate models can provide critical information to the ongoing policy debate on aligning global and national actions to achieve key SDGs related to air pollution and climate change. The comprehensive research framework provided by the compilation of this thesis provides key results that contribute to the understanding of crucial and decisive aspects related to the possible evolution of air pollution emissions in the future.

Key overarching findings include:

- *Attitudes to pollution control will be critical for achievement of reductions in air pollution and achievement of national goals on air quality. With globally successful implementation of strong pollution controls, by mid-century emissions decline globally by 30-50% in the baseline scenarios and up to 70% in the climate mitigation scenarios. With partial implementation of current and planned air pollution controls, global pollutant emissions do not substantially decline and even slightly increase in the mid-term.*

- *Transformations in the energy system due to policies on energy efficiency and access to new technologies and alternate fuels will be critical in determining the global air pollution burden in the future.*
- *The technological transformations afforded by climate mitigation policies could support ongoing efforts on pollution control and are effective in protecting large parts of global population from harmful levels of particulate matter, especially in Asia and Africa. However, the required scale and speed of reductions in air pollution across multiple sectors and pollutants vis-a-vis inherent constraints related to the replacement of fossil fuels over shorter time frames; and the potential tradeoffs from climate policy through the increased use of biomass in the short-run, imply that there will be a need for integrated multi-sector air quality management systems.*
- *In developing countries in South Asia and Africa, policies on energy access will be particularly important in terms of complying with targets on ambient air quality.*

The results highlight the need for adequate strengthening of institutional mechanisms that facilitate multi-sector controls and the provision of adequate infrastructure for monitoring and implementation of policies.

The dissertation identifies an urgent need for policy incentives driven by air quality and health concerns. The research framework also paves the way for future efforts related to the enhancement of methodological sophistication and policy relevance in scenario development concerning air pollution.

KURZFASSUNG

Die vorliegende Dissertation beinhaltet die Entwicklung und die Analyse von langfristigen Szenarien Luftschadstoffemissionen. Das primäre Ziel ist, konsistente und umfassende globale Trajektorien zu entwickeln, die auf Basis einer breiten Palette von Annahmen imstande sind, die zukünftige Freisetzung von Luftschadstoffen in die Atmosphäre abzuschätzen. Dafür werden Zusammenhänge zwischen der Entwicklung des Energiesystems, von Technologien zur Schadstoffminderung, der Gesetzgebung zur Luftreinhaltung und vorhandener institutioneller Kapazitäten analysiert und deren Auswirkungen für die regionale Luftqualität und Gesundheit abgeschätzt. Ein weiteres Ziel ist es, die Synergien aufzuzeigen, die eine ambitionierte Politik zum Klimaschutz auf die erwähnten Umweltwirkungen ausüben kann. Diese Dissertation verwendet eine Reihe von Energie- und Treibhausgasszenarien nach dem aktuellen Stand der Forschung und erweitert und entwickelt sie, um umfassende Schätzungen der Emissionen einer Anzahl von Luftschadstoffen über den Zeitraum eines Jahrhunderts zu ermöglichen. Die Szenarien beinhalten aktualisierte Emissionsinventuren von Luftschadstoffen, die sowohl die Gesetzgebung als auch die technischen Möglichkeiten über die nächsten Jahrzehnte berücksichtigen. Alternative Szenarien wurden entwickelt, die eine unterschiedlich stringente Umsetzung der technischen Möglichkeiten zur Reduktion von Luftschadstoffen über die nächsten Jahrzehnte berücksichtigen. Die mit diesen Szenarien verbundenen Auswirkungen auf die regionale Luftqualität und die Gesundheit der Bevölkerung werden im Detail analysiert. Die Szenarien dieser Dissertation erweitern signifikant frühere langfristige Schätzungen zur Luftverschmutzung durch die Einbeziehung diverser Annahmen zur Umsetzung der bereits implementierten und geplanten Politik zur Luftreinhaltung. Unsicherheiten in Hinblick auf die künftige Implementierung von Maßnahmen und auf die technologischen Entwicklungen im Energiesystem erweisen sich als kritische Größen für die resultierende Luftqualität in den nächsten Jahrzehnten. Klimaschutzmaßnahmen können die laufenden Bemühungen zur Bekämpfung der Luftverschmutzung unterstützen und sind wirksam, weite Teile der Weltbevölkerung vor gesundheitsgefährdenden Konzentrationen von Feinstaub zu schützen, vor allem in Asien und Afrika. Das erforderliche Ausmaß und die Geschwindigkeit der Verringerung der Luftverschmutzung gegenüber den inhärenten Einschränkungen, die der Ersatz von fossilen Brennstoffen mit sich bringt, und insbesondere die Problematik der kurzfristig erforderlichen erhöhten Nutzung von Biomasse, die auch den Ausstoß von Schadstoffen erhöhen kann, implizieren, dass ein Bedarf für ein integriertes multisektorales Luftqualitätsmanagementsystem besteht.

PREFACE

This dissertation is based on a series of papers. 4 of these are first author publications while 3 of these are co-author (second author publications). The papers are listed below in chronological order of publication with my contribution listed. I fully acknowledge all co-authors on all publications. The underlying scenarios used and developed in the dissertation are fully acknowledged both in the papers as well as in the Appendix.

> Riahi, K., **S. Rao**, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic and P. Rafaj (2011). "RCP 8.5—A scenario of comparatively high greenhouse gas emissions " Climatic Change 109: 33–57. http://link.springer.com/article/10.1007/s10584-011-0149-y

SR contributed through development of the scenario with inclusion of pollutant emissions, analysis of the results and participated in writing of the paper.

> **Rao S**, Chirkov V, Dentener F, Dingenen RV, Pachauri S, Purohit P, Amann M, Heyes C, Kinney P, Kolp P, Klimont Z, Riahi K, Schoepp W Environmental modeling and methods for estimation of the global health impacts of air pollution Environmental Modeling and Assessments. 17 613-622 **2012** http://link.springer.com/article/10.1007%2Fs10666-012-9317-3

SR led the effort on laying out the methodology for representing air pollution and impacts and wrote the paper with participation of all co-authors.

> **Rao S**, Pachauri S, Dentener F, Kinney P, Klimont Z, Riahi K, Schoepp, W., Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. Global Environmental Change. **2013**;23(5):1122-30.; http://www.sciencedirect.com/science/article/pii/S0959378013000770

SR led the effort on developing scenarios of air pollution and impacts and wrote the paper with participation of all co-authors

> Rogelj J, **Rao S**, McCollum DL, Pachauri S, Klimont Z, Krey V, et al. Air-pollution emission ranges consistent with the representative concentration pathways. Nature Clim Change. **2014**;4(6):446-50. http://www.nature.com/nclimate/journal/v4/n6/full/nclimate2178.html

SR contributed through scenario contributions, analysis of the results and participated in writing of the paper.

> **Rao S**, Klimont Z, Smith SJ, Van Dingenen R, Dentener F, Bouwman L, et al. Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change.; **2016** http://www.sciencedirect.com/science/article/pii/S0959378016300723

SR led the work on development of the storylines and the multimodel analysis of the scenario results with participation of other colleagues. SR also led the work on representing the pollution scenarios in the MESSAGE model.

Smith SJ, **Rao S**, Riahi K, van Vuuren DP, Calvin KV, Kyle P. Future aerosol emissions: a multi-model comparison. Climatic Change. **2016**:1-12. http://link.springer.com/article/10.1007/s10584-016-1733-y

SR contributed through scenario contributions, analysis of the results and participated in writing of the paper.

Rao S., Klimont Z, Leitao J, Riahi K, , van Dingenen R, Aleluia Reis L, Katherine Calvin, Frank Dentener, Laurent Drouet, Shinichiro Fujimori ,Harmsen, J.H.M, Gunnar Luderer, Chris Heyes, Jessica Strefler, Massimo Tavoni, Detlef van Vuuren; A multi-model assessment of the co-benefits of climate mitigation for global air quality, **2016**, Environment Research Letters, Volume 11, Number 12

SR led the effort on laying out the methodology for representing air pollution and impacts across models and wrote the paper with participation of all co-authors. SR also led the work on representing the pollution scenarios in the MESSAGE model.

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Abbreviations & Units

GHG	Greenhouse gases
LAP	Local Air Pollution
AQ	Air Quality
IAM	Integrated Assessment Model
CO_2	Carbon-dioxide
CO_2-eq	Equivalent emissions of GHGs expressed in CO_2 values
CH_4	Methane
SO_2	Sulfur dioxide
CO	Carbon Monoxide
VOC	Volatile Organic Compounds
PM	Particulate matter
$PM_{2.5}$	Fine particulate matter, with an aerodynamic diameter of less than 2.5 µm
AQG	Air Quality Guidelines, usually expressed as $\mu g/m^3$
GDP	Gross Domestic Product. Defined in Market Exchange Rate (MER) or Purchasing Power Parity (PPP)
PAF	Population-attributable fraction
RR	Relative Risk
DALY	Disability adjusted Life Years (DALYs)

1. INTRODUCTION

Air pollution in urban areas originates from a number of sources including power plants, industrial stacks, vehicular traffic, domestic coal burning, fossil fuel burning and many other anthropogenic activities. In rural areas, the major sources of air pollution are domestic fuel burning, traditional cooking stoves and agricultural emissions such as pollen, biomass burning etc. Naturally occurring processes, like dust storms, volcanic eruptions etc., also contribute to air pollution significantly. As a result, air pollutants such as suspended particulate matter (SPM), particulate matter (PM10), sulfur dioxide (SO_2), oxides of nitrogen (NOx), carbon monoxide (CO), hydrocarbons (HC), volatile organic compounds (VOC), methane (CH_4), benzene, and ammonia (NH3), are released into the air environment.

Combustion of fossil fuels for transportation, power generation, and other human activities produce a complex mixture of pollutants. The precise characteristics of the mixture in a given locale depend on the relative contributions of the different sources of pollution, and on the effects of the local geo-climatic factors. The relative contribution of different combustion sources is a function of economic, social and technological factors.

Particulate matter (PM) is the generic term used for a type of air pollutants, consisting of complex and varying mixtures of particles suspended in the air, which vary in size and composition, and are produced by a wide variety of natural and anthropogenic activities. Major sources of particulate pollution are factories, power plants, refuse incinerators, motor vehicles, construction activity, fires, and natural windblown dust. The size of the particles varies (PM2.5 and PM10 for aerodynamic diameter smaller than 2.5 μm and 10 μm respectively) and different categories have been defined: Ultrafine particles, smaller than 0.1 μm in aerodynamic diameter, Fine particles, smaller than 1 μm, and coarse particles, larger than 1 μm. The size of the particles determines the site in the respiratory tract that they will deposit: PM10 particles deposit mainly in the upper respiratory tract while fine and ultra-fine particles are able to reach the lungs. Among the parameters that play an important role for eliciting health effects are the size and surface of particles, their number and their composition. There is strong evidence to support that ultra-fine and fine particles are more hazardous than larger ones (coarse particles), in terms of mortality and cardiovascular and respiratory effects.

Ambient (outdoor) air quality is a major concern in many parts of the world. Epidemiological research over the past two decades indicates that both acute- and chronic exposure to ambient air pollution is associated with adverse health effects. Air pollution has significant negative impacts on human health, in the form of cardiovascular, respiratory and other effects, on mortality, morbidity and well-being (1-3). More than 80% of the world's population is exposed to levels of air pollution exceeding the World Health Organization (WHO)(http://www.who.int/en/) recommended levels (4) with more than 3.6 million deaths attributed to ambient air pollution and another 4 million from household related sources(5). This has led to air pollution becoming a priority concern in diverse international communities and a renewed focus on standards and policies across multiple sectors to reduce emissions and improve air quality.

1.1. DRIVERS OF AIR POLLUTION

A number of factors contribute to pollution levels. Assuming increases in population and economic growth, emissions are likely to be driven by additional demands for energy and transportation services, among other factors. Countering these factors, economic and policy drivers may result in technology change, including energy efficiency improvements and reduced pollutant emissions rates. Additionally, pollution outcomes are also very much related to policy decisions on a number of other critical issues including energy access to modern fuels; land-use management; urban development; and climate change.

The drivers of pollution are complex and the subject of on-going debate and research (6). Air pollution in a given region can be regarded from a number of viewpoints. From a physical perspective, air pollutant levels are a function of regional emissions, influences of emissions from other regions, regional topography, and regional meteorological and chemical influences. From a health impacts perspective, individual exposure or the surface-level concentrations experienced by individuals is an important indicator. Policy variables include economic, political and institutional capacities for implementing air pollutant polices. While pollution control polices may ultimately be aimed at achieving a particular concentration level, policies as implemented actually specify some combination of overall (sectoral or total) emissions targets and emissions control levels.

Economic growth in general leads to declines in energy intensities of economies. The aggregate ratio depends on the structure of the economy as on the energy intensities of sectors or activities, and changes in the ratio over time are influenced almost as much by changes in the structure of the economy as by changes in sectoral energy intensities. Structural change in the energy system through shifts of production between sub-sectors can have a large impact on energy intensity-for example, the shifts to service based economies in some developing countries. This in turn, affects the pattern of energy use and the resulting levels of air pollution.

Income levels have a significant role in the levels of air pollution in various regions by affecting technology choice as well as the general environmental consciousness in the form of the stringency of legislation. Regarding pollutant emissions, there is no unique relationship between either pollutant levels or emission controls and income (6, 7). However, it is clear that the effectiveness of policies to control pollutant levels has a general tendency to increase with income. This effect is particularly evident for emissions of pollutants contributing to particulate matter (PM) concentrations, including primary PM and precursors of secondary PM, in particular SO_2 and NOx emissions which control typically follows those of primary PM.

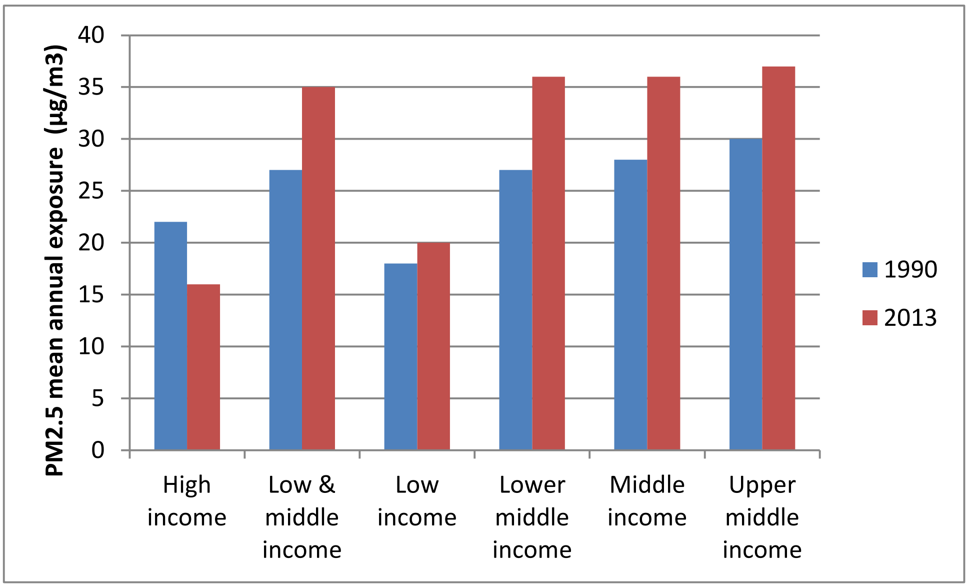


Figure 1-1. Estimated annual average urban ambient PM2.5 concentrations, as a function of GDP per capita.

PM2.5 is the concentration of particulate matter smaller than 2.5 µg in the ambient air. Data derived from World Development Indicators, http://data.worldbank.org/

The observed trends are consistent with the Environmental Kuznets Curve (EKC) hypothesis that postulates that environmental quality first declines, and then improves, with income growth. However, this needs to be viewed side-by side with the reality that many developing countries controls of air quality are happening at faster rates than observed in the past in developed countries due to increased environmental awareness and technological diffusion (8-11). While in developing regions like Asia, sulfur emissions have been growing, recent evidence suggests that emissions growth is slowing down and in many large developing countries like China and India, emissions have begun to drop off due to factors other than income levels. The driving forces appear to be economic liberalization, clean technology diffusion, and new approaches to pollution regulation (11, 12). Thus, income while being an important component of pollution control, cannot wholly explain historical and future trends in air pollution.

The EKC is also criticized as often being dependent on different types of environmental pressure and time-periods. Moreover, critics urge to focus on decomposition of the underlying processes that drive the generic concept (13). Critics of empirically estimated curves have argued that their declining portions are illusory, because either they are cross-sectional snapshots that mask a long-run "race to the bottom" in environmental standards, or because industrial societies will continually produce new pollutants as the old ones are controlled.

A pervasive technological shift in the energy system towards clean technologies is likely to be a significant factor in determining the pollutant levels, especially in the longer term. For example, in the case of sulfur emissions in the power sector, while continued legislation will most likely bring additional reductions, a growing share of clean coal technologies in developing countries implies that emissions from this sector will decline significantly in any case. Income is not the only nor the most important factor determining to what degree best practice technology is adopted and poverty appears to delay but not prevent the adoption of abatement technology (14).

1.2. AIR POLLUTION LEGISLATIONS

Air pollution policies are driven by concerns over impacts on human health, as well as impacts on natural ecosystems and agriculture. Air pollution polices are generally aimed at reaching specified targets for concentration levels of specific pollutants (typically PM10, PM2.5, NO_2, and ozone) but also goals for ecosystem protection (e.g., from acidification) have been pursued in several regions. These targets take a number of forms, including annual averages and maximum one hourly peak levels. Pollution targets are set and periodically revised at both the global level (e.g. WHO) and by national levels. Policy strength is linked to both political and environmental effectiveness (15). The nature of current pollution control policies vary by region and sector. The techniques used by regulatory agencies, to control pollution range from charges for the right to pollute to regulations that impose limits to the amount of a pollutant.

While the large developed countries have already implemented stringent air quality controls, many large developing countries are in the process of legislating tighter controls on pollutant emissions. Diffusion of these policies and technologies toward developing countries takes place and is expected to continue (10). Developing countries have often implemented pollution controls well in advance, relative to income, as compared to historical experience in currently more affluent regions as a result of economic liberalization, clean technology diffusion, and new approaches to pollution regulation in developing countries (10, 11).

Table 1-1: Comparison of Global Air Quality Standards

	WHO	European Union	India	China
PM2.5 24 hours, micrograms per cubic meter	25	50	60 (60)*	15 (35)**
PM2.5 Annual average, micrograms per cubic meter	10	25	40 (40)*	35 (75)**
Sulfur 24 hour, ppb	8	48	80 (80)*	50 (150)**

*Values in brackets denote ecologically sensitive areas; http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php

**Values in brackets denote standards for urban areas; http://transportpolicy.net/index.php?title=China:_Air_Quality_Standards

1.3. AIR POLLUTION AND CLIMATE CHANGE

Long-term climate change mitigation and the stabilization of greenhouse gases (GHGs) have been the focus of increasing attention over the past few decades. Recent research increasingly highlights the need for large-scale GHG emission reductions both over the short and long-term in order to meet stringent climate stabilization goals (16-19).

Recent research increasingly highlights the role that many pollutants play in climate change (20) and the co-benefits of tackling climate change and air pollution together (see for example (21, 22). Many air pollutants have prominent role as radiative forcers and, therefore, regulating their emissions will have an effect on climate (and vice-versa). Ozone, and its precursors, and particulate matter (especially black carbon and sulfate) are both important pollutants and radiative forcers that can, directly or indirectly, contribute to climate change.

At the same time, air quality is sensitive to climate change which affects physical and chemical properties of the atmosphere and thus drives some weather events with favorable conditions to the build-up of pollution episodes (23). However, policies combating climate change lead to improved energy efficiency, structural changes towards less fossil fuel based technologies and other technical measures that often, as a side effect, reduce atmospheric emissions, thus improving air quality. Indeed, air pollutant and greenhouse gas emissions often share common sources, especially those related to combustion of fossil fuels. While climate mitigation measures are primarily targeted at reducing greenhouse emissions, they also have a collateral impact on co-emitted air pollutants. Reduced energy use due to improved energy efficiency, the use of cleaner energy carriers due to less fossil fuel based technologies, as well as the use of modern technology with higher abatement efficiencies or strict requirements for flue gases all reduce primary air pollutant emissions such as SO_2, NOx, CO and NMVOCs. Consequently, climate mitigation policies can also have economic co-benefits in the form of reduced expenditure for air pollution mitigation efforts. With NOx, SO_2 and NMVOCs being precursor emissions to the formation of secondary particles and tropospheric ozone, health related impacts could also potentially be reduced.

The full understanding of all the links and interactions between air pollution and climate change is not an easy undertaking. On the one hand, the change in atmospheric composition and consequential impacts on humans and ecosystems occur in very different scales (e.g., the lifetime of most pollutants is quite short in comparison to the long lifetime of, for example, N_2O). On the other hand, some pollutants have a positive contribution to the radiative budget (e.g., black carbon, O3) while others are cooling the atmosphere (e.g., sulfates and nitrates). Therefore, aiming at reduction of one problem does not necessarily lead to a decrease of the other and some trade-offs need to be weighted. For instance, the implementation of measures such as wood burning as biofuel to reduce use of fossil fuel and consequent climate impact may in fact deteriorate air quality by increased emissions of PM. Another example is the reduction of ammonia (NH3) emissions in agricultural sector that might lead to enhancement (or reduction) of N_2O and/or CH_4 depending on how it is implemented.

Recent studies have posited that while there is research on the co-benefits of climate mitigation policies, the policy impacts of such co-benefits have been nonexistent or limited (24, 25). There are various reasons placed forward on why the co-benefits are undervalued in evaluating the costs of climate mitigation. Some important issues include uncertainty in climate change related damages and difficulties in metrics and valuation. Another difficulty in evaluating the exact benefits of climate polices to air pollution is the different spatial and temporal scales of the two issues being considered.

While air pollution has historically been regarded as a local and regional problem, with policy structures mirroring this attitude, the longer-term global dimensions of the air pollution challenge are increasingly receiving attention. Policies addressing climate change often, as a co-benefit, reduce atmospheric emissions, thus improving air quality and health (26-29). Linking action on air pollution and climate change supports targets aimed for in a number of recent landmark agreements including the Sustainable Development Goals (SDGs)(30) and the recent Paris agreement of the United Nations Framework Convention on Climate Change (UNFCCC)(31). As pointed out by a recent commentary (32), effective action in this regard will require that the connections between multiple goals and targets to be better understood and the local versus global scale synergies and trade-offs evaluated.

1.4. HEALTH IMPACTS OF AIR POLLUTION

Recent research in air pollution epidemiology during the past decade has identified relationships between multi-year exposure to ambient air pollution and a range of specific life-shortening health impacts, including ischemic heart disease, lung cancer, stroke, acute lower respiratory infection, and chronic obstructive pulmonary disease (33). Prospective cohort studies largely confined to Western countries provide the epidemiological basis for health impact assessments. Such studies recruit large, heterogeneous populations and involve long follow-up periods to quantify the mortality effects of chronic exposure to fine particulate matter. Multivariate regression models are defined to relate ambient pollutant concentrations (typically annual averages calculated from on ground-based monitors) to mortality outcomes. These models include adjustments for confounding variables (such as diet and smoking status) expected to correlate with pollutant exposure, related independently to mortality, and not on the causal pathway between exposure and early death. Research in air pollution epidemiology also explores morbidities associated with both acute and chronic exposure to pollution, including exacerbated asthma attacks and emergency room visits.

The Global Burden of Disease (GBD) (http://www.healthdata.org/gbd) Assessment provides estimates of concentration-response functions for three categories and five causes of death: cardiovascular diseases (ischemic heart disease and cerebrovascular disease/stroke), respiratory diseases (acute lower respiratory infection and chronic obstructive pulmonary disease), and lung cancer (34, 35). More recent GBD efforts (36) have continued the cause-specific analysis to hypothesize about the relative risk functions at higher doses of fine particulate matter in ambient air. Under the assumptions of these studies, the source and precise chemical composition of particulates is less important than the absolute quantity of inhaled pollution; as a result, health impacts due to exposure from ambient air, secondhand smoke, and active cigarette smoking can be aggregated and analyzed along a unified dose-response curve. The model is consistent with a biological saturation hypothesis for the mechanisms underlying respiratory and cardiovascular disease. The revised dose-response relationships suggested by the WHO could have important implications for air quality management and public health policy. Under the assumption of biological saturation and a plateau of health effects, areas with dirtier air at baseline are less amenable to improvements in health relative to their cleaner counterparts, because marginal health impacts are highest at relatively low levels of fine particulate matter. As a result, the new approach implies that policymakers should focus on areas with relatively cleaner air to begin with, because it is in these areas where the most health improvements can still be achieved.

The quantification of the impacts and the value of impact reductions on the one hand, and the cost of investments and actions which can deliver those reductions on the other hand while necessary for policy decisions, are difficult to ascertain. The costs and benefits of controls are regionally diverse and depend on the types of controls, the degree of implementation and institutional capacity in place. There are also significant uncertainties associated with the actual estimation of end-point impacts of climate change and air pollution policies including for example the epidemiological evidence of risks of air pollution (see (5) for summary); measurements and inventories of emissions; and radiative forcing related uncertainties (37). Various studies have estimated that the health and related economic costs of outdoor air pollution could be significant and that the monetized health benefits of air pollution related human health can significantly offset the costs of climate change mitigation (38). However, economic valuation of health effects and mortality is fundamentally controversial as it is based on the premise that human life can be expressed in monetary terms.

1.5. Global climate Scenarios

Integrated assessment models (IAMs) (39) have a long history of development and application for issues of both pollution (for e.g. acidification) and climate change mitigation. IAMs increasingly include and report a number of variables related to economic growth, population, land-use and agriculture that are integral in developing consistent future trajectories of GHGs and pollutants. Emissions scenarios are the most commonly employed tool for climate change research and reflect expert judgments regarding plausible future emissions based on research into socioeconomic, environmental, and technological trends represented in integrated assessment models (40). IAMs are typically used to perform numerous scenario runs for analyzing costs and benefits from a wide range of control strategies and to conduct detailed uncertainty and robustness analyses.

The 'Regional Air Pollution Information and Simulation' (RAINS)-model was one of the first tools for the integrated assessment of alternative strategies to reduce acid deposition in Europe and Asia. The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model (http://www.iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.en.html) was launched in 2006 as an extension to the RAINS model, which is used to assess cost-effective response strategies for combating air pollution, such as fine particles and ground-level ozone. The GAINS model provides, at a global level emission scenarios of a number of pollutants until 2050 under a range of pollution control strategies (41, 42). These scenarios are generally focused on the implementation of most-recent national legislations on air pollution over the next few decades, although more recent work has focused on global air pollution scenarios until 2050 (43). GAINS is used for policy analyses under the Convention on Long-range Transboundary Air Pollution (CLRTAP) under the United Nations Economic Commission for Europe (UNECE) (http://www.unece.org/env/lrtap/), including assessment work under the Task Force on Hemispheric Transport of Air Pollution (TF HTAP) (http://www.htap.org/) .

In a parallel development, long-term (century-long) global scenarios for air pollutant emissions are used for Earth system model simulations intended to examine future changes in climate. The scenarios need to reflect plausible future emissions based on socioeconomic, environmental, and technological trends. These scenarios are generally produced by IAMs, which project economic growth, population, energy consumption, land-use and agriculture along with associated GHG and pollutant emissions. Global emission scenarios for the 21st century were developed by (44) for the Integrated Panel on Climate Change (IPCC) (www.ipcc.ch) and updated by other studies (45). While these scenarios were primarily developed for examining the dynamics of the energy system and the resulting impacts on greenhouse gas emissions, they also provided some indication of how air pollutants (e.g., SO_2) may be affected by the changes in the energy system. More recently, the Representative Concentration Pathway (RCP) scenarios (46), were the first set of comprehensive coordinated global scenarios that included a number of air pollutants produced by multiple IAMs. These were primarily developed for the Coupled Model Intercomparison Project phase 5 (CMIP5) (47), an effort led by Working Group on Coupled Modelling (WGCM) under the auspices of the World Climate Research Program (WCRP) (https://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip5) . The RCPs spanned a common range of climate forcing levels and were not associated with specific socio- economic narratives. These scenarios, while including a representation of air pollution legislations, reflected the prevailing view that air quality policies will be successfully implemented globally and that emissions control technology will continue to evolve and as a result show significant declines in particulate matter (PM) and ozone precursor emissions over the 21st century at a global level (48). More recent scenarios like the Global Energy Assessment (GEA) scenarios (17) and the LIMITS climate policy scenarios (49, 50) have included alternative assumptions on pollution control, in an effort to better understand the role of air pollution control in terms of reference scenario development and the co-benefits from climate policies (see for example (27, 38, 51, 52).

The SSPs are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. Information about the scenario process and the SSP framework can be found in (40, 53). The SSPs aim to characterize socioeconomic challenges to mitigation and adaptation in a reference case without explicit climate policies and without consideration of climate change impacts (53). To allow their broad applicability they have to exclude any climate policy, but can include other policies that are not directly related to climate. These scenarios thus lend themselves to an intrinsic representation of air pollution policies with assumptions on the speed and degree of control directly related to the storylines of the scenarios. The framework is built around a matrix that combines climate forcing on one axis (as represented by the RCPs) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage be evaluated. Figure 1-2 summarizes the links between ongoing global scenario processes

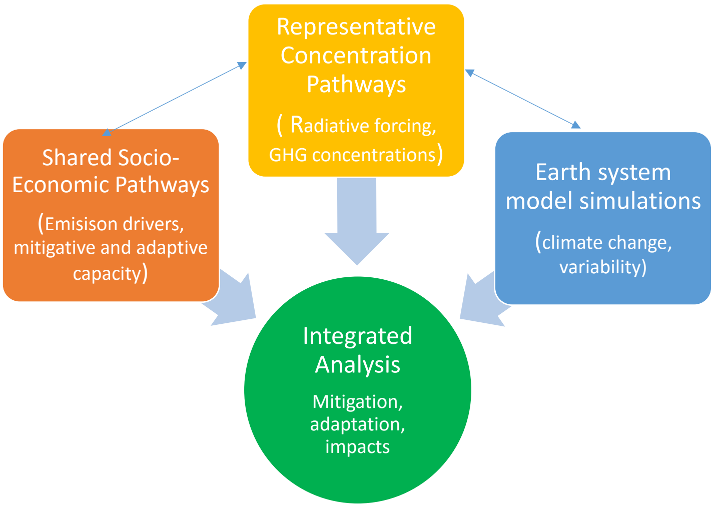


Figure 1-2: Global Climate Scenario Development Processes.

Derived from (37)

1.6. REPRESENTING AIR POLLUTION IN IAMS

An integrated policy approach will require adequate knowledge base and analytical tools that combine information on expected trends in anthropogenic activities that relate to air pollution and information on atmospheric dispersion of emissions including representation of urban areas. This has fueled a critical need for analytical tools and interdisciplinary research that combine information on expected trends in anthropogenic activities that relate to air pollution and greenhouse gases, including urban areas and information on atmospheric dispersion of emissions to adequately examine issues of air quality (24, 54, 55).

For integrated assessment models, a comprehensive inclusion of the development, and impacts of air pollutants means that a number of methodological issues need to be surmounted. These include the need for spatially and temporarily resolved emissions data as well as detailed information on meteorology and other conditions on a global scale to adequately drive atmospheric models. Also pertinent, is the actual estimation of end-point impacts and the various uncertainties that are involved. In order to enable the integration of more sophisticated methods to represent levels of pollution control, there is a need to bridge the gap between the complexity in estimating pollution impacts and the need for simplified representations of the same in IAMs. Another important aspect relates to the historical evidence that pollutant concentration goals will continue to be more ambitious over time, once incomes become sufficiently large; the actual time, stringency, and enforcement success of future targets for a particular region cannot generally be known and must ideally be treated as scenario variable. In a long-term scenario context, it is further necessary that assumptions on air pollution control are consistent with the underlying challenges to climate change mitigation and adaptation. Pollution outcomes in such scenarios can then be expected to be a cumulative result of a range of variables including socio-economic development, technological change, efficiency improvements and policies directed at pollution control as well as alternative concerns including climate change, energy access, and agricultural production.

1.7. RESEARCH QUESTIONS AND OBJECTIVES

This dissertation focuses on the development and analysis of long-term scenarios of multiple greenhouse gases and air pollutants. The primary goal is to develop consistent and comprehensive global trajectories of future air pollution emissions based on wide range of assumptions related to energy systems development, mitigation technologies, air quality legislations and institutional capacity and to analyze their implications for regional air quality and health. A secondary objective is to understand the achievement of air quality and health related goals in the next few decades and the combination of policies that can facilitate that.

This dissertation strives to bridge the gap between the complexity in estimating long-term scenarios of air pollution emissions and their impacts, the ability of available measures, such as emission controls, to mitigate these impacts, and the need for simplified representations of these processes over century time long scales in IAMs.

The central questions for analysis are:

1. How will expected trends of the energy system affect the development of future air pollution?
2. How can we effectively achieve World Health Organization (WHO) or national goals for air quality?
3. How policies can related to air pollution, energy development and climate change mitigation influence the achievement of air quality and health related goals in the next few decades?

To answer these research questions, this dissertation uses a number of recent state-of-the art energy-GHG scenarios, extends, and develops them to provide comprehensive estimates of emissions of a number of air pollutants over a century long time scale. The scenarios are updated to include up-to date information on air pollutant inventories and legislations of air pollution and pollution controls over the next few decades. A number of alternative scenarios based on attitudes to air pollution control over the next few decades are developed. The associated implications of the different scenarios for regional air quality and health impacts are analyzed in detail.

The focus is on ambient air pollution at a global scale. This dissertation describes air pollution emissions and their impacts as related to ambient concentrations of particulate matter and ozone and related human health outcomes. The dissertation does not focus on issues of household air pollution and its impacts, although the papers in the dissertation discuss the implications of policies on access to clean energy in developing countries on ambient air quality. There is increasing evidence that in many developing countries, household air pollution and outdoor air pollution are inherently linked (56, 57). Considerable overlap exists between the underlying disease categories and populations at risk for outdoor and indoor air pollution. As discussed in (58), human exposure to air pollution occurs both indoors and outdoors and an individual's exposure to ambient urban air pollution depends on the relative amounts of time spent indoors and outdoors, the proximity to sources of ambient air pollution, and on the indoor concentration of outdoor pollutants. While it is difficult to accurately estimate the exact extent of the overlap in terms of the resulting impacts, it is estimated at around 16% globally by (59) and recent studies (60) indicate that in some developing nations it could be significant.

As highlighted in Figure 1-3, the focus of the dissertation is related to estimating emissions of air pollution and regional impacts on air quality and health under a multi-policy framework. Hence, while the papers in the dissertation investigate the impacts of climate mitigation policies on selected indicators related to air quality (emissions of key air pollutants, long-term concentrations of PM2.5 and premature mortality), cross-directional impacts as related to the climate (radiative forcing) impacts of mitigation of short-lived climate pollutants are not a focus. While it is clear that these impacts are important, as discussed earlier, a huge body of literature exists on this topic (21, 22, 61).

The health impacts of air pollution are presented in physical indicators including premature deaths (mortality) and morbidity (disability adjusted life years (DALYs). Recent research in air pollution epidemiology during the past decade has identified relationships between multi-year exposure to ambient air pollution and a range of specific life-shortening health impacts, including ischemic heart disease, lung cancer, stroke, acute lower respiratory infection, and chronic obstructive pulmonary disease (33). Various studies have estimated that the health and related economic costs of outdoor air pollution could be significant (38). However, economic valuation of health effects and mortality is fundamentally controversial as it is based on the premise that human life can be expressed in monetary terms.

All scenarios are developed over century long time scales. The scenarios are analyzed across varying time scales to allow for an understanding of key factors affecting the temporal evolution of air pollution. Results on air quality and health are presented for 2030 or 2050 to highlight the policy dimensions of the scenarios.

Figure 1-3 shows the scope of this dissertation.

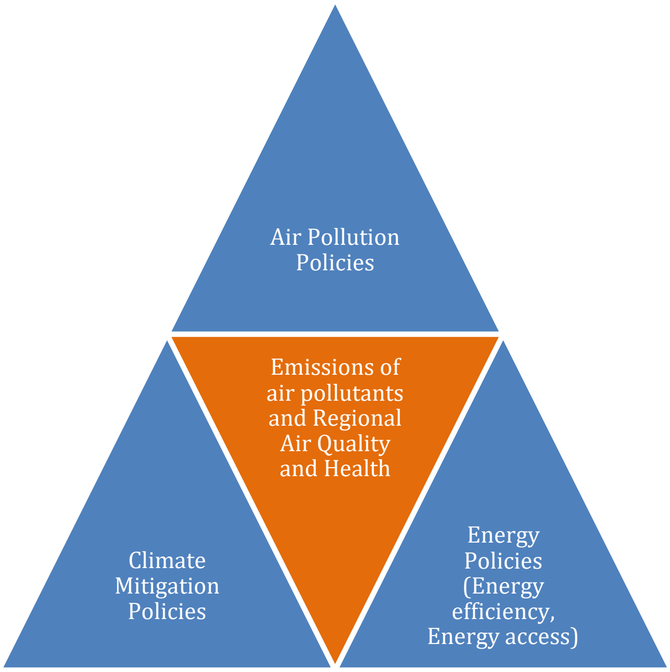


Figure 1-3: Scope of Dissertation

1.8. STRUCTURE OF DISSERTATION

This dissertation is based on 7 published papers. 4 of these are first author publications while 3 of these are co-author (second author publications). The research papers underlying this dissertation describe a series of recent developments in terms of methodological approaches to include air pollution over longer-time frames in scenarios.

Each chapter in the dissertation incrementally builds on the previous one with an aim to indicate progressive advancements in the modeling and development of air pollution scenarios in integrated assessment models (see Figure 1-4). The scenarios span a wide range of assumptions on technological development and extent and implementation of air pollution policies. They further include policies on climate change and energy access in an effort to understand the implications of multiple policies for air pollution and health outcomes.

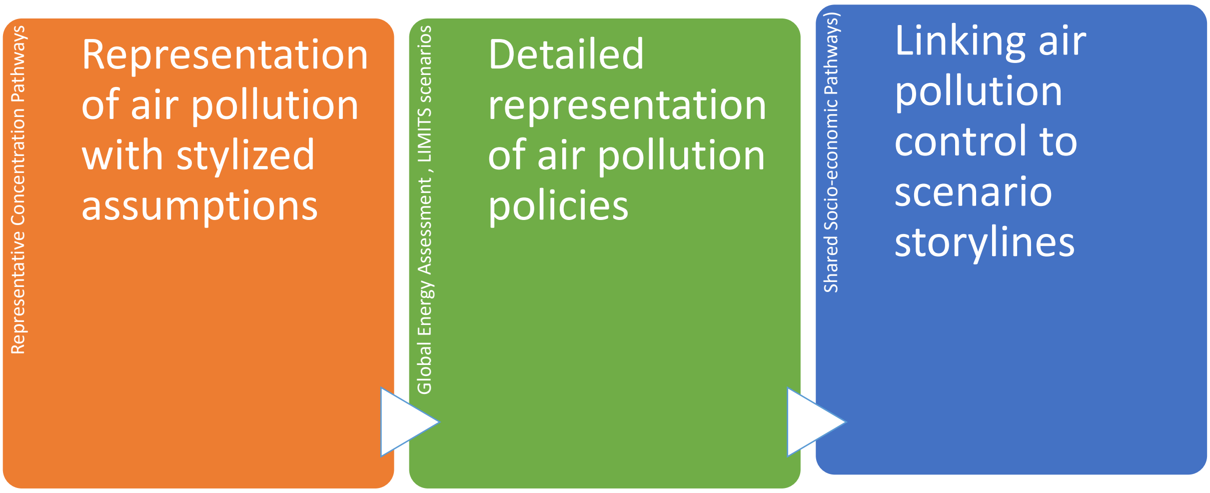


Figure 1-4. : Structure of dissertation

Below is a short description of the following chapters:

Chapter 2 summarizes the methods and tools underlying the dissertation.

Chapter 3 makes the case for the importance of representing air quality legislations in long-term scenarios and highlights the uncertainties associated with modeling air pollution emissions over long-time scales. It uses as a basis for description the RCP scenarios and analyses them in detail with respect to emissions of major air pollutants over century long timescales. The following papers underlie Chapter 3:

- Riahi, K., **S. Rao**, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic and P. Rafaj (2011). "RCP 8.5—A scenario of comparatively high greenhouse gas emissions " Climatic Change 109: 33–57. http://link.springer.com/article/10.1007/s10584-011-0149-y
- Rogelj J, **Rao S**, McCollum DL, Pachauri S, Klimont Z, Krey V, et al. Air-pollution emission ranges consistent with the representative concentration pathways. Nature Clim Change. **2014**;4(6):446-50. http://www.nature.com/nclimate/journal/v4/n6/full/nclimate2178.html
- Smith SJ, **Rao S**, Riahi K, van Vuuren DP, Calvin KV, Kyle P. Future aerosol emissions: a multi-model comparison. Climatic Change. **2016**:1-12. http://link.springer.com/article/10.1007/s10584-016-1733-y

Chapter 4 next focuses on developing scenarios of outdoor air pollution and related health related impacts, given different sets of policies on air pollution, climate change and energy access. The objective of this chapter is to assess how effective such policy combinations could be in delivering improved air quality and health related outcomes.

The following papers are part of Chapter 4:

- **Rao S**, Chirkov V, Dentener F, Dingenen RV, Pachauri S, Purohit P, Amann M, Heyes C, Kinney P, Kolp P, Klimont Z, Riahi K, Schoepp W., Environmental modeling and methods for estimation of the global health impacts of air pollution Environmental Modeling and Assessments. 17 613-622 **2012** http://link.springer.com/article/10.1007%2Fs10666-012-9317-3
- **Rao S**, Pachauri S, Dentener F, Kinney P, Klimont Z, Riahi K, Schoepp, W., Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. Global Environmental Change. **2013**;23(5):1122-30.; http://www.sciencedirect.com/science/article/pii/S0959378013000770
- **Rao S**., Klimont Z, Leitao J, Riahi K, , van Dingenen R, Aleluia Reis L, Katherine Calvin, Frank Dentener, Laurent Drouet, Shinichiro Fujimori ,Harmsen, J.H.M, Gunnar Luderer, Chris Heyes, Jessica Strefler, Massimo Tavoni, Detlef van Vuren; A multi-model assessment of the co-benefits of climate mitigation for global air quality , 2016, Environmental Research Letters, Volume 11, Number 12 http://iopscience.iop.org/article/10.1088/1748-9326/11/12/124013/meta;jsessionid=6F486BDB07D596C9385AAA3DD26621E0.c1.iopscience.cld.iop.org
-

Chapter 5 presents the next stage of development in air pollution representation in IAMs. The objective is to propose scenarios of long/term air pollution that are internally consistent with socio/economic development and challenges to climate mitigation. It uses as a basis the Shared Socio Economic Pathways (SSPs) which are a new generation of scenarios and storylines, primarily framed within the context of climate change mitigation and adaptation. The goal is to develop plausible ranges of air pollutant emissions in the SSP scenarios, based on internally consistent and coherent assumptions on the degree and implementation of future air pollution control. The following papers are part of Chapter 5:

- **Rao S**, Klimont Z, Smith SJ, Van Dingenen R, Dentener F, Bouwman L, et al. Future air pollution in the Shared Socio-economic Pathways. Global Environmental Change.; **2016** http://www.sciencedirect.com/science/article/pii/S0959378016300723
-

Chapter 6 presents the key conclusions of the dissertation.

2. RESEARCH METHODS

In this chapter, the focus is on the modeling framework and scenarios applied in the analysis and subsequent sections detail the methodological contributions for this dissertation. While the papers underlying this dissertation include a detailed description of assumptions made in each individual case, this chapter describes the overall methodological basis.

2.1. DESCRIPTION OF MODELING FRAMEWORK

Given that IAMs do not generally represent explicit pollution control technologies on a detailed level, detailed below is an approach where scenario parameters are broadly represented in terms of changes in emission factors derived from a more detailed air pollution model. This approach allows a relatively simplistic method to represent quantitatively, concepts related to the speed and degree of implementation of pollution control developed and described earlier.

Air quality is estimated using a global air quality source-receptor model (AQ-SRM). This approach of linking emission outcomes from IAMs to a reduced form air quality model enables the computation of multi-model, multi-scenario air quality outcomes. Annual average PM2.5 concentrations (fine particulate matter with diameter less than 2.5 mm) as well as six-month average ozone concentrations are calculated.

Figure 2-1 shows the generic structure of the modeling framework.

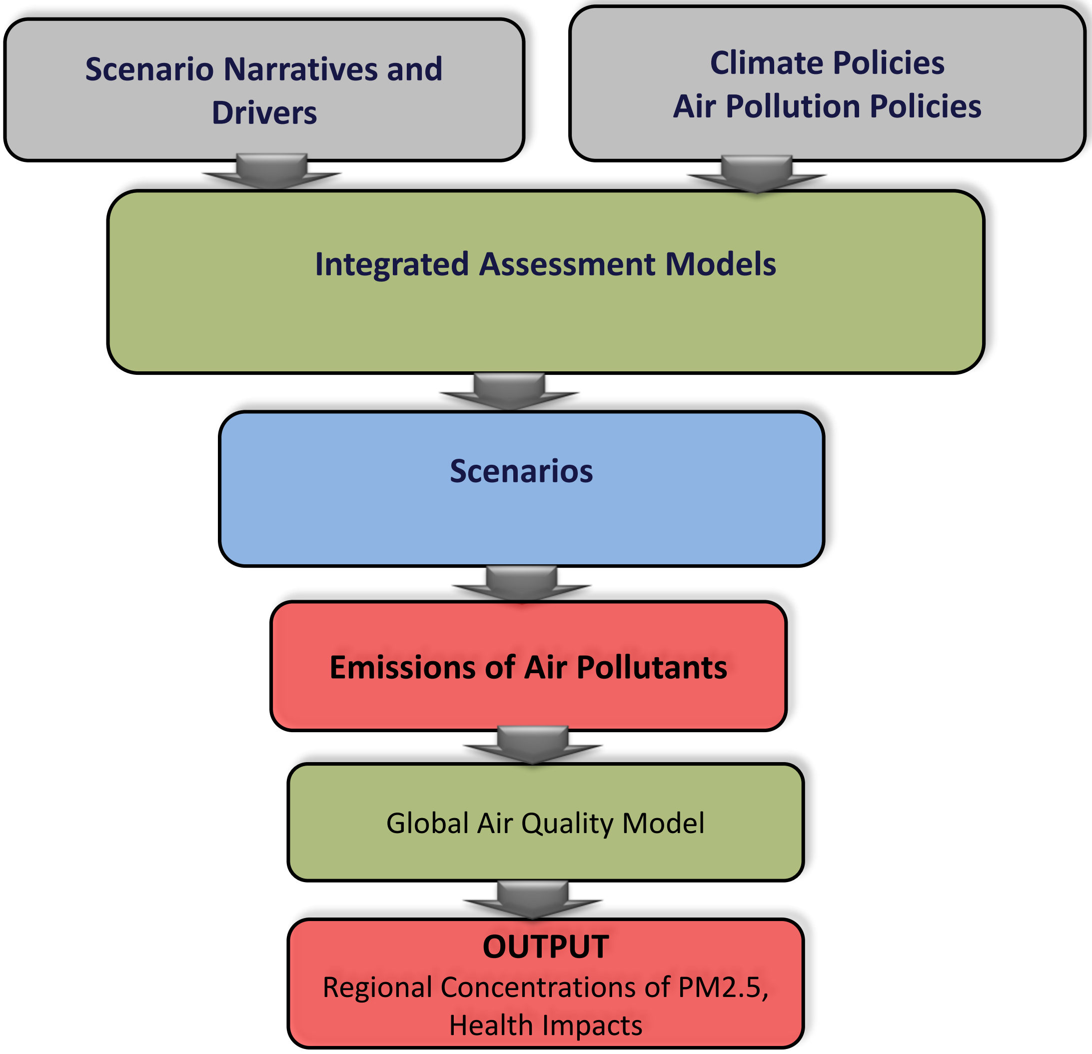


Figure 2-1: Generic Modeling Framework

2.2. REPRESENTING AIR POLLUTION CONTROLS IN IAMS

This section describes the development of a specific example of an energy system model within an integrated modeling framework to represent emissions of air pollutants over a century long time scale. It uses the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (62-65)

2.2.1. Description of IAM

MESSAGE is a systems-engineering optimization model used for medium-to long-term energy system planning, energy policy analysis and scenario development (65, 66). The model maps the entire energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services. All technologies in the energy system are associated with a number of characteristics such as energy inputs and outputs, capital and operational costs, facility lifetimes, emissions of various types per unit activity, maximum possible penetration rates and start year. The model's current version, MESSAGE IV, provides global and sub-regional information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. It is a long-term global model with a time horizon of a century (1990-2100).

The model configures the evolution of the energy system in ten year time steps and determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs. The model's principal results comprise among others estimates of technology-specific multi-sector response strategies for specific climate stabilization target. The choice of the individual mitigation options across gases and sectors is driven by the relative economics of the abatement measures, assuming full temporal and spatial flexibility (i.e., emissions reduction measures are assumed to occur when and where they are cheapest to implement).

The degree of technological detail in the representation of an energy system is flexible and depends on the geographical and temporal scope of the problem being analyzed. A typical model application is constructed by specifying performance characteristics of a set of technologies and defining a Reference Energy System (RES) to be included in a given study/analysis that includes all the possible energy chains that the model can make use of (Figure 2-2). In the course of a model run, MESSAGE then determines how much of the available technologies and resources are actually used to satisfy a particular end-use demand, subject to various constraints, while minimizing total discounted energy system costs.

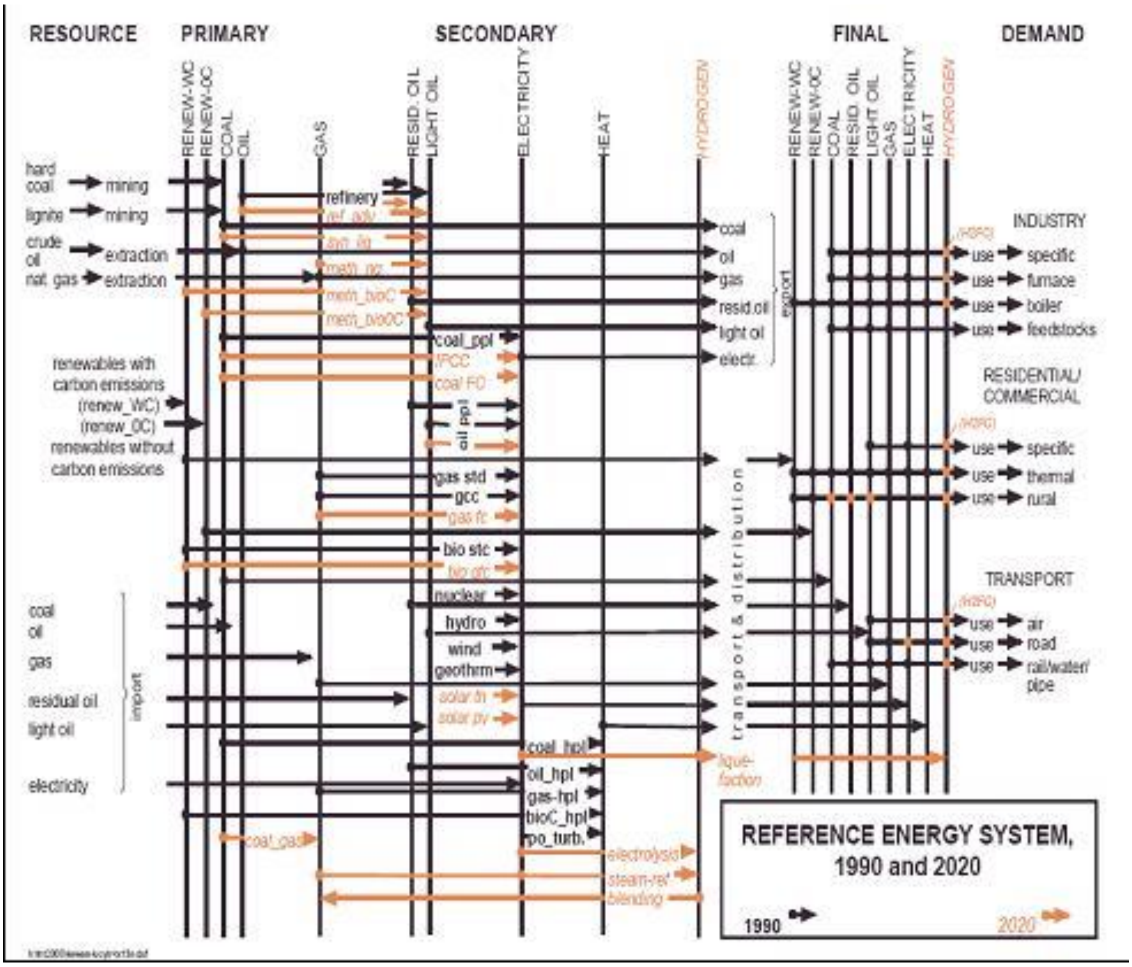


Figure 2-2: Schematic diagram of the basic energy system structure in the MESSAGE model

(www.iiasa.ac.at/ene)

MESSAGE has been used in an integrated modeling framework (62, 64, 67) and has been linked to various other models to provide a better representation of economic, land-use and forest sector interactions. The principal results comprise the estimation of technologically specific multi-sector response strategies for a range of alternative climate stabilization. The framework covers all major sectors, including agriculture, forestry, energy, and industrial sources, and permits the concurrent assessment of major sustainability challenges and how to address them.

The MESSAGE model includes a detailed representation of energy-related and land-use CO_2 emissions (45, 63, 68, 69) Energy related CO_2 mitigation options include technology and fuel shifts; efficiency improvements; and carbon capture. A number of specific mitigation technologies are modeled bottom-up in MESSAGE with a dynamic representation of costs and efficiencies. MESSAGE also includes a detailed representation of carbon capture and sequestration from both fossil fuel and biomass combustion.

MESSAGE directly calculates CO_2 emissions due to fossil fuels, cement production and gas flaring. Emissions from land-use change are exogenous to the model. The electricity sector is responsible for more than thirty-five percent of total CO_2 emissions worldwide. There are a number of options for reducing emissions from this sector in the long term. These include switching from fossil fuels to renewable or nuclear power, efficiency improvements, fuel shifting (from coal to gas), and carbon capture.

$$\begin{aligned}
&\sum_{p\in Periods}\Bigg\{\overset{\text{Discount factor}}{\boxed{DC_m^p}}\times plen_p\times\Bigg[\overbrace{\boxed{\sum_{j\in TechA}\sum_{l\in LDR} eff_{f,j,p}\times X_{i,j,l,p}\times vom_{i,j,p}}}^{\text{Variable O\&M costs}}\\
&+\overbrace{\boxed{\sum_{h\in TechB}\sum_{po\in PO_p}\left(plen_{po}\times fom_{h,po}\times Y_{h,po}\right)}}^{\text{Fixed O\&M costs}}+\overbrace{\boxed{\sum_{r\in Erec}\sum_{g\in Grades}\left(cres_{r,g,p}\times R_{r,g,p}\right)}}^{\text{Costs of resource use}}\Bigg]\Bigg\}\\
&+\sum_{p\in Periods}\Bigg\{\overset{\text{Discount factor}}{\boxed{DC_b^p}}\times plen_p\times\underbrace{\boxed{\Bigg[\sum_{h\in TechB}\sum_{t=1}^{ctime}\beta^{plen_p-t}\left(Y_{h,p}\times inv^{*}_{h,p}\times fri_{h,p,t}\right)\Bigg]}}_{\text{Costs of capacity addition and replacement}}\Bigg\}
\end{aligned}$$

Equation 2-1: Total System Cost in MESSAGE-

Optimization is used to calculate the least-cost energy supply system. The criterion is the minimization of the total discounted energy system cost, subject to the constraints representing demands, resource scarcity and capacity bounds.

System costs include:

Operation costs

- Variable Operation and maintenance (O&M) costs
- Fixed O&M costs

Resource costs

- Cost of the resource extracted

Expansion costs

- Investment costs for capacity addition and replacement

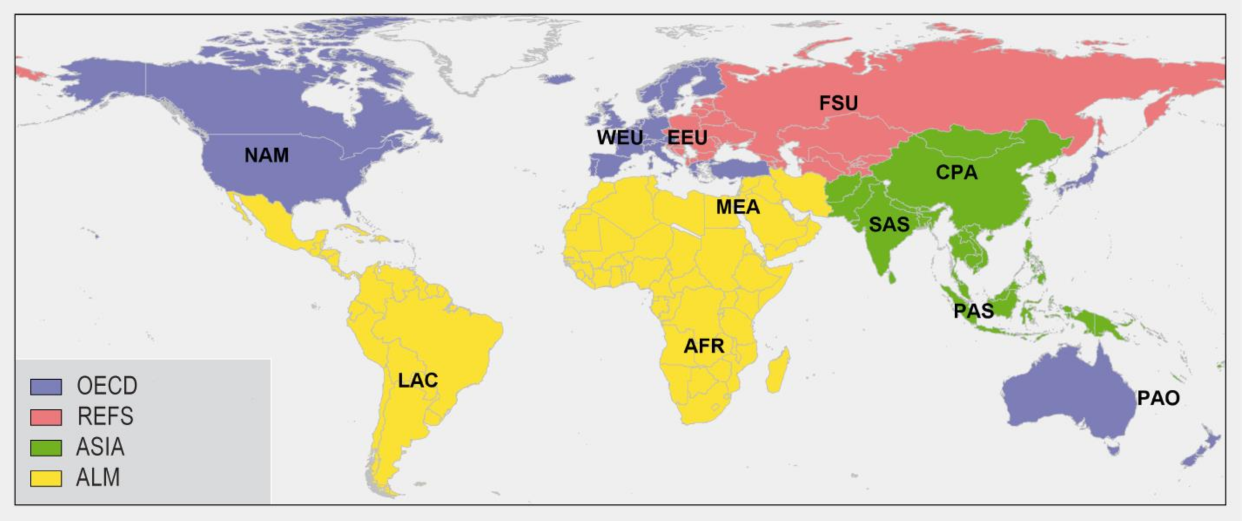
Other costs

- Penalties and costs introduced through the relations

Discounting makes the costs occurring in different points in time comparable by using weights given to the cost incurred at different periods in the total system cost.

Linear Programming is used for optimization- the objective and all of the constraints are linear functions of the decision variables.

Figure 2-3: Illustration of World Regions in MESSAGE



2.2.2. Air Pollution model

The GAINS (Greenhouse gas – Air pollution Interactions and Synergies) model (41, 42) has been developed as a tool to identify emission control strategies that achieve given targets on air quality and greenhouse gas emissions at least costs. It quantifies the full DPSIR (demand-pressure-state-impact-response) chain for the emissions of air pollutants and greenhouse gases. The GAINS model incorporates data and information on all the different elements in the DPSIR chain and specifies connections between these different aspects. In particular, GAINS quantifies the DPSIR chain of air pollution from the driving forces (economic activities, energy combustion, agricultural production, etc.) to health and ecosystems effects.

The GAINS model captures the multi-pollutant/multi-effect nature of atmospheric pollution. It addresses impacts of air pollution on human health, vegetation and aquatic ecosystems, and considers the release of emissions that exert radiative forcing. The model follows emissions of sulfur dioxide (SO_2), nitrogen oxides (NOx), various fractions of fine particulate matter (PM), ammonia (NH3) and volatile organic compounds (VOC).

The GAINS model (http://gains.iiasa.ac.at) is currently implemented globally on regional, national or provincial levels for 45 countries in Europe, for the Annex I countries of the Kyoto Protocol, for fast growing economies of China and India, as well as for remaining countries in the East and South Asia, Africa, Middle East and South America. It covers the time horizon up to 2030. For each of the air pollutants, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of mitigation measures and the extent to which such measures are applied. This dataset reflects recent developments in the air pollution legislation across the world and draws on data collection, model evaluation, and discussion with air quality policy, measurement and modelling communities, as well as various ongoing EU funded initiatives (70-74).

In the stand-alone GAINS model, emissions E of an air pollutant in a country i are calculated as the product of energy activity levels A in a sector s consuming a fuel f, multiplied by the “uncontrolled” emission factor EF in absence of any emission control measures, a factor eff adjusting for the removal efficiency of emission control measures m, and the application rate X of such measures.

$$E_i = \sum_{s,f,m} E_{i,s,f,m} = \sum_{s,f,m} A_{i,s,f} * EF_{i,s,f} * (1 - eff_m) * X_{i,s,f,m}$$

Activity rates A are exogenous input to the GAINS model, derived from external energy projections or, for the purposes of this study, from the energy scenario developed with the MESSAGE model.

The set of parameters EF, eff and X defines a “control strategy” that reflects the level of implementation of specific emission control measures in a country at a given time. The GAINS database contains information about several hundreds of abatement measures in numerous sectors, applicable to a range of activities of fuel types.

Through the time-dependent implementation rates X of specific emission control measures the GAINS model reflects the penetration of mitigation measures in each country, e.g., as prescribed by national air quality regulations. The technical and economic descriptions of available emission control measures as well as their country-specific implementation schedules focus on the period up to 2030.

CLE: ‘current legislation’ - These emission factors assume efficient implementation of existing environmental legislation. It thus describes a scenario of pollution control where countries implement all planned legislation until 2030 with adequate institutional support. The CLE emission factors are “fleet average” values that are the aggregate emission factor of all ages of equipment operating in the given year.

MTFR: ‘maximum technically feasible reduction’ - These emission factors assume full implementation of ‘best available technology’ as it exists today by 2030 independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions. While, the full penetration of MTFR measures in the near-term is not a feasible scenario, these values serve rather as ultimately achievable air pollutant emission factors for conventional technologies considered being available at the present time.

This reflects recent developments in the air pollution legislation across the world and draws on data collection, model evaluation, and discussion with air quality policy, measurement and modelling communities and is documented in (43, 70, 73).

Table 2-1 describes the various types of legislations behind these two air pollution policy packages.

Table 2-1: Representative types of pollutant emission legislations and assumptions

Sector	Current Legislation (CLE)	Maximum Feasible Reduction(MFR)
Road Transport	Directives on the SO_2 content in liquid fuels; directives on quality of petrol and diesel fuels; adoption of EURO III-V standards for light and heavy duty cars after 2010 (or national equivalents)	• High-efficiency flue gases desulfurization (FGD) on existing and new large boilers • Use of low-sulfur fuels and simple FGD techniques for smaller combustion sectors • High-efficiency controls on process emission sources

Industry and Power Plants	Use of high efficient electrostatic precipitators (ESP) in the power and industrial sectors, increased use of low SO_2 coal, increasing penetration of flue gas desulfurization (FGD) after 2005 in new and existing plants, primary measures for control of NOx	• Selective catalytic reduction at large plants in industry and in the power sector • Combustion modifications for smaller sources in industry and in the residential and commercial sectors • High-efficiency controls on process emission sources

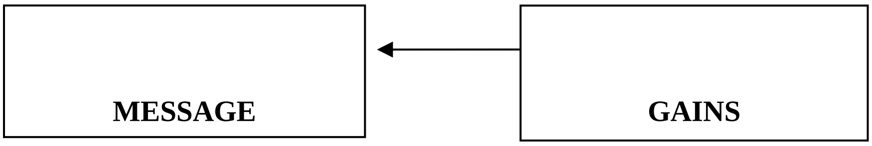
Inventory data and information on short-term (until 2030) pollutant legislations across the chapters in this dissertation are derived from the GAINS model (75, 76). This dataset has been documented in (41, 43, 48, 72).

2.2.3. Representing Air Pollution Policies

The underlying projections of energy activities that determine the levels of GHGs and air pollutants are provided by MESSAGE. This involves aggregation of activity (e.g., various fuels) and technology (e.g., type of combustion technique, penetration of control technology) into MESSAGE fuels and sectors as well as regional aggregation, where needed. Sector coverage included fossil fuel and biomass combustion in residential, industrial, transportation and electricity sectors.

Emission factor estimates are provided for:

- All energy-related combustion (supply and demand), conversion, and transformation sectors.
- Years 2000, 2005, 2010, 2020, 2030
- Sulfur dioxide (SO_2), nitrogen oxides (NOx), organic carbon (OC), black carbon (BC), carbon monoxide (CO), and non-methane volatile organic carbons (NMVOC).



$$AEF_{a,t}^{MESSAGE} = \frac{E_{a,t}^{GAINS}}{A_{a,t}^{GAINS}}$$

Figure 2-4: Representation of Pollutant Emissions in MESSAGE

In addition to the spatial aggregation, the methodology also groups physical, technological and institutional characteristics on emission sources of individual countries that are explicitly considered in GAINS to match the more aggregated level of detail of the MESSAGE model. For this purpose, abated emission factors (AEF) are defined as appropriate linkages. For each MESSAGE world region, such AEFs are derived for the all sector-fuel combinations provided by the MESSAGE model. For 2030 they are calculated from the GAINS emission scenarios by dividing total emissions calculated by GAINS by the corresponding activity levels considered in MESSAGE:

$$AEF_{i,s,f,y}^{MESSAGE} = \frac{E_{i,s,f,y}^{GAINS}}{A_{i,s,f,y}^{GAINS}}$$

Equation 2-2: Emission factors, MESSAGE-GAINS linkage

It should be the noted that the energy scenarios underlying the GAINS and MESSAGE models are independent, i.e., no attempt has been made to link the energy system activities in the two models. The linkages are only established at the level of emission abatement measures.

Table 2-2: Mapping of major emission source categories of the MESSAGE and GAINS models.

MESSAGE fuel/sector		←	GAINS fuel	GAINS sector			
Residential and Commercial	biomass_rc	←	OS1 OS2	Domestic (DOM)			
	coal_rc	←	HC1 HC2 HC3 BC1 BC2 DC				
	gas_rc	←	GAS				
	loil_rc	←	MD GSL LPG				
	foil_rc	←	HF				
	eth_rc	←	ETH				
	meth_rc	←	MTH				
	h2_rc	←	H2				
Industry	biomass_i	←	OS1 OS2	Industry combustion (IN_OC)	Industry boilers (IN_BO)	Off-road machinery and construction (TRA_OT_CNS)	
	coal_i	←	HC1 HC2 HC3 BC1 BC2 DC				
	gas_i	←	GAS				
	loil_i	←	MD GSL LPG				
	foil_i	←	HF				
	eth_i	←	ETH				
	meth_i	←	MTH				
	h2_i	←	H2				
Transport	coal_trp	←	HC1 HC2 HC3 BC1 BC2 DC	Road (TRA_RD_LD2, TRA_RD_M4, TRA_RD_LD4C, TRA_RD_LD4T, TRA_RD_HDT, TRA_RD_HDB)	Off-road (TRA_OT_LD, TRA_OT_LB, TRA_OT_AGR, TRA_OT_RAI)	Aviation (TRA_OT_AIR)	Shipping (TRA_OT_INW, TRA_OTS)
	gas_trp	←	GAS				
	loil_trp	←	MD GSL LPG				
	foil_trp	←	HF				
	eth_ic_trp	←	ETH				
	meth_ic_trp	←	MTH				
	h2_ic_trp	←	H2				
Non-enenrgy uses	coal_fs	←	HC1 HC2 HC3 BC1 BC2 DC	Non-enenrgy uses (NONEN)			
	gas_fs	←	GAS				
	loil_fs	←	MD GSL LPG HF				
	foil_fs	←	HF				
	eth_fs	←	ETH				
	meth_fs	←	MTH				
Power & heat plants incl. CCS	bio_ppl	←	OS1	Existing power plants (PP_EX_OTH)	New plants (PP_NEW)		
	mw_ppl	←	OS2				
	gas_ppl	←	GAS				
	loil_ppl	←	MD GSL LPG				
	foil_ppl	←	HF				
	coal_ppl_u	←	HC1 HC2 HC3 DC BC1 BC2				
	coal_ppl	←	HC1 HC2 HC3 DC BC1 BC2		New plants (PP_NEW)		
	coal_adv	←	HC1 HC2 HC3 DC BC1 BC2				
	igcc	←	HC1 HC2 HC3 DC BC1 BC2	IGCC plants (PP_IGCC)			
Own use and transformation	extraction_coa	←	HC1 HC2 HC3	Conversion combustion (CON_COMB)			
	extraction_gas	←	GAS				
	extraction_oil	←	HF				
	lignite_extr	←	BC1 BC2				
	ref_hil	←	HF		Refineries (PR_REF)		
	ref_lol	←	HF				

In the above formula, abated emission factors are computed for the period until the year 2030, i.e., the latest year for which GAINS provides detailed information.

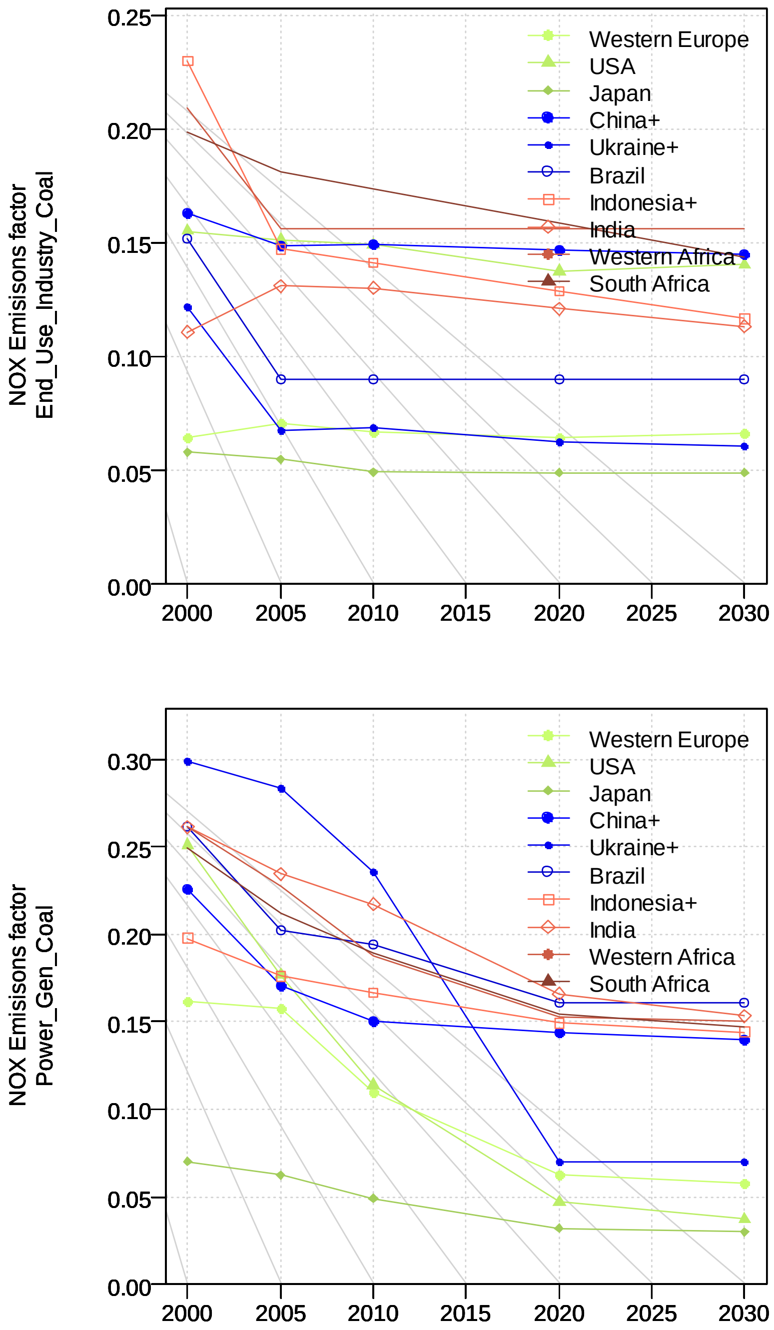


Figure 2-5: Examples of Emission Factors from GAINS implemented in MESSAGE

2.2.4. Representation of Long-Term evolution of pollution controls

While a wide range of developments is conceivable in terms of emission factor development beyond 2030, the likely range of trends in emission factors could be constrained by two cases:

(i) a pessimistic assumption that technologies and legislation would not change beyond 2030,

$$AEF_{i,s,f,y>2030} = AEF_{i,s,f,y_{2030}}$$

(ii) a more optimistic assumption that emission standards (of new built equipment) in each country would converge over time to today’s world best available technology.

The MFTR values are assumed to be static themselves and do not change with time. This implies that there is no implied speculation on the impact of innovation on further improving the reduction efficiency of the best measures included. While this may be conservative for the pathways and regions with high penetration of MTFR equivalent technology, on the other hand, given that most MFTR values here are based on current small-scale applications, there is an implicit assumption that technological progress in the scenarios will mature these technologies and allow for wide application over the longer term. Note, however, that such a change would require dedicated policy decisions, and does not reflect worldwide ‘business as usual’. Furthermore, typical energy scenarios do not assume such an autonomous improvement for the emissions of greenhouse gases, which could introduce an inconsistency to the story lines that are considered for greenhouse gases.

The scenarios in this dissertation explore a wide range of assumptions that span across the above two variants.

In earlier versions of the scenarios described in Chapter 4, emission coefficients are scaled proportionally with the time evolution of GDP-per-capita in the respective MESSAGE region for a given baseline scenario after 2030. In the long-run, the emission factors converge across regions following the assumption that the higher environmental quality will be associated with increasing welfare.

$$AEF_{i,s,f,y} = AEF_{i,s,f,y_{2030}} * \frac{GDP^{CAP}_{y_{2030}}}{GDP^{CAP}_{y}}$$

At the same time, the calculation algorithm assures that the abated emission factor for any region will not shrink beyond the levels that are today achievable through implementation of best available abatement technology for a given pollutant.

$$AEF^{CLE}_{i,s,f,y} \leq AEF^{MFR}_{i,s,f,y}$$

Based on (11) , increasing pollutant controls are assumed to be in place as income levels grow beyond levels of 6000$ /capita GDP (expressed in purchasing power parity).

Emission factors then decline for individual technologies as a direct function of GDP/capita. At the same time, the calculation algorithm assures that the abated emission factor (AEF) for any region will not shrink beyond the levels achievable by implementation of the best available abatement technology for a given pollutant.

The later generations of scenarios in Chapters 5 and 6 in this dissertation do not explicitly assume a turning point based on income but make a range of assumptions on the eventual convergence of global emission controls towards current maximum feasible technological limits. As the various stages of scenario development described in Chapters 4-6 indicate, these assumptions are extremely important in understanding the longer-term evolution of air pollution scenarios.

2.2.5. Representing other sources of Air Pollution

A number of other sectors were included to assess total emissions of air pollution. These include in particular international shipping, waste (landfills) and agriculture related emissions (animals and biomass burning). A summary is provided below with further details available in (63, 77)

2.2.5.1. INTERNATIONAL SHIPPING

The main pollutants emitted from international shipping are carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), sulfur dioxide (SO_2), black carbon (BC) and particulate organic matter (POM). A number of recent reports indicate that emissions of air pollutants and greenhouse gases from the shipping sector have increased substantially in the last two decades, contributing to both climate change and air pollution problems. There have been a number of agreements with respect to international shipping including the International Convention for the Prevention of Pollution from Ships or Marine Pollution Convention (MARPOL) was adopted on 2 November 1973 at the International Maritime Organization (IMO). MARPOL Annex VI (78) sets limits on sulfur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances. The annex includes a global cap of 4.5% m/m on the sulfur content of fuel oil and calls on IMO to monitor the worldwide average sulfur content of fuel.

The projections of SO_2 and NO_x emissions from international ships reported here are based on the methodology described in (79). An important assumption concerning the future exhausts from ships is related to the expected efficiency improvements and the use of alternative fuels. Varying levels of efficiency improvement are assumed from 0% to 25%. It is further assumed that all new ships will comply with the IMO standards. (79) indicates that the original IMO compliance would reduce in 2050 average NO_x emission factors for shipping by 30% relative to present day (IMO old), while the updated IMO standards reduce specific emissions by 70% (IMO new).

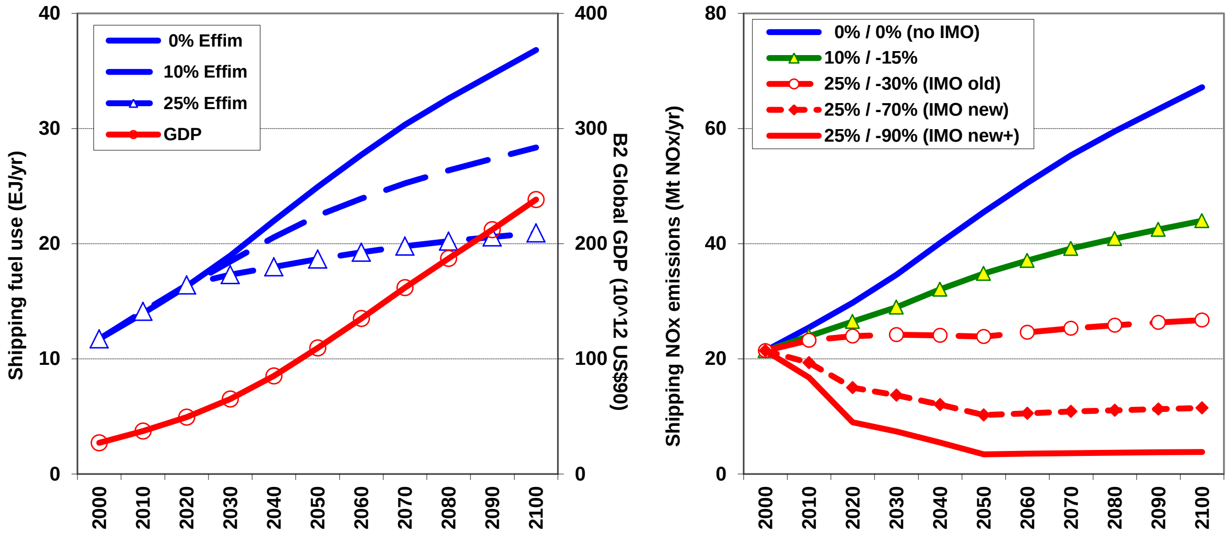


Figure 2-6: Examples of Estimates of Global Fuel Use and Emissions from International Shipping

(using different assumptions on efficiency improvements and implementation of IMO regulations as implemented in the B2 IPCC SRES scenario)

2.2.5.2. AVIATION

Emissions of aircraft include carbon dioxide (CO2), water vapor (H2O), nitric oxide (NO), nitrogen dioxide (NO2), carbon monoxide (CO), a variety of hydrocarbons (HC), sulfur oxides, soot and other particles. Different aspects of the impact of aircraft emissions on the atmosphere have been identified, including changes in greenhouse gases, particles, contrails, and cirrus cloud formation (80).

In order to determine the 'aviation' related component of transportation emissions, base year estimates of aviation related air pollution are derived from (81). Comprehensive global estimates of aviation related fuel use and emissions are developed based on estimates and methodology from (81). The approach is based on the derivation of long-term revenue passenger kilometers (RPK) derived as a function of the underlying GDP of the scenario. Aviation fuel use efficiency assumed to increase in all regions at varying rates but assumed to converge in the 1-1.5 MJ/pkm range in 2100. **Feil! Fant ikke referansekilden.**

2.2.5.3. Solid Waste (Landfills)

Waste-generation rates can be correlated to various indicators of affluence, including gross domestic product (GDP)/cap, energy consumption/cap, and private final consumption per capita.

For CH4 emissions from solid waste, IPCC country-specific mass-balance methodology is used (82) to obtain estimates of global emissions. Based on long-term trends in waste generation rates, recycling and gas recovery, long-term emission profiles are developed. For example, based on land availability constraints and current trends in most developed countries, the rates of recycling and incineration are assumed to increase around the world, thus leading to less waste being dumped in the landfills. Technological change is further assumed through better management of landfills in the future i.e., a transition from open dumping to covered landfills.

$$\boldsymbol{Methane\ emissions} \\ = \left(\boldsymbol{MWST} * \boldsymbol{MSWF} * \boldsymbol{MCF} * \boldsymbol{DOC} * \boldsymbol{DOCF} * \left(\boldsymbol{F} * \left(\frac{\mathbf{16}}{\mathbf{12}}\right) - \boldsymbol{R}\right) * (\mathbf{1} - \boldsymbol{OX})\right)$$

Where:

MSWT : total MSW generated (Gg/yr)

MSWF : fraction of MSW disposed to solid waste disposal sites

MCF : methane correction factor (fraction)

DOC : degradable organic carbon (fraction) (kg C/ kg SW)

DOCF : fraction DOC dissimilated

F : fraction of CH_4 in landfill gas (IPCC default is 0.5)

16/12 : conversion of C to CH_4

R : recovered CH_4 (Gg/yr)

OX : oxidation factor (fraction – IPCC default is 0)

Equation 2-3: Methane emissions, landfills

The method assumes that all the potential CH4 emissions are released during the same year the waste is disposed. IPCC Guidelines are used to provide default values, where country-specific quantities and data are not available.

For the non-energy sources, diverse mitigation options are considered. The technical complexity of these source reduction options can vary significantly, although this does not greatly influence their effectiveness. For example in the solid waste sector, labor-intensive composting is more common in developing countries as compared to high-skill machinery in developed countries. In the solid waste sector, the recovered CH4 from landfills is directly used as gas by nearby industries or converted to electricity for end-use.

2.2.5.4. WASTEWATER

Wastewater from households and organic processes in industry contain nitrogen and organic compounds that wastewater treatment plants decompose before discharge. The main gaseous products are CO2 and molecular nitrogen but during the process also CH4 and N2O are formed and released. Industrial wastewater, principally from the food processing and pulp and paper industries, is the major contributor, making up about 95% of the total emissions (SAR II). Domestic sewage comes from both urban and rural areas, with the latter being more predominant in most developing countries.

Short-term emissions (until 2020) are sourced from (83) include for example the EU Urban Wastewater Treatment Directive that regulates the release of waterborne pollutants in wastewater from urban households and food industry. For emissions after 2020, in the case of industrial wastewater emissions, industrial GDP is used as a driver for these emissions. For domestic wastewater emissions, in developed countries, national population is used as a driver of emissions. For developing countries, where open sewers (urban) and latrines (rural) are major sources, GDP is used as a driver for future emissions based on the assumption that open sewers and sanitation infrastructure will change with GDP.

Diverse processes are used to treat wastewater. Due to extensive water shortages in developing countries, recycling of wastewater is often economical. As a side-effect to improved water quality, such conversions also reduce the formation and release of CH4. Many treatments like anaerobic digesters lead to recovery of methane. However, due to lack of adequate data, mitigation is not specifically modeled for this source over the long-term.

2.2.5.5. AGRICULTURE

Methane is produced as part of normal digestive process in animals and exhaled or eructed by the animal. Ruminants (e.g., cattle, buffalo, sheep, goats, and camels) are major emitters. Rice production from wet fields is also a major contributor to CH4 emissions in developing countries. Additionally liquid manure disposal like lagoons, ponds etc. lead to anaerobic decomposition and hence methane emissions.

Mitigation options are introduced using simplified marginal abatement cost curves (MACs) from (84, 85). These MACs are determined by the series of breakeven price calculations for the suite of available options for each sector and region. Each point along the curve indicates the abatement potential given the economically feasible mitigation technologies at a given carbon price. The result of this analysis are a series of MACs that reflect aggregated breakeven prices for implementing mitigation options in a given sector and region.

Estimates of NO_x, CO and VOC emissions for agriculture (non-combustion) related sources were based on (86) for the year 2000. Future emissions were further calculated based on a number of sector-based drivers. It is important to note that the chapters in the dissertation describe progressive improvements in the development of agricultural emissions.

Table 2-3 summarizes the assumed drivers of different emission sources while Table 2-4 lists some characteristics of key mitigation options.

Table 2-3: Agriculture and Land Use Pollutants, scope and assumed drivers

Source	**Definition**	**Pollutants**	**Assumed Drivers**
Waste	Landfills, Wastewater, Non-energy incineration	SO_2, NO_x, BC, OC, CO, VOC, CH_4	1. Urban Population 2. Total Population
Agriculture	Livestock, Manure management, Rice Production, Soil	NO_x, CO, VOC, CH_4	1. Fertilizer Use 2. Manure Production 3. Rice Production, Area of rice cultivation 4. Livestock Population, Meat Production 5. Total Crop Production
Agricultural Waste Burning	Waste Burning on Fields	SO_2, NO_x, BC, OC, CO,VOC, CH_4	Share of agricultural residue burnt on field

International Shipping	Bunkers in international waters	SO_2, NO_x, BC, OC, CO, VOC	Fuel use in bunkers (estimated using Total GDP)
Aviation	Domestic and International Aviation	SO_2, NO_x, BC, OC, CO, VOC	Fuel use in airplanes (estimated using Total GDP (as a measure of air-based mobility)

Table 2-4: **Costs and technical characteristics of some important non-CO_2 mitigation technologies (Costs per ton of Carbon Equivalent)**

		Costs and reduction efficiency		
Emission sources	**Mitigation technologies**	Capital Costs* *($/tCE)*	O&M costs* *($/tCE)*	Efficiency** *(%)*
CH_4				
Manure management	Farm-scale digesters	1000-5000	20-500	100
	Centralized digesters	1300	30-200	25-50
Solid waste	Anaerobic digesters	1200-2800	40-400	95-100
	Composting	1300-1500	50-500	95-100
	Heat/Electricity production	25-600	6-35	70-75
	Flaring	100-150	2-20	75

* The cost and technical data for the various mitigation options is based on the technology-specific data sets from (87), and Schaefer et al., (2004), updated in (88).

** It is assumed that with rising income, the current low labor costs in many developing countries increase gradually over the century. The reduction efficiencies represent the pure technical applicability of a respective option and are not reduced by any associated economic applicability.

2.3. Estimating The Impacts of Air Pollution

The emission outcomes from all IAMs are further linked to a series of atmospheric models that calculate PM2.5 surface concentrations taking as input annual emission rates of pollutants for 56 regions. For population exposure calculations, the resulting PM.5 grid maps are interpolated to 7.5'x7.5' to match high resolution population grid maps (67, 89).

Health impacts are calculated as a function of total regional population weighted anthropogenic $PM_{2.5}$ concentrations (including secondary effects not including the effects of dust, sea salt and secondary aerosols). The health related impacts of ozone are not estimated, although recent evidence suggests that this could be significant (see for example (3)). Health impacts of ambient air pollution were estimated using the population-attributable fraction (PAF) approach based on the gradient of risk between the theoretical minimum level of air pollution exposure and the estimated observed exposure. An approach was applied similar to that detailed in which involved:

1) Estimating total population exposures to PM2.5

2) Choosing appropriate exposure-response factors for PM2.5

3) Determining the current rates of morbidity and mortality in the population of concern

4) Estimating the attributed number of deaths and diseases.

More detailed information on health end-points, population age classes and CRFs used are given in Table 2-5.

Table 2-5: Baseline Mortality and DALYs, World

Health outcome	**GBD Category WHO 2009**	**2005**		**2030**	
		Deaths >30 years *(millions)*	**DALYs*** *(millions)*	**Deaths >30 years** *(millions)*	**DALYs*** *(millions)*
Ischemic Heart Disease	107	1.46	14.87	2.10	19.71
Stroke	106	0.91	7.91	1.41	10.99
Chronic obstructive pulmonary disease (COPD)	112	0.65	7.52	1.24	14.02
Lung Cancer	67	0.13	1.25	0.30	

* calculated with a 3% discount rate

These combined disease categories are a major cause of overall mortality globally for populations greater than 30 years and 38% of all deaths and 13% of all DALYs in 2008 can be attributed to these causes There are however significant regional differences. While the share of these causes is particularly high in overall mortality in OECD regions, for developing regions, regional differences exist. While in rapidly developing regions, these diseases are now a major cause of death and disability, in other regions like Sub Saharan Africa, they are not the major contributor and other causes are more significant.

The exposure-response function (quantitative variation of a health outcome per unit of pollutant load) was derived from the GBD based meta-analytical assessment of various (international) studies selected from the peer-reviewed epidemiological literature. The effect estimate (gradient) was calculated as the variance weighted average across the results of all studies included in the meta-analysis. Some important issues related to using cohort based dose response functions have been noted in the literature. These include the transfer of dose response functions across regions; the possibility of particularly susceptible subgroups among the population; the use of the chronic exposure studies for mortality; and; the use of centrally located, population-orientated monitors rather than true personal exposure time.

The impact of air pollution on mortality is calculated based on the long-term effects. This approach is chosen because the impact of air pollution is a combination of acute short-term as well as cumulative long-term effects. For example, lifetime air pollution exposure may lead to recurrent injury and, in the long term, cause chronic morbidity and, as a consequence, reduce life expectancy. In these cases, the occurrence of death may not be associated with the air pollution exposure on a particular day (short-term effect) but rather with the course of the chronic morbidity, leading to shortening in life.

The population attributed fraction to exposure can be estimated as:

$$\mathrm{PAF} = \mathrm{P} * \frac{\mathrm{RR} - 1}{[\mathrm{P} * (\mathrm{RR} - 1) + 1]}$$

Equation 2-4: PAF, Health Impacts Methodology

where P = exposure expressed in $\mathrm{PM}_{2.5}$ concentrations, and RR = relative risk for exposed versus non-exposed populations.

Once the fraction of a disease that is attributed to a risk factor has been established, the attributed mortality or burden is simply the product of the total death or million disability adjusted life years DALY estimates for the disease and the attributed fraction.

Considerable overlap exists between the underlying disease categories and populations at risk for outdoor and indoor air pollution. As discussed in (58), human exposure to air pollution occurs both indoors and outdoors and an individual's exposure to ambient urban air pollution depends on the relative amounts of time spent indoors and outdoors, the proximity to sources of ambient air pollution, and on the indoor concentration of outdoor pollutants. While it is difficult to accurately estimate the exact extent of the overlap in terms of the resulting impacts, it is estimated at around 16% globally by (5) and recent studies (60) indicate that in some developing nations it could be significant. The methodology adopted here does not estimate the overlap but discusses the possible shares of the outdoor air pollution related burden that can be attributed to household air pollution. There is also recent literature which suggests that the composition of PM2.5 could potentially have implications this would have for the impacts on health (see for example (90, 91) but the methodology here does not attempt to quantify these sub-fractions separately.

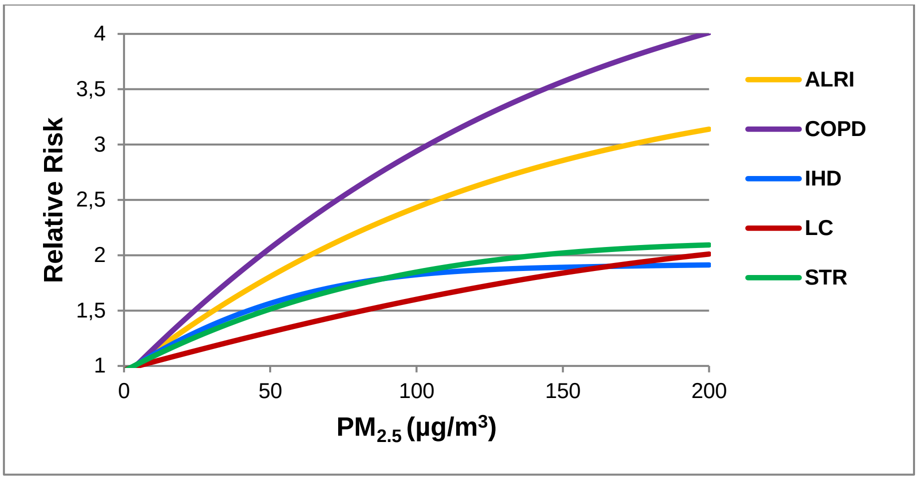


Figure 3: WHO Global Burden of Disease Relative Risk estimates for PM2.5 exposure (ALRI, acute lower respiratory infection; COPD, chronic obstructive pulmonary disease; IHD, ischemic heart disease; LC, lung cancer; STR, stroke). For concentrations below 7 µg/m^3, relative risk is assumed to be 1.

Based on the broad methodological framework described in this chapter, the remaining chapters describe the specific application of this framework to scenario development and key results emerging from these scenarios in terms of emissions of air pollutants, air quality and health.

3. IMPORTANCE OF FUTURE AIR QUALITY LEGISLATIONS IN LONG-TERM SCENARIOS

This chapter makes the case for the importance of representing air quality legislations in long-term scenarios and highlights the uncertainties associated with modeling air pollution emissions over long-time scales. It uses the RCP scenarios as a basis to understand the challenges in accounting for air pollution over long time scales. The RCP scenarios (46) are recent long-term (until 2100) scenarios of pollution. These scenarios were developed to span a range of climate forcing levels and are not associated with specific socio-economic narratives (40). They were developed with the support of different integrated assessment models (IAMs) and yield net forcing outcomes by the end of the century ranging from 2.6 to 8.5 W $m-^{2}$ .The scenarios included for the first time a comprehensive representation of multiple air pollutants across century-long time frames, from technologically detailed, long-term integrated assessment models. Although assumptions on air pollution policies were not coordinated across the scenarios, all models included individual representations of air pollution controls. The RCPs did not intend to span the full uncertainty of future air-pollutant emissions, but present possible, internally consistent air-pollutant pathways. Understanding the pollutant emission trends in the RCPs is important as they represent the first effort by the IAM research community to account for multiple air pollutants comprehensively over century-long time scales. The RCP scenarios have been widely used, including for CMIP5 climate model simulations (47).

3.1. DESCRIPTION OF RESEARCH

The research underlying this chapter is based on a series of papers that develop long-term scenarios of air pollution consistent with the RCP radiative forcing targets in an effort to understand what the key challenges are in terms of representing air pollution across such long periods.

In the first paper in the series (92), a number of air pollutants are represented in the MESSAGE model to derive the RCP8.5 using the methodology described in Chapter 3. The MESSAGE modeling framework to derive projections for pollutant gases, including sulfur dioxide (SO_2), nitrogen oxide (NOx), carbon monoxide (CO), reduction in emissions intensity based on the assumption that higher environmental quality will be associated with increasing welfare.

The second paper in the series (52) systematically varies pollution control assumptions to explore a range of air-pollutant emissions consistent with each RCP in a single modelling framework. This provides a point of comparison for understanding the stringency of pollution controls implied by the original RCPs. and air-pollutant emissions at four distinct levels of air-pollution control stringency. The air-pollution control levels range from no improvements relative to 2005 to very stringent reductions that push the frontier of end-of-pipe pollution control technologies.

The third paper in the series (93) then compares projections over the twenty-first century of SO_2, BC, and OC emissions from three technologically detailed, long-term integrated assessment models. The character of the projections and the response of emissions due to a comprehensive climate policy are discussed, focusing on the sectoral level. This analysis focuses on century-scale emission projections for SO_2, black carbon (BC), and organic carbon (OC). The IAM models simulate regional energy and land-use, their global interactions, and the greenhouse gas and pollutant emissions that result from these anthropogenic activities. They differ, however, in model structure and future assumptions for driving factors such as technology development and pollutant control levels. Comparing results from these three models yields insight into how differences in model structure and assumptions affects pollutant emission projections.

3.2. SUMMARY OF RESULTS

In a continuation of historical experience, aerosol and precursor emissions are increasingly decoupled from carbon dioxide emissions over the 21st century due to a combination of emission controls and technology shifts over time. Implementation of a comprehensive climate policy further reduces emissions, although there is significant variation in this response by sector and by model: the response has many similarities between models for the energy transformation and transportation sectors, with more diversity in the response for the building and industrial sectors. Much of these differences can be traced to specific characteristics of reference case end-use and supply-side technology deployment and emissions control assumptions.

Emission intensity, measured relative to carbon dioxide emissions, decreases substantially over time, but the assumed rate of decrease varies by substance, sector, and model. These differences stem from different assumptions for pollution controls, technology characteristics, and model behavior at the sectoral level. Widespread adoption of inherently low emitting technologies, such as integrated gas combined cycle (IGCC) coal combustion or hydrogen fuel cell vehicles will result in low emissions, which can be an important factor motivating the adoption of such technologies.

Varying levels of legislation, economic growth and technological progress across regions imply that the emission intensities evolve differently in the short and medium term as seen in the examples of emissions intensity declines in the case of SO_2 and NO_X in the power sector and oil based transport sectors. In the OECD regions, stringent air quality legislations combined with already high economic growth imply that emission intensities are already quite low and expected to decline even further by 2030. For economies in transition and medium development countries, while current income levels are still much lower than the OECD regions, current legislations imply that by 2030, quite significant declines in emissions intensities can be expected from an increasing use of Flue Gas Desulfurization (FGD) in the power sector and increased EURO (or equivalent national) standards in transport. For those regions with both currently low-income levels and limited air quality legislations, declines are limited until 2030.

An important driving force of long-term declines in air pollutants is a pervasive technological shift in the energy system towards clean technologies. For example, in the case of SO_2 emissions in the power sector, while continued legislation will most likely bring additional reductions, a growing share of clean coal technologies likes IGCC in developing countries implies that emissions from this sector will decline significantly in any case. Globally available best practices including the use of catalytic converters also imply that in the transport sector, in spite of a continued use of liquid fuels, there is a likely decline in intensities.

Technological change can contribute to declining overall emission intensities over time, even if air-pollution policy remains the same. For example, technology and fuel-specific emission factors in the scenarios underlying the frozen legislation case (the most pessimistic case here) are frozen at their 2005 levels. However, even in absence of climate change mitigation, new technologies are adopted over the course of the century in the underlying scenarios, for example, for reasons of cost-effectiveness or because retired power plants are replaced by current technology. These new technologies result in overall improved and cleaner combustion processes and thus imply that, even in high emission scenarios and in the absence of any additional air-pollution controls, emission intensities of air pollutants at the sectorial level can decline over time.

Environmental legislations in combination with ongoing structural and technological change will imply that in the long-term, pollutant emissions may decline at a faster rate than CO_2 as seen in the example of SO_2 emissions. For example, while structural change may have a large impact on CO_2 as well as pollutant emissions in the residential and industrial sectors, the power sector remains a major contributor to CO_2 emissions by the end of the century; although SO_2 emissions from this sector are almost negligible due to increasing use of IGCC type technologies. In the transport sector in the absence of large price signals, CO_2 emissions continue to rise globally while in most developing regions, there is either a slowing down of growth of pollutants from this sector or even a decline where air quality legislations are stringent enough to offset growing demand.

Although all RCPs do include some improvement of air-quality policies over the twenty-first century, consistent air-pollutant emissions can be both significantly higher and significantly lower. For almost all pollutants, stringent air-quality legislation could further reduce emissions beyond the RCP levels during the first half of this century. However, significant increases in air pollution would be consistent only in a high CO2 - emission world, such as RCP8.5. Other drivers besides air-quality controls and GHG mitigation influence the quantity of air pollutants released to the atmosphere. In particular, policies that promote energy access for poverty eradication attempt to induce a shift in the energy use of poor populations, from traditional biomass burning to modern forms of energy are important. By doing so, they also significantly reduce certain air-pollutant emissions.

Using the insights developed from this chapter, the next chapter focuses on a new generation of air pollution scenarios that include a broader range of uncertainties related to air pollution control.

4. ASSESSING THE IMPACTS OF INTEGRATED POLICIES ON AIR POLLUTION AND CLIMATE CHANGE FOR AIR QUALITY AND HEALTH

The chapter describes the importance of assessing air quality outcomes across integrated policies related to air pollution control, access to clean energy and climate change mitigation. This chapter focuses on the development of scenarios of outdoor and household air pollution and related health impacts in 2030, given different sets of policies on air pollution, climate change and energy access which are presented in detail in the recently published Global Energy Assessment (67). The specific goal of this chapter is to assess how effective such policy combinations could be in delivering improved air quality and health related outcomes. The underlying modeling framework used in this paper has been presented in detail in (94) and combines an integrated assessment model and an atmospheric chemistry transport model for the spatial distribution of outdoor air pollution exposures globally. WHO Comparative Risk Assessment methods (95) are used and include a number of updates to methodology based on recent literature to estimate both ambient and household health related outcomes of the chosen policies. Global results are presented for 2030 and include spatially detailed emissions of air pollutants, ambient concentrations of PM2.5, health impacts in terms of mortality and DALYs from both ambient and household air pollution, and the associated costs of policies.

4.1. DESCRIPTION OF RESEARCH

The research underlying this chapter has been summarized in three published papers. Each paper incrementally builds on the previous one with an aim to understand how different levels of air pollution controls interact with policies on climate change and energy access to improve air quality in different regions.

The first paper in the series (94) describes a methodological basis that can be applied to specifically evaluate the atmospheric implications and health impacts of energy policies. Based on state-of-the-art modeling tools and an assessment of methodologies, it provides a template for quantifying the global health impacts of ambient and household air pollution. The results are validated for 2005. The health impact assessment approach used includes the link to an energy model for detailed sector based estimation of emissions and an accounting of urban and rural exposures at a spatial level.

In the second paper (96), the methodological basis is then expanded to include projections of future emissions of a number of air pollutants examine scenarios of outdoor and household air pollution and related health impacts in 2030, given different sets of policies on air pollution, climate change and energy access for the Global Energy Assessment scenarios (17).

Three variants of future pollution control are included

- *CLE: "current legislation"; full and timely implementation of all existing and planned air pollution legislation until 2030; full implementation of the best available emission control technologies as exists today by 2100 (independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions).*
- *FLE: "fixed legislation"; No further emission controls beyond those in place in 2010.*
- *SLE: "stringent legislation"; Rapid pollution control with full implementation of the best available emission control technologies by 2050.*

The specific goal of this paper is to assess how effective such policy combinations could be in delivering improved air quality and health related outcomes. WHO Comparative Risk Assessment methods are used and include a number of updates to methodology based on recent literature to estimate both ambient and household health related outcomes of the chosen policies. Global results are presented for 2030 and include spatially detailed emissions of air pollutants, ambient concentrations of PM2.5, health impacts in terms of disability adjusted life years (DALYs) from both ambient and household air pollution, and the associated costs of policies.

In the third paper in the series (97), a similar methodology as in paper 2 is extended to multiple IAMs and the an ensemble of six integrated assessment models (IAMs) along with a reduced-form air quality source-receptor model (AQ-SRM) are used to evaluate the potential co-benefits of climate policies for regional air quality. This represents present the first multi-model comparison study developed to focus on the co-benefits of climate policies for regional air quality. The goal is to provide critical information to the ongoing policy debate on aligning global and national actions to achieve key SDGs related to air pollution and climate change. A recent set of global climate policy scenarios based on post-2020 commitments under the Durban platform and a long-term two degrees temperature change target in 2100 (50) are updated with a set of near-term regional air pollution policies across all participating IAMs. Under these common policy assumptions, the co-benefits of climate policies are assessed across different models for varying levels of implementation of air pollution control. Results are presented in terms of emissions of a number of air pollutants for key sectors and across 10 global regions. Regional concentrations of fine particulate matter (PM2.5) are calculated using a reduced-form global air quality source-receptor model (AQ-SRM) and presented in comparison to the World Health Organization (WHO) air quality guidelines (98).

4.2. SUMMARY OF RESULTS

The results support a number of recent parallel estimates on the impacts of air pollution globally. More than 80% of the world's population currently exceed the WHO AQG for PM2.5 of 10 μg/ m^3 while more than 30% also exceed the WHO Interim Target-Tier 1 level of 35 μg/m^3. Ambient concentrations in developing countries, particularly in Asia, are high due to large populations and significant emissions from the industrial and transportation sectors. Ambient air pollution is estimated to result in 2.7 million annual deaths or 23 million annual (DALYs) worldwide in 2005. This represents around 5% of all deaths, 2% of all DALYs and around 12% of the total burden that can be attributed to cardiovascular, respiratory and lung cancer related causes. More than 70% of this burden is felt in Asia alone.

The results also point to the importance of implementing air pollution legislations as planned and the relevance of increasing the stringency of controls to improve air quality and health outcomes globally. Looking across a range of pollution control scenarios, the results indicate that if outdoor air pollution legislation remained frozen at 2005 levels, this would lead to a global increase of nearly 50% in outdoor air pollution related DALYs in 2030 compared to 2005. With current outdoor air quality legislation, DALYs still increase by more than 30% as compared to the 2005 level. While increase in PM2.5 concentrations is clearly key, an additional factor for increased health impacts is the growth in population above 30 years of age, especially in developing countries, where large increases can be expected in these age cohorts in the next two decades. It is also necessary to note that the underlying share of cardiopulmonary disease and lung cancer related causes in the overall burden of diseases increases significantly from current levels in many developing countries in 2030, reflecting a baseline shift from infectious diseases to chronic ones, thus also contributing to the increased health impacts from outdoor air pollution.

With a full global commitment to implementing all current and planned air quality legislations, the results indicate slight decline in global SO_2 and PM2.5 emissions of around 2% while NO_x emissions increase by 15% compared to 2005 levels. Global population-weighted anthropogenic PM2.5 concentrations in 2030 rise to 34 mg/m^3 compared to 26 mg/m^3 in 2005. The globally modest impacts of currently legislated air quality policies can be explained in particular by increased NO_x and PM2.5 emissions from the transportation sector in developing countries, which offset the reductions resulting from the implementation of air pollution policies in OECD countries. For SO_2 emissions, adequate pollution controls in the electricity generation sector and the penetration of advanced coal facilities implies that emissions decline significantly in most models in this sector. However, relatively poor controls in other sectors like industry for example and a growing use of fossil fuel use could imply an increase in emissions. For NOx emissions, the differences across models in the medium term are larger due to a number of factors including, a lag in controls in the industrial sector in many countries; the high pollutant intensity in processes such as steel making; and the increasing use of liquid fuels in the transportation sector. For example, fossil-fuel based liquids comprise on average 92% of total transportation final energy in 2050 in all scenarios here, with assumptions on the relative costs of fuel substitution and infrastructure development being a common constraint. For BC emissions from the residential sector, assumptions on biomass use in the residential sector in developing countries is seen to have a major impact on the reductions from current air quality controls.

Climate policies lead to significant reductions in near-term emissions of air pollutants, while simultaneously resulting in large declines in GHG emissions. The reductions derive mainly from resulting improvements in energy efficiency; substitution of fossil fuels; adoption of advanced energy technologies; and an overall increase in the share of zero-carbon electricity. The technological transitions entailed by climate policies are effective in controlling for the increases in pollutant emissions in the REF scenario, even with full implementation of current and planned air pollution controls. This clearly highlights the relevance of multiple approaches to near-term air pollution control. With lax implementation of direct pollution control, climate policies lead to larger reductions in air pollutants while with more stringent implementation of direct controls reductions are more limited. It is important to note that assumptions on the technological limits of direct emission controls are an important factor in terms of the ability of climate policies to afford further reductions in air pollutants.

The emission scenarios here clearly significantly extend the range of the RCP scenarios because of both alternative assumptions on pollution control, as well as the alternative developments in the underlying reference and mitigation scenarios. This suggests that multiple uncertainties as represented here should inform scenario development related to future air quality to ensure that policies are adequately designed to anticipate them.

The next chapter describes the further evolution of representing pollution control in a long-term scenario context and makes the case for linking attitudes to pollution control to underlying socio-economic conditions.

5. SCENARIO NARRATIVES FOR LONG-TERM AIR POLLUTION

This chapter presents the next stage of development in air pollution representation in IAMs. It uses as a basis the Shared Socio Economic Pathways (SSPs) which are a new generation of scenarios and storylines primarily framed within the context of climate change mitigation and adaptation. The SSP narratives (53, 99) comprise a textual description of how the future might unfold, including a description of major socio-economic, demographic, technological, lifestyle, policy, institutional and other trends. The objective here is to develop plausible ranges of future air pollutant emission development pathways in the SSP scenarios, which are based on internally consistent and coherent assumptions on the degree and implementation of future air pollution control.

5.1. Description of Research

The main research underlying this chapter is fully described in a recently published paper (100). Assumptions on future pollution control are linked to the underlying socio/economic narratives thus allowing for a more realistic understanding of how pollution control may evolve in the future. The aim in developing these long-term scenarios is an internally self-consistent set of plausible futures for pollutant emissions.

To this purpose, a set of alternative assumptions alternative assumptions on the degree and implementation of 'pollution control' in the SSP scenarios is developed. These assumptions reflect historical evidence and prevailing attitudes on pollution control; and potential attitudes to the health and environmental impacts of air pollution in the future. These alternative development pathways for pollution control are then linked to specific SSP narratives. Key results from different IAM interpretations of the SSP scenarios in terms of air pollutant emissions and regional ambient air quality are summarized.

The following characteristics were identified for air pollution narratives:

1. Pollution control targets (e.g. concentration standards), which we specify relative to those in current OECD countries.

2. The speed at which developing countries 'catch up' with these levels and effectiveness of policies in current OECD countries.

3. The pathways for pollution control technologies, including the technological frontier that represents best practice values at a given time.

Based on these characteristics three alternative assumptions for future pollution controls (strong, medium and weak) are then developed which are further mapped to specific SSP scenarios.

The medium pollution control scenario envisions a world that continues following current trends. Due to the diffusion of technology and knowledge, there is some 'catch-up', where countries achieve levels of emission control and policy efficacy in advance, in terms of income levels, of the historical record in current OECD countries. Pollution concentration targets become more ambitious over the century as income grows, the commitment to set and enforce pollution targets becoming increasingly effective, and more value is placed on health and environment protection. To reach these targets, some regions will ultimately require implementation of very efficient technologies, some perhaps requiring advances over current technology levels. Regions with large population densities or adverse physical conditions (e.g. geographic features that lead to frequent high pollution episodes) may not achieve their desired outcomes.

The strong pollution control scenarios assume that increasing health and environmental concerns result in successful achievement of pollutant targets substantially lower than current levels in the medium to long term. Associated with this scenario is a faster rate of technology development (related to pollution control), with greater effectiveness as compared to current technologies. The ambitious air quality goals in the strong pollution control scenario would require, in some regions, implementation of current best available technology (and perhaps even beyond) and assure overall enforcement of environmental laws supported by efficiently operating institutions.

Weak pollution control scenarios assume that the implementation of pollution controls is delayed and less ambitious in the long-term compared to the medium scenario. This may be due to the large challenges several regions face, including, high emission densities in developing countries' megacities, failure to develop adequate air quality monitoring, and/or weaker institutions resulting in poor enforcement of respective legislation. The problems are aggravated by the assumption that international cooperation is weaker resulting in low ambition or slow development of international laws that also leads to slower rates of technological improvements and trans-boundary pollution contributes to higher background concentrations in many regions.

The strong pollution control narrative is assumed for the SSP1 and SSP5 scenarios due to their high levels of development, focus on human capital, and reduced inequality. Conversely low pollution control narrative is associated with the SSP3 and SSP4 scenarios due to their lower levels of development and greater inequality. The SSP2 scenario is mapped to the medium pollution control narrative. The speed and absolute value to which country groups converge is differentiated across the SSPs. Even with similar assumptions on pollution control, pollution outcomes in specific SSP scenarios will differ due to varying assumptions on economic and population growth, energy consumption patterns, and other scenario characteristics.

The quantitative trajectories of emission factors are based on implementation of current legislations, the extent to which lower-income regions catch-up to OECD levels in terms of implementation (e.g. emission factor reductions), and the amount of technological change, such as the extent emission factors might approach current maximum technically feasible reduction levels.

5.2. SUMMARY OF RESULTS

Pollutant emissions in the SSP scenarios span across a much wider range than the RCP scenarios. In general, baseline SSP3 emissions are significantly higher than the largest RCP values, with NOx and BC emissions in the SSP1 baseline case lower than the lowest RCP value. While scenario dynamics and assumptions on transportation and access to clean energy for cooking in developing countries are major drivers of emission outcomes of NOx and BC, respectively, another aspect is the updated set of pollutant control assumptions and the emission factors used in this study. Results for remaining pollutants show similar trends.

Assumptions about the evolution of pollutant emission controls could have a significant role in determining future outcomes for air pollution; particularly in the short-to medium term although over the longer-term, transitions in the energy system could be a significant factor. The SSP1 and SSP5 scenarios with strong pollution controls bring the most significant reductions in air pollutant emissions; by mid-century emissions decline globally by 30-50% in the reference scenarios and up to 70% in the climate mitigation scenarios. The SSP2, middle of the road scenario, generally achieves reductions by 2100 similar to SSP5. The SSP3 scenario, on the other hand, shows a very different future where global pollutant emissions do not substantially decline and even slightly increase in the mid-term. In spite of improving emission intensity in all regions, the improvements in the developing world are too small to offset growth in fossil fuel use and other emission drivers. Even by the end of the century when emission intensities in the highest polluting regions decline to the current OECD levels, global emissions remain high in SSP3, barely below the current levels.

The climate mitigation scenarios result in most cases in co-benefits in terms of lower pollutant emissions than the baselines. The largest co-benefits from climate policy occur in the weak pollution control, SSP3 scenario, which also has the highest corresponding baseline emissions, while the SSP1/5 scenarios show limited reductions in air pollutants from climate policies. While SO_2 and NOx emissions show the largest reductions and the model ranges within the SSPs are much smaller than in baseline cases, BC emissions do not decline as much as a result of assumptions on fuel-substitution in the residential sector. Except for the strongest climate policy cases considered, the air pollution control policies in SSP3 still result in relatively higher air pollutant emissions, although there are significant reductions in SO2 and NOx . The emission trajectories for the SSP4 marker scenario are similar, although lower than, those in SSP3. By the end of the century, however, SO_2, NOx, and BC emission levels are comparable to those of SSP2. Overall, climate mitigation brings much larger emission reductions for SO_2 and NOx, especially in the mid-term, while for other pollutants the impact of assumptions about air pollution policy and clean energy access policy is more significant.

6. CONCLUSIONS

6.1. SCIENTIFIC CONTRIBUTIONS

The findings in this dissertation support the notion that scenarios generated by energy–economy–climate models can provide critical information to the ongoing policy debate on aligning global and national actions to achieve key SDGs related to air pollution and climate change. The scenarios developed in the dissertation significantly extend previous estimates of long-term air pollution through the inclusion of a range of assumptions related to the implementation of current and planned air pollution policies. The use of a systems framework developed here allows the assessment of interactions between long-term climate objectives and shorter-term air quality goals, which are highly relevant given the current need to link climate change mitigation with sustainable development agendas in many countries.

The results indicate that uncertainties related to implementation of future pollution control and technological developments in the energy system are critical in terms of air pollution outcomes in the next few decades. The technological transformations afforded by climate mitigation policies could support ongoing efforts on pollution control and are effective in protecting large parts of global population from harmful levels of particulate matter, especially in Asia and Africa. However, the required scale and speed of reductions in air pollution across multiple sectors and pollutants vis-a-vis inherent constraints related to the replacement of fossil fuels over shorter time frames; and the potential tradeoffs from climate policy through the increased use of biomass in the short-run, imply that there will be a need for integrated multi-sector air quality management systems. In developing countries, policies on energy access will be particularly important in terms of complying with WHO targets on ambient air quality. The results highlight the need for adequate strengthening of institutional mechanisms that facilitate multi-sector controls and the provision of adequate infrastructure for monitoring and implementation of policies.

Attitudes to pollution control will be critical for achievement of reductions in air pollution and achievement of WHO goals on air quality. With globally successful implementation of strong pollution controls, by mid-century emissions decline globally by 30-50% in the baseline scenarios and up to 70% in the climate mitigation scenarios. With partial implementation of current and planned air pollution controls, global pollutant emissions do not substantially decline and even slightly increase in the mid-term. In spite of improving emission intensity in all regions, the improvements in the developing world are too small to offset growth in fossil fuel use and other emission drivers in the next few decades.

Climate policies are found to be beneficial in terms of improving air quality and can deliver substantial reductions in pollutant emissions in the near term although the extent and distribution of co-benefits are heterogeneous across pollutants and sectors and depend on the air pollution control measures in place. Climate policies by themselves may not effectively control short-term air pollution and increasing biomass use for cooking resulting from high fossil fuel prices could imply an increase in pollutant emissions from this sector. The achievement of WHO air quality goals will require additional policies on energy access in South Asia and Africa.

6.2. POLICY IMPLICATIONS

The results described in this dissertation highlight the relevance of streamlined responses to ambient air pollution to achieve significant improvements in air quality and thus improve overall health outcomes. Achieving sustainable low pollution futures will require intensified action on pollution control and will need to be supported by adequate and coordinated institutional capacity. A key to developing a robust response to the challenge of air pollution will need to include robust implementation of integrated air quality management systems incorporating strengthening of institutional mechanisms, assessment of air quality (monitoring, emission inventories, source apportionment, air pollution exposure and damage), evaluation of control strategies, and the development of integrated strategies.

The use of multiple instruments that include technology-advancement policies in addition to direct emission controls could potentially offset uncertainty related to potential market failures (101). However, with current policies, many regions are found to only partially capitalize on the potential to achieve appreciable improvements in air quality and health. Traditional 'end-of pipe' pollution control may have less of a role in reducing emissions than the effects of socio-economic growth and related fuel and technological shifts (102). Thus ‘pollution control’ itself should be carefully designed to include a wide range of multi-sector efforts targeted at appreciable improvements in air quality and health (103, 104). In developing countries, this will imply a need for additional policies on access to clean energy for cooking. This could potentially reduce household air pollution and afford significant additional improvements in health (105, 106). Green R&D and technology implementation for hydrogen fuel cell, advanced biofuel conversion and improved batteries for electric and hybrid vehicles will be essential in order to create the potential for significant reductions in transport emissions –both GHG and air pollutants. Policy shifts involving transport demand management, mass-transit transport systems, and fuel efficiency will be necessary.

While it is clear that the differential costs of pollution and greenhouse gas control imply that climate policies cannot substitute for traditional air pollution control, there is increasing evidence that the ‘co-benefits’ argument is still a valuable one in countries dealing with multiple challenges. It can provide an advantage in terms of designing policies that deliver significant air quality benefits in the more near-term. Policies will need to be carefully designed to ensure that such co-benefits are realized and tradeoffs resulting from increased biomass use are reduced. There will also need to be new financing mechanisms in place that can integrate non-market concerns and ensure that the needs of the energy poor are met in a manner that is beneficial for both climate change and air quality.

Other challenges in terms of policy formulation include, the prioritization of health impacts in a multiple impact setting; the relevance of community action to reduce integrated exposures; the need for extensive rural monitoring; addressing the social inequities in air pollution; integration of public health and regulatory policies for air quality protection into the main priorities of primary health care system; effective monitoring and evaluation; and a focus on the identification of instruments by which emissions can be reduced (107).

Comprehensive action on air pollution on a global scale will require addressing wider social determinants of health, through comprehensive action focusing on prevention and control and the engaging of multiple government ministries, participation of civil society organizations, private healthcare sector, media, and donor organizations, NGOs. Due to the enormous health impacts of air pollution, the health sector should be a driving force in leadership for air pollution reductions, including convening and informing stakeholders about health risks, and informing about strategies that optimize pollution reductions with maximal health benefits. This includes advocating for effective cross-sector measures to combat pollution.

6.3. SUGGESTIONS FOR FUTURE RESEARCH

Future research can extend the framework and results presented in this dissertation.

In terms of methodology, efforts could include additional interpretations including for example realizations of the pollution narratives with different IAMs and might thus provide a richer basis for analysis. Another important aspect is more sophisticated quantitative approaches to representing the narratives in IAMs, including for example, more direct use of emissions to concentration relationships and impacts, which would allow for endogenous estimation of pollutant levels. Similar emission factors do not necessarily translate into similar concentrations across regions, and that there could be a need to adjust control policies to match the local circumstances in each region. This is particularly true as regions get wealthier and have more resources that could be allocated towards controlling pollution levels. Thus while the quantitative approach adopted here is relatively simplistic, as integration methodologies advance, greater consistency can be achieved in future work

The current scenarios developed and explored in this dissertation do not account for large changes in the degree of pollution control. For example, as sulfur dioxide emissions decrease, nitrogen species and secondary organic aerosols can become important determinants of particulate concentrations, which might change the focus of pollutant control efforts. Inclusion of such iterative effects could substantially alter the levels of such pollutants.

The scenarios underlying this dissertation do not include a direct representation of pollutant control costs, although a few studies have also now begun to incorporate pollutant emission control costs into integrated assessment models (108). Ultimately, more advanced representations of pollution control costs, and technological changes over time would allow much greater consistency in long-term pollutant emission scenarios and improve their real-world applicability.

This dissertation has used stylized approaches to look at issues related to the combined exposures from ambient and household related pollution. However, there is a further need to look closer at how overall health outcomes can be maximized in countries where both outdoor and household related air pollution are significant contributors to the health related burden.

There is a need for integrated analysis that takes into account the multiple effects that non-CO_2 compounds can have in the atmosphere, in terrestrial ecosystems, in freshwater and marine systems (109). Expanding the scope of future analysis to analyze pollution from different sources in a more integrated manner is a relevant area of future research.

Downscaling and spatial interpretations of the scenarios will be vital to develop climate model projections as well as for detailed health and ecosystem analysis. This could be particularly useful in terms of additional regional, including a closer look at health and ecosystem implications.

The costs of air pollution control are likely to also significantly impact technology and fuel choices in the future, thus also determining the actual extent to which such policies are implemented. While this dissertation provides some insights into the magnitudes and types of costs, there is scope for more integrated analysis that looks for example at co-optimization approaches to the air pollution problem (110). Such methodological advances would contribute significantly to understanding the actual costs and impacts of meeting specific air pollution related goals.

To conclude, the past few years have seen an immense development in the understanding and methodological capability to intrinsically include air pollution within scenarios developed by IAMs. Future efforts will significantly enhance this endeavor.

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APPENDIX

DESCRIPTION OF SCENARIOS

RCP Scenarios

The Representative Concentration Pathways (RCPs) are a set of four scenarios that were selected to span the range of radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W/m2 in the year 2100(40). The RCPs prescribe emission and concentration developments of atmospheric constituents that affect the Earths' radiation budget, and serve as a basis for climate and atmospheric chemistry modeling experiments, that may contribute to the 5th Assessment Report of the IPCC. The emission and concentration trends of the RCPs may result from different socio-economic and policy assumptions. In this sense, the RCPs are not a new fully integrated set of scenarios based on a common set of socio-economic assumptions (this in contrast to the SRES-scenarios).

The four RCPs were selected from an analysis of the peer reviewed literature. The selection process relied on previous assessment of the literature – considering several hundreds of publications – conducted by the IPCC Working Group III during development of the Fourth Assessment Report. An individual scenario was then selected for each RCP. The selected RCP scenarios (RCP8.5, RCP6.0, RCP4.5, and RCP2.6) are scenarios from the modelling teams/models NIES/AIM, IIASA/MESSAGE, PNNL/MiniCAM, and PBL/IMAGE, respectively. Each of the RCPs was produced by a different integrated assessment model; therefore, each has its own reference scenario(40, 46).

The RCP2.6 scenario (also called RCP3-PD, where PD stands for Peak to 3 W/m2 in 2050 followed by a Decline to 2.6 W/m2 in 2100) is the most stringent climate mitigation scenario in the RCP-set. It assumes drastic emission reductions necessary to limit global temperature increase to below 2 degrees. In the study selected to represent the RCP2.6 scenario (van Vuuren et al., 2006b; 2007), global population grows to 9 billion in 2050, and slightly declines in Western and Eastern Europe (to 490 million, including Norway, Switzerland, Iceland and non-EU Balkan countries; this is a -0.1% per year decrease averaged over 2000-2050). Global GDP increases by 2.8%

per year (resulting in almost than a factor 4 increase between 2000-2050), for Western and Eastern Europe GDP increases by 1.7% per year over this period (resulting in more than a factor 2 increase between 2000-2050).

In the RCP4.5 scenario, global radiative forcing reaches about 4 W/m2 in 2050 and only slightly increases to 4.5 W/m2 until 2065 and stabilizes thereafter. Global population reaches a maximum of more than 9 billion in 2065 and then declines to 8.7 billion in 2100. European population (including Turkey) remains more or less stable at 575 million. Global GDP is assumed to increase by a factor of 3, and almost doubles for Europe between 2005 and 2050 (Clarke et al. 2007; Thomson et al. 2011).

Unlike the GEA projections, in the RCP2.6 and RCP4.5 scenarios, air pollution policies are not explicitly taken into account. Here, it is assumed for the whole period under investigation that increasing income will lead to more stringent emission standards (environmental Kuznets curve theorem), while for the GEA scenarios this theorem is applied only for the years after 2030. The improvement of emission factors is differentiated between country groups, sectors and fuel types.

Table S-1, Overview of Representative Concentration Pathways. (from (40)

Description	
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m2 in 2100.
RCP6.0	Stabilization without overshoot pathway to 6 W/m2 at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m2 at stabilization after 2100
RCP2.6 (RCP-3PD)	Peak in radiative forcing at around 3.1 W/m2 by 2050, then returning to 2.6 W/m2 by 2100

Global Energy Assessment Scenarios

Chapter 5 uses a set of scenarios from the Global Energy Assessment (GEA) (17, 67). This describes alternative energy system transformations or pathways towards a more sustainable future defined by normative objectives related to environmental impacts of energy conversion and use, energy security, and energy access. A major distinguishing characteristic of the mitigation scenarios is the level of future energy demand, which sizes the challenge to achieve rapid reductions in GHG emissions: High, Middle and Low which are referred to as GEA-H, GEA-M and GEA-H.

The GEA scenario comprises essentially one scenario, describing alternative energy system transformations or pathways towards a more sustainable future defined by normative objectives related to environmental impacts of energy conversion and use, energy security, and energy access. All pathways fulfill these objectives by reaching specific and clear targets. Another common feature to all pathways are economic and demographic changes that are consistent with the GEA aspirational goals toward sustainable development. In order to attain the sustainability objectives described above, GEA develops and analyses a number of energy transition pathways. All pathways share a realistic set of socioeconomic and demographic trends. However, they differ substantively in their demand-side assumptions as they comprise varying levels of efficiency improvements and shifts in the level and type of energy service demand. This in turn reflects a greater or lesser degree of emphasis on the demand-side by policy makers and investors. These alternative demand projections also have very different implications for the combination of resources and technologies on the supply-side that can provide for the demand of final users for energy services. A total of 60 alternative pathways are modeled and explored. These are organized into 3 pathway groups corresponding to comparatively low, high, and intermediate levels of energy demand. Within each group, a range of pathways explores alternative transformations in the transportation sector. The GEA pathways share a common median demographic projection whereby the global population increases from almost 7 billion today to around 9 billon people by the 2050s before declining toward the end of the century.

The GEA mitigation scenarios offer an opportunity of comparing alternative approaches to sustainable development by providing a better understanding of the various possible combinations of the measures required, over which time frames and at what costs are needed to effectively change the energy system. Out of the six mitigation scenarios, three assume a gradual phase-out of nuclear. The scenarios labeled as "*high*", "*middle*" and "*low*" signify different approaches to the energy system transformation. The names of the cases correspond to their respective focus between energy demand versus supply. While it is clear that an effective transformation requires a combination of both demand- and supply-side changes, it is the emphasis *on which*, that represents a critical point of divergence of the scenarios. A major distinguishing characteristic of the mitigation scenarios is thus the level of future energy demand, which sizes the challenge to achieve rapid reductions in GHG emissions:

- *High or Supply* – The "*high*" scenario emphasizes the supply-side transformation at a relatively high energy demand. The focus on demand side investments is limited, while alternative low- or zero-emission technologies such as CCS need to upscale rapidly to replace the GHG intensive fossil fuels.
- *Low or Efficiency* – The "*low*" scenario emphasizes demand-side conservation and efficiency improvements in end-use applications (e.g., super-insulated houses or industrial processes with lower energy inputs). The scenario also includes a focus on renewable energies. Both the *high* and *low* scenarios emphasize aggressive efficiency standards in the transport sector, calling for a modal shift in transportation infrastructure and behavioral and lifestyle changes.
- *Middle or Mix* – While the *low* and *high* scenarios have a somewhat inverse relationship, the *middle* scenario toes the line between demand and supply side improvements. The *middle* scenario is characterized by higher levels of regional diversity and choice. Rather than certain supply and demand options dominating the global structure, the *middle* scenario exhibits a higher resilience to potential innovation failures and allows diverse strategies governed by regional requirements

An additional branching point of the GEA Scenarios are two sets of assumptions about the transport sector transition, i.e. "advanced transportation" and "conventional transportation". The "advanced transportation" setup is characterized by a transition to electricity and/or hydrogen as main transportation fuels in the medium- to long-term. By 2050, this transition is just taking off, and these two fuels would have to deliver between 10% and 30% of the transport sector's final energy consumption, strongly dependent on the overall transportation demand. In contrast, the 'conventional transportation' sector tends to follow a regionally more diversified path, depicting the co-evolution of a wide portfolio of fuels and technologies.

Key Indicators, GEA Scenarios

	2005		**2050**			
	Industrialized[1]	**Developing**	**Industrialized**		**Developing**	
			Low	*High*	*Low*	*High*
GDP per capita ($\text{US}_{2005}\$$ at MER	3487–40050	671–4905	24446–52535	24446–52535	6029–19829	6029–19829
Total final energy (GJ per capita)	73–219	7–46	62–98	104–156	28–50	32–71
Residential and commercial						
Electricity demand (GJ per capita)[3]	11–45	1–6	22–33	35–46	8–15	10–20
Transportation						
Passenger-kilometers per capita[4]	14,293	2499	15,925	20,302	3892	4632
Car	8778	404	6539	11,045	1009	1775
Bus and train	2855	1461	3334	3205	1368	1342
Fuel use for mobility (GJ per capita)	30.8	2.4	24.0	33.3	4.6	5.9
Fuel use for freight (GJ per capita)	13.0	2.4	12.4	14.3	2.8	3.3
Industry						
Final energy (GJ per capita)	26–65	3–17	33–46	42–63	15–26	17–33
Process heat (all thermal)	15–28	2–11	12–17	16–24	8–13	9–16
Feedstock	6–23	0.3–6	6–14	9–20	1–7	1–11
Other (nonthermal, e.g., electric)	4–15	1–4	12–16	17–19	5–9	5–12

Derived from (111)

SSP scenarios

Chapter 6 uses the SSP scenarios fully documented and described in (112). The SSPs depict five different global futures (SSP1–5) with substantially different socio-economic conditions. Each SSP is described by a narrative (qualitative) scenario (53). Four of the narratives (SSP1, SSP3, SSP4, and SSP5), are defined by the various combinations of high or low socio-economic challenges to climate change adaptation and mitigation. A fifth narrative (SSP2) describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme in any of the dimensions, but rather follow middle-of-the-road pathways. As part of the scenario development process, consistent and harmonized quantitative elaborations of population; urbanization and economic development have been developed for all the SSPs. The quantitative elaborations of the SSP narratives are then referred to as 'baseline' scenarios.

The SSP narratives themselves do not include explicit climate policies. However, additional climate mitigation runs have been developed that include for each SSP baseline, additional long-term radiative forcing targets of 2.6, 4.5 and 6.0 W/m^2 in 2100. Climate mitigation scenarios in the SSP framework, further include a number of additional assumptions on specific issues related to the level of international cooperation; the timing of the mitigation effort over time; and the extent of fragmentation (particularly in the short-to medium-term). These are characterized as shared policy assumptions (SPAs) which describe for each SSP narrative, the most relevant characteristics of future climate mitigation policies, consistent with the overall SSP narrative as well as the SSP baseline scenario developments (see [19] for further description). The mitigation effort of the SSP scenarios is then a function of both the stringency of the target and the underlying energy and carbon intensities in the baselines. This could result in some cases in infeasibilities in terms of meeting mitigation targets (for a complete overview of the SSP baseline and climate mitigation scenarios see [19]).

A number of IAMs ran the elaborations of SSP scenarios. For simplification, for each of the five SSPs, one marker IAM has been identified (representative of a specific SSP from a single IAM). The selection was guided by consideration of internal consistency across different SSP interpretations as well as the ability of a model to represent the specific storylines. This helped to ensure also that the differences between models were well represented in the final set of marker SSPs. Additional replications of the SSPs from 'non marker' models then provide insights into possible alternative projections of the same storyline. The multi-model approach was important for understanding the robustness of the results and the uncertainties associated with the different SSPs.

Summary of the SSP Scenarios (112)

Identifier	**Descriptor**	**Central SPA assumptions for Climate Mitigation**
SSP1	Sustainability	Early accession with global collaboration as of 2020
SSP2	Middle-of-the-road	Some delays in establishing global action with regions transitioning to global cooperation between 2020-40
SSP3	Regional rivalry	Late accession – higher income regions join global regime between 2020-2040, while lower income regions follow between 2030-2050
SSP4	Inequality	Same as SSP1
SSP5	Fossil-fueled development	Same as SSP2

The SSPs are designed to cover the range of RCP forcing levels. However, given that the SSPS define different levels of mitigative and adaptive capacity, not every SSP is consistent with a given RCP level.

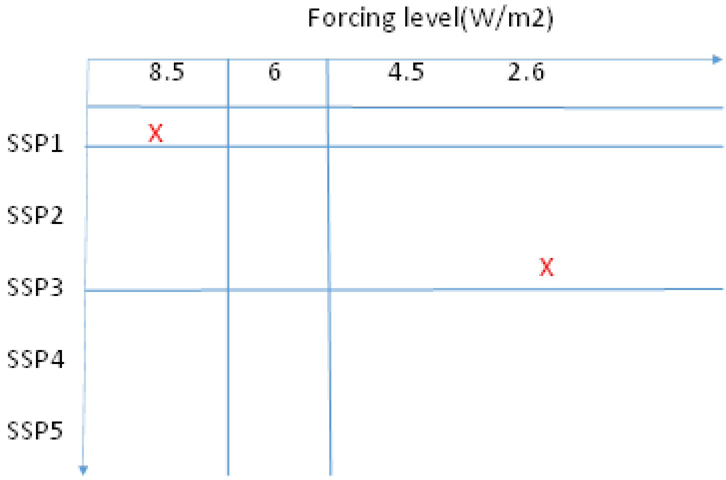

FIG S1: ILLUSTRATIVE MATRIX OF SSP-RCP LINKS

Papers for Chapter 3

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RCP 8.5—A scenario of comparatively high greenhouse gas emissions

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Abstract This paper summarizes the main characteristics of the RCP8.5 scenario. The RCP8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and GHG emissions in absence of climate change policies. Compared to the total set of Representative Concentration Pathways (RCPs), RCP8.5 thus corresponds to the pathway with the highest greenhouse gas emissions. Using the IIASA Integrated Assessment Framework and the MESSAGE model for the development of the RCP8.5, we focus in this paper on two important extensions compared to earlier scenarios: 1) the development of spatially explicit air pollution projections, and 2) enhancements in the land-use and land-cover change projections. In addition, we explore scenario variants that use RCP8.5 as a baseline, and assume different degrees of greenhouse gas mitigation policies to reduce radiative forcing. Based on our modeling framework, we find it technically possible to limit forcing from RCP8.5 to lower levels comparable to the other RCPs (2.6 to 6 W/m^2). Our scenario analysis further indicates that climate policy-induced changes of global energy supply and demand may lead to significant co-benefits for other policy priorities, such as local air pollution.

1 Introduction

The Representative Concentration Pathways (RCPs) form a set of greenhouse gas concentration and emissions pathways designed to support research on impacts and potential policy responses to climate change (Moss et al. 2010; van Vuuren et al. 2011a). As a set, the RCPs cover the range of forcing levels associated with emission scenarios published in the literature. The Representative Concentration Pathway (RCP) 8.5 corresponds to a high greenhouse gas emissions pathway compared to the scenario literature (Fisher et al. 2007; IPCC 2008), and hence also to the upper bound of the RCPs. RCP8.5 is a so-called 'baseline' scenario that does

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not include any specific climate mitigation target. The greenhouse gas emissions and concentrations in this scenario increase considerably over time, leading to a radiative forcing of 8.5 W/m^2 at the end of the century.

Underlying assumptions about main scenario drivers of the RCP8.5, such as demographic and economic trends or assumptions about technological change are based upon the revised and extended storyline of the IPCC A2 scenario published in Riahi et al. (2007). Many scenario assumptions and outcomes of the RCP8.5 are thus derived directly from the co-called A2r scenario (Riahi et al. 2007), which was selected from the literature to serve as the basis for the RCP8.5 (for an overview of RCPs, see van Vuuren et al. (2011a), and for the RCP process and selection see Moss et al. (2010), and IPCC (2008)).

While many scenario assumptions and results of the RCP8.5 are already well documented, we review in this paper some of the main scenario characteristics with respect to the relative positioning compared to the broader scenario literature. In addition, we summarize main methodological improvements and extensions that were necessary to make the RCP8.5 ready for its main purpose, i.e., to serve as input to the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the climate community. CMIP5 forms an important element in the development of the next generation of climate projections for the forthcoming IPCC Fifth Assessment Report (AR5). Finally, we use the RCP8.5 as a baseline for developing scenarios that lead to similar forcing levels as the other RCPs summarized in this SI (i.e. 2.6, 4.5 and 6.0 W/m^2). For this purpose, we introduce constraints on greenhouse gas emissions within the RCP8.5 storyline.

The main methodological improvements of the RCP8.5 since the original publication of the A2r scenario of Riahi et al. (2007) include the explicit representation of present and planned air quality legislation for the projection of regional air pollutant emissions; new downscaling approaches for pollutant emissions that account for dynamic changes in spatial relationships between exposure and mitigation; and finally, a more refined accounting of land-use categories for the spatial representation of the land-transformation, including in particular a new definition for grasslands.[1]

The paper is structured as follows. Section 2 presents an overview of the modeling framework with primary focus on the new methodological enhancements. Section 3 details the results of both the RCP8.5 and a set of climate mitigation scenarios that lead the forcing levels similar to the other RCPs. We first compare the main RCP trends to the broader scenario literature, and then present implications for the energy-system, land-cover changes, and emissions. Finally, Section 4 provides a summary of the main findings.

2 Methodology

2.1 IIASA modeling framework

RCP8.5 was developed using the IIASA Integrated Assessment Modeling Framework that encompasses detailed representations of the principal GHG-emitting sectors—energy, industry, agriculture, and forestry. The framework combines a careful blend of rich disciplinary models that operate at different spatial resolutions that are interlinked and integrated into an overall assessment framework (Fig. 1). Integration is achieved through a

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[1] The A2r scenario included some details of land use categories such as cultivated land, built-up land and forests and grassland area (for further details see Tubiello and Fischer 2007).

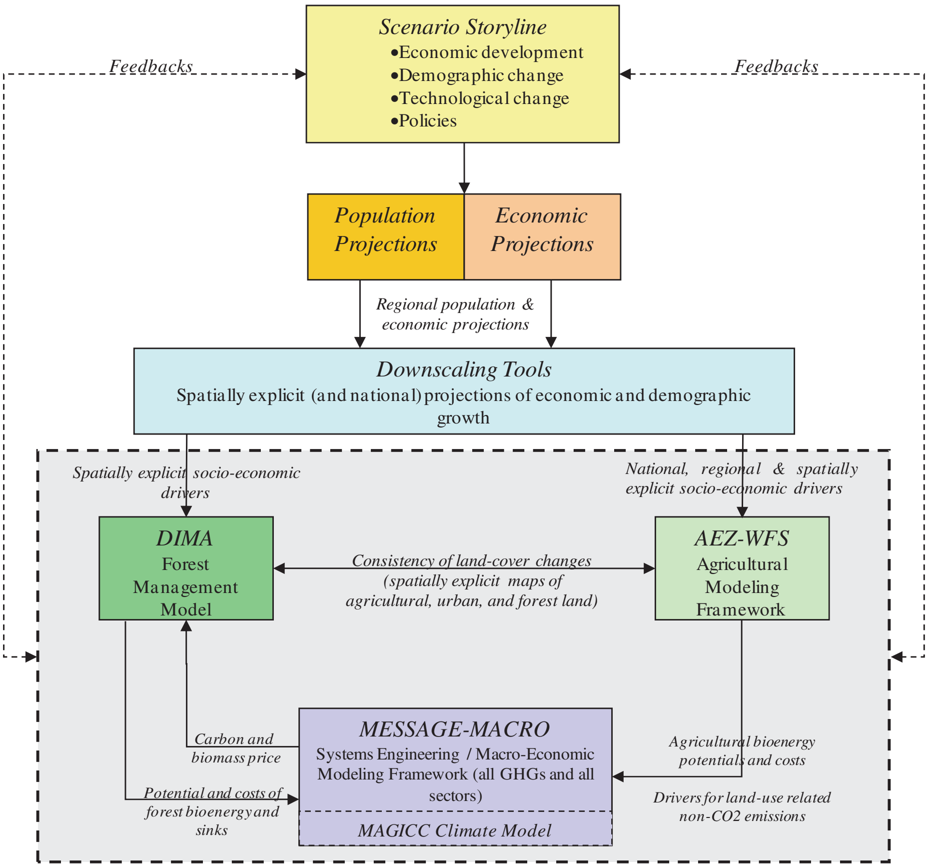

Fig. 1 IIASA modeling framework (adapted from Riahi et al. 2007)

series of hard and soft linkages between the individual components, to ensure internal scenario consistency and plausibility (Riahi et al. 2007).

The three principal models of the IA framework (Fig. 1) are MESSAGE–MACRO (Messner and Strubegger 1995; Rao and Riahi 2006), DIMA (Rokityanskiy et al. 2007) and AEZ–WFS (Fischer et al. 2007) (see below for further details). The three models are driven by a set of harmonized inputs at the regional, national, and grid (0.5×0.5°) level. For this purpose, the regional population and GDP scenarios of the A2r scenario (see Section 3.1) are disaggregated to the level of countries through a combination of decomposition and optimization methods. In a subsequent second step, national results are further disaggregated to the grid-cell level, which provides spatially explicit patterns of population and economic activities (Grubler et al. 2007). The latter indicators are particularly important for the spatially explicit modeling of emissions and land-cover changes in the forestry and agriculture sectors. They provide the basis for the estimation of comparable indicators (such as relative land prices or population exposures to pollutant emissions) that define e.g. the relative comparative advantages of agriculture- and forestry-based activities or the stringency of spatial pollutant emissions reductions.

The MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) stands at the heart of the integrated assessment framework. It is a systems-engineering optimization model used for medium-to long-term energy system planning, energy policy analysis and scenario development. The model maps the entire energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport and distribution to end-use services. The model's current version provides global and sub-regional information on the utilization of domestic resources, energy imports and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, inter-fuel substitution processes, as well as temporal trajectories for primary, secondary, final, and useful energy. In addition to the energy system, the model includes a stylized representation of the forest and agricultural sector and related GHG emissions mitigation potentials. It is a long-term global model operating at the level of 11 world-regions and a time horizon of a century (1990–2100). For each scenario the model calculates the least cost solution for the energy system given a set of assumptions about main drivers such as energy demand, resources, technology performance and environmental constraints.[2]

The AEZ–WFS (Agro-Ecological Zoning—World Food System) model framework projects alternative development paths of the agriculture sector using three components: (i) a spatially detailed agronomic module assessing crop suitability and land productivity (AEZ); (ii) an applied general equilibrium model of the world food system (WFS); and (iii) a spatial downscaling model allocating the aggregate WFS production levels and agricultural land use to spatial biophysical resources. AEZ simulates land-resource availability, crop suitability, farm-level management options, and crop production potentials as a function of climate, technology, economic productivity, and other factors (for further details see Fischer et al. 2002, 2009; Fischer 2009). Land is broadly classified as built-up land, cultivated land, forests, grass/wood land areas, including managed and natural grassland areas, and sparsely vegetated and other land. WFS is an agro-economic model (Fischer et al. 2005, 2009) that estimates regional agricultural consumption, production, trade and land use. Applying the AEZ-WFS framework, use and conversion of land is determined for food and feed production to meet the global demand in accordance with agronomic requirements, availability of land resources, and consistent with national incomes and lifestyles of consumers. Land for residential use and transport infrastructure is assigned according to spatial population distribution and density. The remaining land, i.e. part of grass/wood land, forest areas and sparsely vegetated areas, is further evaluated in the DIMA model (see below) for possible use in dedicated bioenergy systems and for forestry purposes (for additional details see Tubiello and Fischer 2007). Agricultural residue supplies based on the agricultural land use are also available for energy use and picked up where cost-effective. The delineation of pasture and unmanaged grasslands is based on the projections of livestock numbers computed in the WFS model.

The DIMA model (Dynamic Integrated Model of Forestry and Alternative Land Use; Rokityanskiy et al. 2007) is used to quantify the economic potential of global forests, explicitly modeling the interactions and feedbacks between ecosystems and land use related activities. Regional demand trajectories for timber and prices for carbon and bioenergy are major drivers for the relevant estimates. Food security is maintained by introducing an exogenous scenario-specific minimum amount of agricultural and urban land per grid cell as projected by AEZ-WFS (and used as input by DIMA). The DIMA model is a spatial model operating on a $0.5\times0.5°$ grid raster. It determines for each grid and time interval, which of the forestry processes (afforestation, reforestation, deforestation, or conservation and management options) would be applied in order to meet a specific regional timber demand and how much woody

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[2] As computational algorithm the model uses linear programming with a commercial solver (CPLEX) to compute minimum discounted system costs over the entire time-frame. The time horizon is split into 5 year time-steps between historical periods 1990–2010, and 10 year time periods between 2010 and 2100.

bioenergy and forest sink potential would be available for a given combination of carbon and bioenergy prices. Main determinants of the land-use choices in each grid are assumptions about the costs of forest production and harvesting, land-prices and productivity, age structure of standing forest, and age-specific plant growth. Forest dynamics are thus a result of interactions between demand-pull (price of bioenergy and carbon as well as timber demand), and inertia on the supply-side (imputed through growth limitation of the forest). A schematic illustration of the main linkages between the three principal models is shown in Fig. 1.

In the sequel of Section 2 we discuss the main methodological improvements for the RCP8.5. We particularly focus on those aspects most relevant for the development of spatial land-cover and emissions projections, which serve as inputs to the climate modeling community (see also Hurtt et al. 2011 and Lamarque et al. 2011 in this SI).

2.2 Spatial land use and land-cover change projections

The spatial land cover information of the RCP8.5 builds upon the dynamic land-use projections available from the original A2r scenario as published in Fischer et al. 2007; Tubiello and Fischer 2007, and Riahi et al. 2007. The categories comprise 1) built-up land (residential plus infrastructure), 2) cultivated land (arable and permanent crops, separated by irrigated and non-irrigated land), 3) forests (separated by managed and unmanaged forests), 4) grassland/woodland/shrubland (GWS), and 5) other land (water, desert, rocks, and ice).

Major improvements of the RCP8.5 (compared to the original A2r scenario) include updates with respect to the representation of base-year land-cover statistics, updates in the AEZ resource inventory, as well as the split of the aggregated GWS category into pasture and natural grasslands. The latter was done specifically as input for the climate modeling teams of the IPCC-AR5 to represent dynamic land-cover changes in their future climate projections.

The base-year (2000) land inventory uses a continuous representation of different shares of land-uses at 5 min latitude/longitude, i.e. each 5 min grid cell is characterized by shares of the above classes.

Six geographic datasets were used for the compilation of an inventory of seven major land cover/land use categories: (1) GLC2000 land cover, regional and global classifications at 30 arc-seconds (JRC 2006); (2) IFPRI Agricultural Extent database, which is a global land cover categorization providing 17 land cover classes at 30 arc-seconds (IFPRI 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCCD 2001), EROS Data Centre (EDC 2000); (3) The Global Forest Resources Assessment 2000 of FAO (FAO 2001) at 30 arc-seconds resolution; (4) Digital Global Map of Irrigated Areas (GMIA) version 4.0.1 of (Siebert et al. 2007) at 5 arc-minute latitude/longitude resolution, providing by grid-cell the percentage land area equipped with irrigation infrastructure; (5) IUCN-WCMC protected areas inventory at 30-arc-seconds (http://www.unep-wcmc.org/wdpa/index.htm), and (6) Spatial population density inventory (30 arc-seconds) for year 2000 developed by FAO-SDRN, based on spatial data of LANDSCAN 2003, LandScanTM Global Population Database (http://www.ornl.gov/landscan/), with calibration to UN 2000 population figures.

An iterative calculation procedure has been implemented to estimate land cover class weights, consistent with aggregate FAO land statistics and spatial land cover patterns obtained from (the above mentioned) remotely sensed data, allowing the quantification of major land use/land cover shares in individual 5 arc-minute latitude/longitude grid-cells. The estimated class weights define for each land cover class the presence of respectively cultivated land and forest. Starting values of class weights used in the iterative procedure were obtained by cross-country regression of statistical data of cultivated and forest land against land cover class distributions obtained from GIS, aggregated to national level. The percentage of urban/built-up land in a grid-cell was estimated based on presence of respective land cover classes as well as regression equations, obtained using various sub-national statistical data, relating built-up land with number of people and population density.

When land is spatially allocated to various uses in the AEZ-WFS model sequence, first the conversion to built-up land is quantified, driven by changes in population numbers and density. Second, changes in agricultural land simulated in WFS are spatially allocated, simultaneously affecting the other land use types, except built-up land. Finally, other land use changes (not driven by agriculture or built-up conversion), mainly between forest and grass/wood land types, are accounted for. The conversion of agricultural land is allocated to the spatial grid for 10-year time steps by solving a series of multi-criteria optimization problems for each of the countries/regions of the world food system model.

The criteria used in the land conversion module depend on whether there is a decrease or increase of cultivated land in a region. In the case of a decrease the main criteria include demand for built-up land and abandonment of marginally productive agricultural land. In case of increases of cultivated land, the land conversion algorithm takes land demand from the world food system equilibrium and applies various constraints and criteria, including: (i) the total amount of land converted from and to agriculture in each region of the world food system model, (ii) the productivity, availability and current use of land resources in the country/regions of the world food system model, (iii) agronomic suitability of land for conversion to crop production, (iv) legal land use limitations, i.e. protection status, (iv) spatial suitability/propensity of ecosystems to be converted to agricultural land, and (v) land accessibility, i.e. in particular a grid-cell's distance from existing agricultural activities.

The classification of GWS into areas that predominantly correspond to pastures vs. natural GWS is based on spatial calculations of fodder supply versus livestock feed requirements. For this purpose feed balance calculations were performed to compare estimated feed requirements of livestock in a grid-cell to estimated feed supply from grassland and cropland in each grid cell. Feed requirements were calculated as energy requirements per unit of a reference livestock times number of ruminants (cattle, buffalo, sheep, goat). Feed supply assumes a grass harvest index of 60% (on grass/wood land) and a harvest index of 30% crop residues on crop land in the grid cell. These calculations were done at 5 min latitude/longitude and aggregated later to 0.5×0.5° resolution of the RCP8.5. By doing so the global grass/wood land cover was classified into four different categories. For areas with no ruminants or a share of GWS <10% in a grid-cell, these grid-cells were assigned to class 1; class 2 comprises areas with a ratio of feed requirements over feed supply of less than 0.1; class 3 corresponds to calculated ratios of 0.1 to 0.5, and finally class 4 corresponds to ratios greater than 0.5. The resulting global map of grazing intensity is presented in Fig. 2.

2.3 Pollutant emissions

2.3.1 Base year estimates and environmental legislation

For the estimation of air pollutant emissions we rely on detailed technology activity data and emissions coefficients from the Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS, Amann et al. 2008a, b) and the recent assessment of environmental legislation until 2030 (Cofala et al. 2007). The activity data including improvements of emissions coefficients due to legislation was subsequently aggregated and implemented into the MESSAGE modeling framework to derive projections for pollutant gases, including sulfur-dioxide (SO_2), nitrogen oxide (NO_x), carbon monoxide (CO),

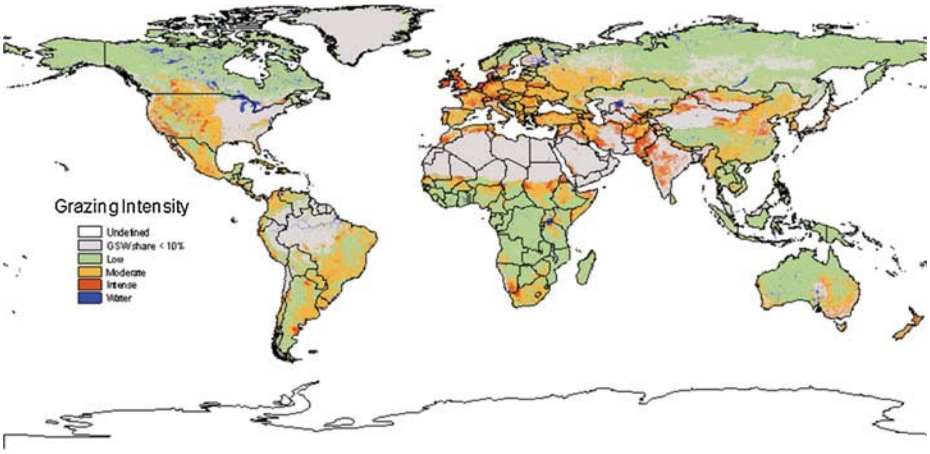

Fig. 2 Grazing intensity of grass, wood, and shrublands for the year 2000. Areas of moderate and intensive grazing were classified as pasture, while other areas with lower grazing intensity as predominantly natural

volatile organic compounds (VOCs), black and organic carbon aerosols (BC and OC). Details of the methodology describing the linkage between MESSAGE and GAINS are summarized in Rafaj et al. (2010).

The main sectors covered in our analysis include power plants, fossil fuel extraction, gas flaring, waste and biomass burning (deforestation, savannah burning, and vegetation fires), industry (combustion and process), domestic (residential and commercial sectors), and road transport. We separately include estimates of air pollutants from international shipping and aviation sectors, which have recently been identified as important sources of air pollutants. Projections of emissions from international ships are based on the methodology described in Eyring et al. (2005a, b) and reflect the implementation of recent updates of IMO standards (amendments to the MARPOL Annex VI regulations). Lee et al. (2005) is used to derive estimates of aviation fuel consumption and controls.

The main control policies and strategies for air pollutants until 2030 across different sectors in both OECD & Non-OECD regions are detailed in Table 1.[3]

For the medium to long term trends of RCP8.5 (beyond 2030) we assume a further reduction in emissions intensity based on the assumption that higher environmental quality will be associated with increasing welfare. To mimic this behavior, the Environmental Kuznets Curve (EKC) theory is applied to derive changes in future emission coefficients (see e.g. Dasgupta et al. 2001). Based on empirical observations, the EKC assumes first an increase in emissions (with increasing economic activities) followed by a decrease. Many EKC studies assume an income level between 5000 and 8000 $/cap as the turning point for the introduction of stringent environmental controls. Recent evidence, however, suggests that in many developing countries controls of air quality are introduced at faster rates than suggested by the experience of industrialized countries in the past (see Dasgupta et al. 2001; Smith et al. 2005). Increased environmental awareness and accelerated technological diffusion are major contributors to this trend. The turning point of the EKC are likely to happen thus at lower GDP/capita levels than assumed earlier. Consequently, we use in the RCP8.5 analysis an income level of 5000$/capita as the threshold for increasing environmental consciousness

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[3] The implementation of these policies and technologies vary across different regions.

Table 1 Control measures for pollutant emissions (2000–2030)

Sector	Control policies and strategies
Road Transport	Directives on the SO_2 content in liquid fuels; directives on quality of petrol and diesel fuels; adoption of pollution standards for light and heavy duty cars after 2010 (EURO III–IV, CARB, Tier II, other national equivalents)
Industry and Power Plants	Use of high efficient electrostatic precipitators (ESP) in the power and industrial sectors, increased use of low SO2 coal, increasing penetration of flue gas desulphurization (FGD) after 2005 in new and existing plants, primary measures for control of NO_x
Domestic	Shift from solid biomass based fuels towards clean cooking fuels and improved cooking stoves, standards on sulfur contents in domestic fuels
International Shipping	Revised MARPOL Annex VI regulations[a]
Others	Reduced flaring, improved NO_x controls in waste incinerators, decreased agricultural waste burning, forest fire control approaching OECD standards throughout the world, etc.

[a] International Maritime Organization announced amendments to MARPOL Annex VI regulations which include progressive reduction SO2 emissions from ships, progressively to 0.50%. Progressive reductions in nitrogen oxide (NO_x) emissions from marine engines were also agreed, with the most stringent controls on so-called "Tier III" engines.

triggering declines in emissions intensities.[4] For resulting development of emissions intensities and overall emissions trends see Section 3 on "results".

As a final step in the development of the regional projections of the RCP, the MESSAGE model results for all major air pollutant emissions and reactive GHGs were harmonized with the historical and current inventories as described in Granier et al. (2011). A simple harmonization algorithm was assumed, where emissions growth of the native MESSAGE results were combined with the base-year values from Granier et al. (2011). For some sectors, where the algorithm led to qualitative changes in the overall trends, a declining offset over time was employed for the harmonization.

2.3.2 Downscaling of pollutant emissions

In addition to detailed representation of air-pollution legislation, another important improvement of the RCP8.5 comprises the development of new downscaling algorithms for the spatially explicit projections of pollutant emissions. These spatial air pollutant projections are important inputs to the AR5 climate experiments, and related atmospheric chemistry models (Lamarque et al. 2011).

The vast majority of downscaling approaches have traditionally employed proportional downscaling (van Vuuren et al. 2010), where emissions of individual grid-cells are scaled following aggregate changes at the regional level. While proportional algorithms are simple to implement and easy to reproduce, they generally do not account for important local differences in efforts to reduce pollutant emissions. Empirical evidence, for example, shows that efforts to reduce air-pollution have generally been stronger where the returns in terms

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[4] In order to explore uncertainties in the actual implementation of legislation beyond 2030, a sensitivity analysis was carried out (Rafaj et al. 2010). Results indicate that the effect on the long-term pollutant emissions depend on assumptions about further improvements in intensities beyond 2030. This effect was found to be significant for NO_x, but comparatively smaller for other emissions where technical shifts dominate (CO, SO_2). It is thus important to note that air pollutant emissions trends in RCP8.5 are the result of dedicated policy interference. The trends should thus not be interpreted as autonomous developments in absence of air pollution policies.

of health benefits have been the largest. In the past this has been particularly the case in cities of today's industrialized countries, where dedicated urban air pollution legislation has successfully reduced exposure and thus health impacts for millions of people (WEA 2000).

This trend is likely to continue in the future, particularly in the developing world, where urban air quality is one of the prime concerns. We thus employ an exposure-driven spatial algorithm for the downscaling of the regional air-pollutant emissions projection. By doing so, we generate dynamic spatial maps at the resolution of $0.5\times0.5°$ for all world regions and major pollutant emissions (SO_2, NO_x, CO, BC, OC, VOCs). As a surrogate proxy for the spatial distribution of exposure we compute "population x emissions" of each grid-cell. The weight of each individual cell in the aggregate regional exposure (i.e., the numerical sum of all exposure values of the cells in the region) defines the allocation of emissions reductions for each cell. As a result emissions are reduced most in those cells with the highest exposure. Vice versa, in cells with either very low population or low emissions density the reductions are comparatively smaller. Technically, we solve the problem by creating a rank-size distribution of each region from the cells with the highest exposure to those with lowest. We start reducing emissions first in those cells that have the highest exposure.[5] Following a review of Air Quality Monitoring Information of US cities (EPA 2008; see also UNEP and WHO 1996) we adopt a maximum rate of reduction of up to 80% emissions reduction per decade for each grid-cell.[6]

Obviously, the exposure driven algorithm is applied only if emissions are reduced on the regional level due to increasing stringency of air pollution legislation. In the case of regionally increasing emissions, we use spatial changes of economic activity (GDP) as a proxy to allocate increasing emissions across grid-cells. I.e., we assume that emissions increase proportionally to where economic activity is accelerating the strongest. For the spatial distribution of population and GDP we rely on the downscaled projections of the original scenario (A2r) as described in Grubler et al. 2007 (data can be downloaded at http://www.iiasa.ac.at/web-apps/ggi/GgiDb/).

Figure 3 gives a schematic illustration of the effect of the exposure algorithm for SO_2 emissions in the Centrally Planned Asia region (including China) between 2020 and 2100. The two important features are: 1) that top exposed cells corresponding to the Chinese mega-cities improve air quality by about two orders of magnitudes by 2050, and 2) improvements in cities are complemented by important distributional changes, shifting e.g. emissions intensive activities to surrounding neighborhoods of cells with lower population density. For a comparison see also resulting spatial maps of SO_2 emissions in Fig. 11 (Section 3).

2.4 Scenarios considered in this paper

The main scenario described in this paper is the RCP8.5. As indicated in the introduction, however, we also use the MESSAGE model for the development of mitigation scenarios that use the RCP8.5 as a baseline. As targets for the mitigation scenarios we adopt forcing levels of 2.6, 4.5 and 6 W/m^2 by the end of the century, which corresponds to the same radiative forcing levels as assumed by the other RCPs in this SI (see van Vuuren et al. 2011b; Thomson et al. 2011; Masui et al. 2011). For each mitigation scenario the MESSAGE optimization model computes least-cost pathways to stay below the specified target. This corresponds to the introduction of a cumulative GHG emissions budget and a

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[5] For example, if a grid-cell has 0.5% of the aggregated regional exposure at time t_0, then 0.5% of the regional emissions reductions between t_0 and t_1 are allocated to that specific cell.

[6] EPA (2008) reports on air pollution trends of US cities between 1990 and 2008. For CO, O_3, and SO_2 the most rapid air quality improvements among the US cities were between 60 and 80% per decade.

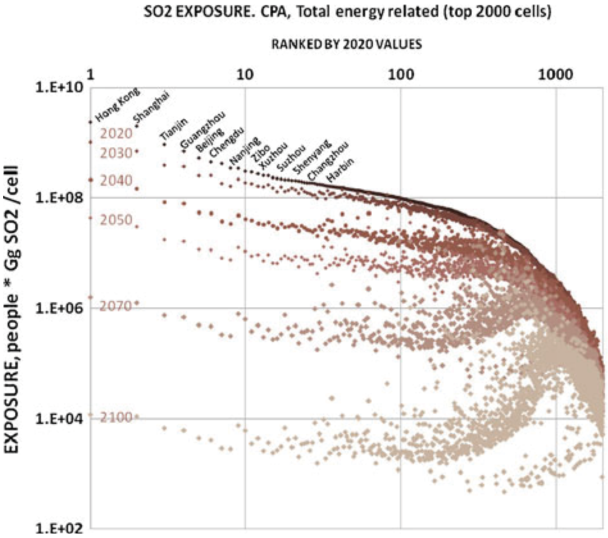

Fig. 3 SO_2 exposure (population x emissions) of grid-cells with highest exposure in Centrally Planned Asia (CPA). Different colors indicate changes in exposure over time from 2020 to 2100. All cells are ordered according to their rank-size distribution in 2020

globally uniform price vector for greenhouse gas emissions (assuming full temporal and spatial flexibility in emission reductions across regions and gases).

3 Scenario assumptions and results

3.1 Storyline and main scenario drivers of RCP8.5

The RCP8.5 is based on the A2r scenario (Riahi et al. 2007), which provides an updated and revised quantification of the original IPCC A2 SRES scenario storyline (Nakicenovic et al. 2000). With a few exceptions, including an updated base year calibration (to 2005) and a revised representation of short-term energy trends, especially in developing countries, the RCP8.5 builds thus upon the socio-economic and demographic background, resource assumptions and technological base of the A2r scenario.[7]

The scenario's storyline describes a heterogeneous world with continuously increasing global population, resulting in a global population of 12 billion by 2100. Per capita income growth is slow and both internationally as well as regionally there is only little convergence between high and low income countries. Global GDP reaches around 250 trillion US2005$ in 2100. The slow economic development also implies little progress in terms of efficiency. Combined with the high population growth, this leads to high energy demands. Still, international trade in energy and technology is limited and overall rates of technological progress is modest. The inherent emphasis on greater self-sufficiency of individual countries and regions assumed in the scenario implies a reliance on domestically available resources. Resource availability is not necessarily a constraint but easily accessible conventional oil and gas become relatively scarce in comparison to more difficult to harvest unconventional fuels like tar sands or oil shale. Given the overall slow rate of technological improvements in low-carbon technologies, the future energy system moves toward coal-

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[7] The MESSAGE model projects historical time periods from 1990 onwards, and is calibrated to reproduce past trends up to the year 2005. As the harmonization of the RCPs was done for the year 2000, we show in most of the figures historical trends up to 2000 only.

intensive technology choices with high GHG emissions. Environmental concerns in the A2 world are locally strong, especially in high and medium income regions. Food security is also a major concern, especially in low-income regions and agricultural productivity increases to feed a steadily increasing population.[8]

Compared to the broader integrated assessment literature, the RCP8.5 represents thus a scenario with high global population and intermediate development in terms of total GDP (Fig. 4). Per capita income, however, stays at comparatively low levels of about 20,000 US $2005 in the long term (2100), which is considerably below the median of the scenario literature. Another important characteristic of the RCP8.5 scenario is its relatively slow improvement in primary energy intensity of 0.5% per year over the course of the century. This trend reflects the storyline assumption of slow technological change. Energy intensity improvement rates are thus well below historical average (about 1% per year between 1940 and 2000). Compared to the scenario literature RCP8.5 depicts thus a relatively conservative business as usual case with low income, high population and high energy demand due to only modest improvements in energy intensity (Fig. 4).

3.2 Development of the energy system

3.2.1 Energy system of RCP8.5

As discussed earlier, the RCP 8.5 is a baseline scenario with no explicit climate policy, representing the highest RCP scenario in terms of GHG emissions. In this section we will first briefly describe the main energy system changes of the RCP 8.5 baseline. In addition to baseline trends, we will congruently analyze also the required GHG emissions reductions in order to limit radiative forcing to levels comparable to the other RCPs highlighted in this SI. We primarily focus in this section on the transition of the energy system and move later to results for land-use (Section 3.3) and GHG and pollutant emissions (Section 3.4).

A growing population and economy combined with assumptions about slow improvements of energy efficiency lead in RCP8.5 to a large scale increase of primary energy demand by almost a factor of three over the course of the century (Fig. 5). This demand is primarily met by fossil fuels in RCP 8.5. There are two main reasons for this trend. First, the scenario assumes consistent with its storyline a relatively slow pace for innovation in advanced non-fossil technology, leading for these technologies to modest cost and performance improvements (e.g., learning rates for renewables are below 10% per doubling of capacity; see also Riahi et al. 2007 for further detail). Fossil fuel technologies remain thus economically more attractive in RCP8.5. Secondly, availability of large amounts of unconventional fossil resources extends the use of fossil fuels beyond presently extractable reserves (BP 2010). The cumulative extraction of unconventional fossil resources lies, however, within the upper bounds of theoretically extractable occurrences from the literature (Rogner 1997; BGR 2009; WEC 2007).[9]

Coal use in particular increases almost 10 fold by 2100 and there is a continued reliance on oil in the transportation sector. This fossil fuel continuance does not necessarily mean a complete lack of technological progress. In contrast to most other technologies, there are significant improvements in existing fossil alternatives as well as the penetration of a number of new advanced fossil technologies, thus increasing their efficiency and

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[8] For further details on the scenario storyline see Riahi et al. 2007.

[9] In RCP8.5 unconventional natural gas extraction amounts to 17 ZJ and unconventional oil extraction to about 21 ZJ over the course of the century.

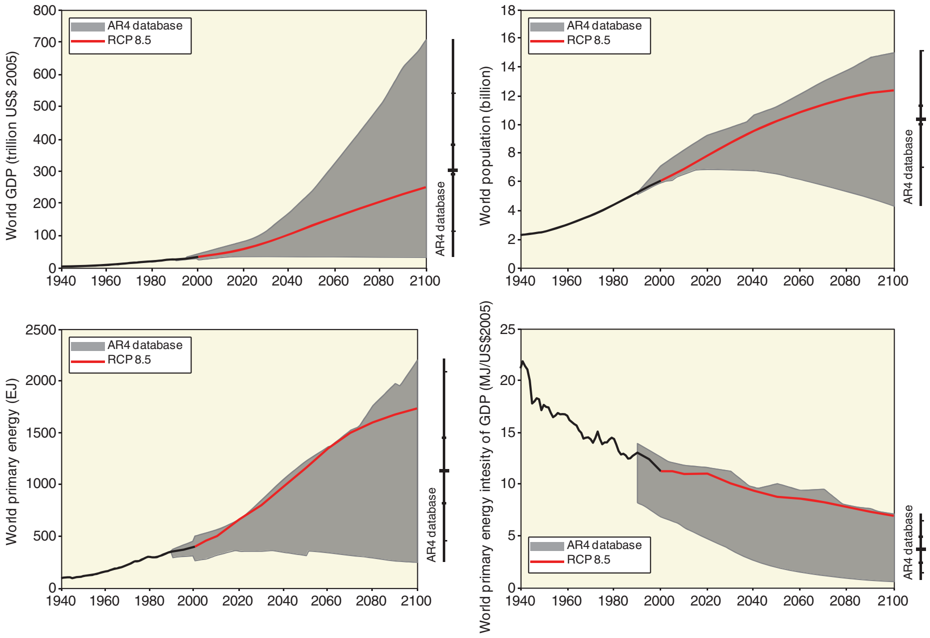

Fig. 4 Global development of main scenario drivers in RCP 8.5 (*red lines*) compared to the range of scenarios from the literature (*grey areas*: IPCC AR4 scenario database; Fisher et al. 2007; Nakicenovic et al. 2006). Right hand vertical lines give the AR4 database range in 2100, including the 5th, 25th, 50th, 75th, and 95th percentile of the AR4 scenario distribution

performance in the longer-term. In the electricity sector, this results in a shift towards clean coal technologies from current sub-critical coal capacities. In addition, with conventional oil becoming increasingly scarce, a shift toward more expensive unconventional oil sources takes place by 2050 and the subsequent increases in fossil fuel prices also leads an increased penetration of "synthetic" fuels like coal-based liquids. The increase in fossil fuel

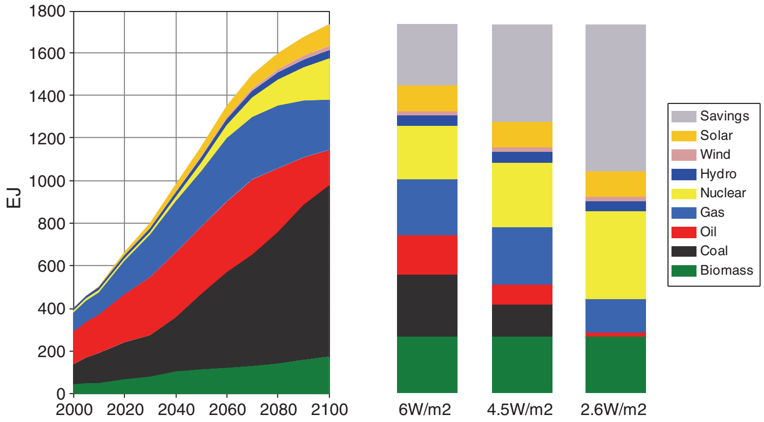

Fig. 5 Development of global primary energy supply in RCP8.5 (*left-hand panel*) and global primary energy supply in 2100 in the associated mitigation cases stabilizing radiative forcing at levels of 6, 4.5, and 2.6 W/m^2 (*right-hand bars*). Note that primary energy is accounted using the direct equivalent method

prices (about a doubling of both natural gas and oil prices by mid-century) triggers also some growth for nuclear electricity and hydro power, especially in the longer-term. Overall, however, fossil fuels continue to dominate the primary energy portfolio over the entire time horizon of the RCP8.5 scenario (Fig. 5).

In terms of final energy, significant transformations occur in the manner in which energy is used in RCP8.5 (Fig. 6). Particularly electricity continues its historical growth and becomes the dominant mode of energy use mostly in the residential and partly also in the industrial sector. In the long term (beyond 2050) electricity is provided in RCP8.5 to a large extent from non-fossil sources (nuclear and biomass).

3.2.2 Impact of mitigation measures

The high energy demand and fossil intensity associated with RCP8.5 implies that achieving climate stabilization will require a massive reduction of emissions and drastic energy system transformations compared to the baseline. In fact, previous studies indicated that achieving low climate stabilization levels from the A2r scenario—the predecessor of RCP8.5—may technically not be feasible (Rao et al. 2008). The earlier studies employed though a qualitative criterion for target attainability that limited energy intensity improvement of a given stabilization targets to stay within relatively narrow margins of the baseline scenario storyline (see Riahi et al. 2007 and Rao et al. 2008). In our assessment, however, we allow pronounced reductions in energy demand beyond this criterion and observe that 2.6 W/m^2 target under a fossil intensive RCP8.5 scenario would become feasible, if more rapid energy intensity improvements were possible to achieve.

In addition to responses in energy demand, our analysis considers a number of options for reducing energy-related CO$_2$ emissions on the supply-side of the energy system (see Riahi et al. 2007 for details). These include switching from fossil fuels to renewable or nuclear power; fuel switching to low-carbon fossil fuels (e.g., from coal to natural gas); and carbon capture and storage (both fossil and biomass based). Also included in this analysis is the full basket of non-CO$_2$ gases and related mitigation options (see Rao and Riahi 2006 for details), both energy related (e.g. extraction and transport of

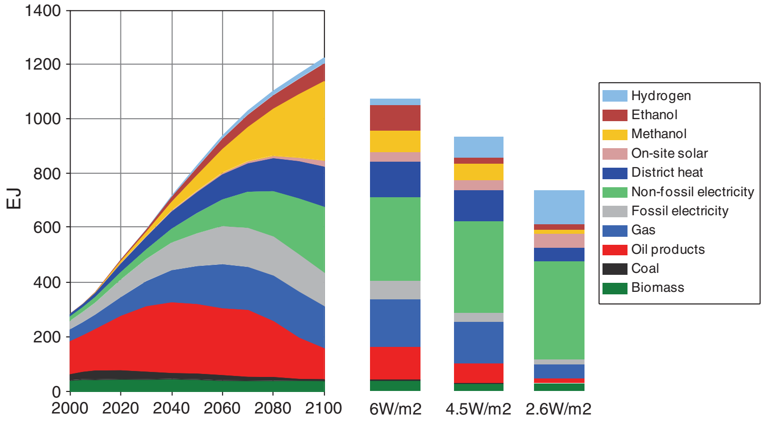

Fig. 6 Development of global final energy in RCP8.5 (*left-hand panel*), and global final energy in 2100 in the associated mitigation cases stabilizing radiative forcing at levels of 6, 4.5, and 2.6 W/m^2

coal, natural gas, and oil) and non-energy related (livestock, municipal solid waste, manure management, rice cultivation, wastewater, and crop residue burning).[10]

The primary energy mix of the climate mitigation scenarios (reaching 6, 4.5, and 2.6 W/m^2 radiative forcing by the end of the century) are illustrated in the right bars of Fig. 5. In the short and medium term, transition options like fossil based CCS (in particular natural gas with CCS) become particularly important while in the longer-term, dominant technological options include energy conservation and efficiency improvements, nuclear, and biomass with carbon capture (BECCS). This trend is robust across all analyzed stabilization targets, but is obviously most pronounced in the low 2.6 W/m^2 forcing scenario. While electricity from other renewables, like solar PV, increase their contribution in the longer-term, the majority of the carbon free electricity comes from centralized nuclear and biomass power plants. This technology choice reflects the underlying storyline of the RCP8.5 and related technology assumptions, which favor traditional centralized supply-options (including fossil CCS, nuclear and biomass). The results highlight that in principle lower stabilization goals might be possible to reach from high baselines as the RCP8.5, and that mitigation solutions would not necessarily require a shift from large-scale centralized energy production to dispersed intermittent sources (for a discussion of alternative mitigation paradigms with higher shares of intermittent renewables see Riahi et al. 2007).

In terms of final energy, the pace of electrification is accelerated further in the climate mitigation scenarios, where non-fossil electricity becomes a major driver of the decarbonization, leading to electricity shares in final energy of up to about 60% by 2100 (compared to about 30% in RCP8.5). Oil use peaks around middle of the century and declines in the longer term. In RCP8.5 the resulting gap for the supply of liquid fuels is filled by other liquefaction processes like coal- and biomass-based liquids. In the climate mitigation scenarios, hydrogen becomes an additional important long-term final energy carrier in the transport sector. Important wide ranging consequences of the transformation away from oil-products to electricity and hydrogen are at the one hand improvements of regional energy security in terms of decreased oil dependency (oil imports). At the other hand the transformation enables also major environmental improvements through decreasing pollutant emissions, particularly in urban areas (see Section 3.5).

Figure 7 compares the required pace of energy intensity and carbon intensity improvements in the RCP8.5 and the mitigation scenarios that have been derived with historical trends and selected scenarios from the literature (SRES B1 and B2). Reducing GHG emissions requires both demand-side changes (improvements in energy intensity) as well as supply-side structural changes (improvements in carbon intensity of the economy). The required pace of the transition is particularly challenging in the case of the low target of 2.6 W/m^2. In terms of carbon intensity the 2.6 W/m^2 scenario shows for example a six-fold increase in the rate of decarbonization compared to the RCP8.5 baseline. This corresponds also to a major trend-break and a five-fold acceleration of the decarbonization pace compared to the long run historical improvement rate for the world (1940 to 2000). With respect to energy intensity the 2.6 W/m^2 is less ambitious. It depicts improvement rates roughly in line with historical trends between 1940 and 2000 of about 1% per year. This rate is also comparable to assumptions for intermediate baseline scenarios in the literature such as the B2 SRES (Fig. 7). While this improvement rate is quite modest considering the

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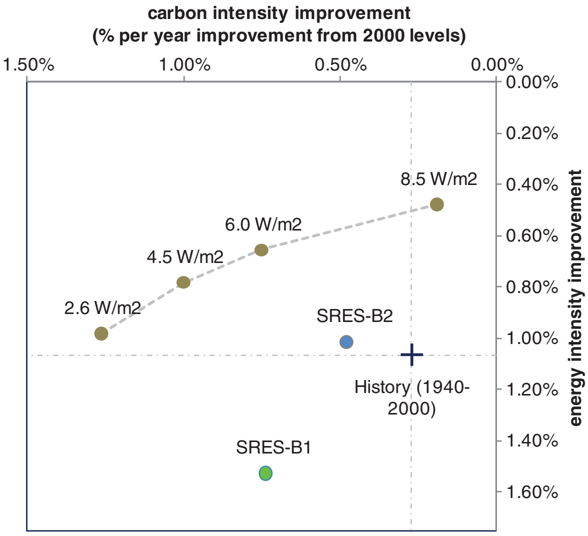
[10] Note that the mitigation scenarios assume full "when and where" flexibility to reduce emissions, subject to a global cumulative GHG emissions constraint for each radiative forcing level. Different measures are thus deployed based on endogenous model decisions to derive a least-cost solution.

Fig. 7 Long-term energy intensity and carbon intensity improvement rates between 2000 and 2100 for RCP8.5, related mitigation scenarios developed with the MESSAGE model, and the B2/B1 scenarios from SRES (Nakicenovic et al. 2000). The “cross” indicates the relative position of historical intensity improvements compared to future developments of the scenarios



stringent climate target, it means nevertheless a drastic departure from the RCP8.5 baseline, where energy intensity improves at only half this rate (0.5% per year). Our results thus also indicate the importance of path dependency and conditionality of the transformation strategy depending on the choice of the baseline and its underlying assumptions. Clearly, any of the climate targets would have been achieved by a different mix of measures (and costs) if we had used for example the sustainable SRES B1scenario with its relatively high rates of improvements as the counterfactual of our analysis (see Fig. 7).

3.3 Land-use and land-cover change

Some 1.6 billion ha of land are currently used for crop production, with nearly 1 billion ha under cultivation in the developing countries. During the last 30 years the world’s crop area expanded by some 5 million ha annually, with Latin America alone accounting for 35% of this increase. The potential for arable land expansion exists predominately in South America and Africa where just seven countries account for 70% of this potential. There is relatively little scope for arable land expansion in Asia, which is home to some 60% of the world’s population. These constraints are also reflected by the land-use change dynamics of the RCP 8.5 scenario. Projected global use of cultivated land in the RCP8.5 scenario increases by about 185 million ha during 2000 to 2050 and another 120 million hectares during 2050 to 2100. While aggregate arable land use in developed countries slightly decreases, all of the net increases occur in developing countries. Africa and South America together account for 85% of the increase. This strong expansion in agricultural resource use is driven by the socio-economic context assumed in the underlying emission scenario with a population increase to over 10 billion people in 2050 rising to 12 billion people by 2100. Even then yield improvements and intensification are assumed to account for most of the needed production increases: while global agricultural output in the scenario increases by 85% until 2050 and 135% until 2080, cultivated land expands respectively by 12% and 16% above year 2000 levels (Fig. 8).

An important characteristic of RCP8.5 are transformative changes the biomass use for energy purposes from presently traditional (non-commercial) use in the developing world to

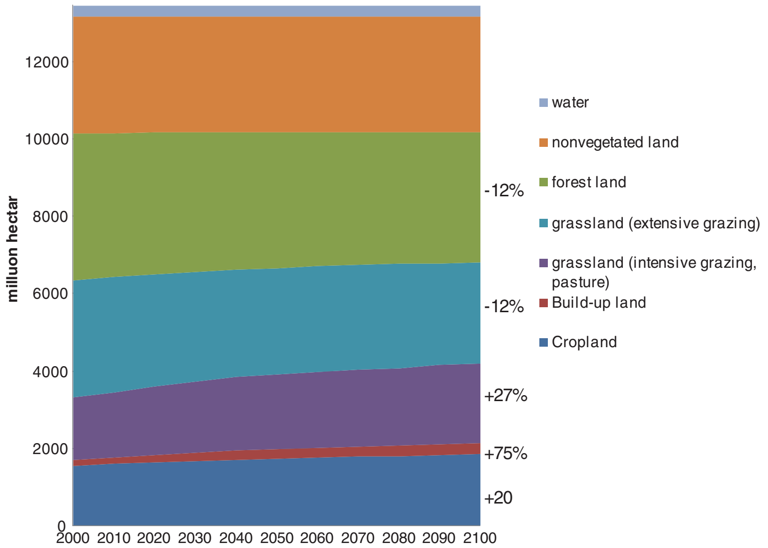


Fig. 8 Global land use by category in RCP8.5

commercial use in dedicated bio-energy conversion facilities (for power and heat) in the future. Globally the contribution of bioenergy is increasing in RCP8.5 from about 40 EJ in 2000 to more than 150 EJ by 2100. The vast majority of this biomass is harvested in forests, resulting in increased land-requirements for secondary managed forests. While total area of forests is declining in RCP8.5 (Fig. 8), the share of managed forests and harvested areas for biomass are thus increasing considerably. The latter grows from about 17 million ha to more than 26 million ha by 2100. Uncertainties in the interpretation of the underlying land developments are nevertheless very large. Hurtt et al. (2011) for example estimate about a factor of six higher land requirements for the same amount of wood harvest for the year 2000. Differences between the estimates increase over time. The results indicate the need for further harmonization of underlying data and definitions of carbon harvest in forest models.

3.4 GHG emissions

3.4.1 GHG emissions in RCP8.5

GHG emissions of the RCP8.5 continue to rise as a result of the high fossil-intensity of the energy sector as well as increasing population and associated high demand for food. The development of main GHG emissions of RCP8.5 and the corresponding mitigation scenarios is shown in Fig. 9. The RCP8.5 emissions are high, not only compared to the overall emissions scenario literature, but also compared to the set of baseline scenarios. In RCP8.5 CO_2-eq. emissions more than double by 2050 and increase by three fold to about 120 $GtCO_2$-eq. by 2100 (compared to 2000). Roughly about three quarter of this increase is due to rising CO_2 emissions from the energy sector. The rest of the increase is mainly due to increasing use of fertilizers and intensification of agricultural production, giving rise to the main source of N_2O emissions. In addition, increases in life-stock population, rice production, and enteric fermentation processes drive emissions of methane (CH_4).

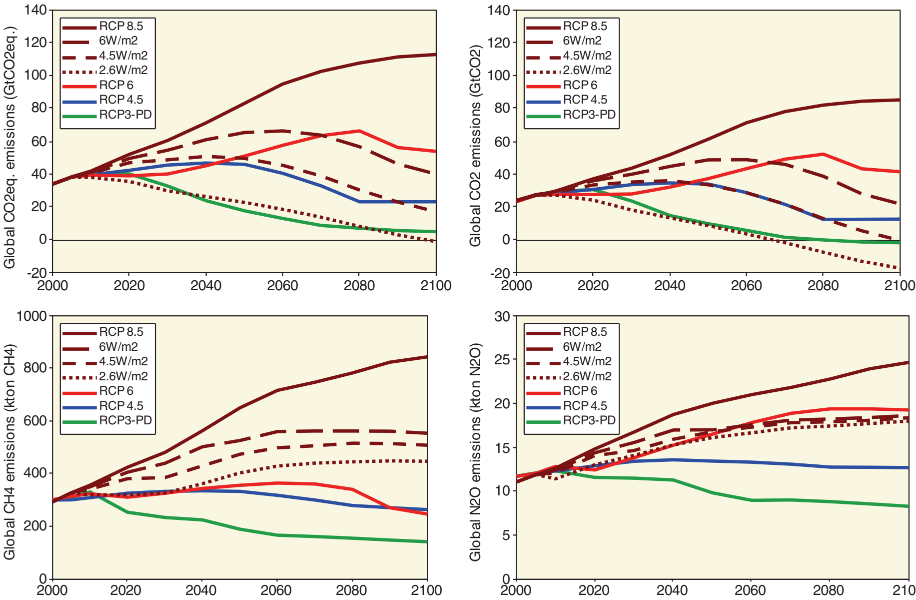


Fig. 9 Development of global GHG emissions (CO2-eq., CO_2, CH_4, and N_2O) in RCP8.5 and MESSAGE mitigation scenarios of this study (*brown lines*). For a comparison the trends of the official RCPs described elsewhere in this SI are shown as well (red = RCP6, blue = RCP4.5, green = RCP3-PD)

The high GHG emissions in RCP8.5 imply the need of large-scale emissions reductions to limit radiative forcing to levels comparable to the other RCPs. For the mitigation potentials from livestock and agricultural sectors we rely on estimates from Rao and Riahi (2006), which assumes no major technological breakthroughs in these sectors. Globally the mitigation potential is thus limited to about 50% and 30% of the RCP8.5 baseline emissions for CH_4 and N_2O respectively. This explains also the comparatively limited role of CH_4 and N_2O emissions mitigation in our mitigation scenarios compared to the official RCP2.6,[11] RCP4.5, and RCP6 (see Fig. 9 and papers on the other RCPs in this SI).

3.4.2 GHG Emissions in the mitigation scenarios

The comparatively limited potential for non-CO_2 mitigation options in RCP8.5 implies also that the bulk of the emissions reductions in the longer term will need to come from CO_2 in the energy sector (Fig. 9). Cumulative CO_2 emissions in RCP8.5 amount to about 7300 $GtCO_2$ over the course of the entire century. In order to limit forcing to 6 W/m^2 about 40% of these emissions would need to be avoided. The more stringent targets require further emissions mitigation in the order of 60% and 87% of the RCP8.5 emissions to stay below the 4.5 and 2.6 W/m2 target. The cumulative mitigation requirements have large implications for the emissions pathways, which in all mitigation scenarios are characterized by a peak and decline of CO_2 emissions. As indicated in Fig. 9, the peak of emissions in the scenario leading to 6 W/m^2 occurs around middle of the century. If, however, emissions

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[11] Note that RCP2.6 is often also referred to as RCP3-PD, indicating that its radiative forcing pathway is peaking at about 3 W/m^2 and declining later to 2.6 W/m^2. In the sequel of the paper we will refer to this RCP as RCP2.6.

growth over the next decades is considerably slower than in our scenarios (as illustrated by the official RCP6), the same target could be achieved with a later peaking date around 2080. Staying below 2.6 W/m^2 requires much more rapid emissions reductions, leading to comparatively limited flexibility for the peak of emissions. Both the official RCP2.6 and our 2.6 W/m^2 scenario indicate the need of emissions to peak before around 2020. This finding is also consistent with other assessments in the literature (e.g., van Vuuren and Riahi 2011). There are nevertheless important differences between the CO_2 emissions pathways, particularly with respect to the required negative emissions for limiting forcing to below 2.6 W/m^2. As illustrated by Fig. 9, there is a considerably larger need for negative emissions in our scenario than in the official RCP2.6. The main reason for this difference is the higher non-CO_2 emissions in our scenario, which are compensated by more pronounced negative CO_2 emissions compared to the official RCP2.6 in the long term (Fig. 9).

3.5 Emission of air pollutants

3.5.1 Air pollutants in RCP8.5

While RCP8.5 depicts baseline developments in absence of climate mitigation policies, air quality legislation plays an important role for the scenarios' projection of pollutant emissions. This reflects the fact that in contrast to climate policies, air quality measures have already been introduced in many parts of the world. Specifically, RCP8.5 assumes the successful implementation of present and planned environmental legislation over the next two decades to 2030. Beyond 2030 we further assume that increasing affluence may lead to tightening of pollutant legislation in the long term (see also Section 2.3.1).

RCP8.5 explicitly considers varying levels of legislation, economic growth and technological progress across regions, resulting in regionally different developments for emission intensities as illustrated in Fig. 10. Air quality standards are presently the highest in the OECD region. Emission intensities in the OECD are thus already comparatively low, and planned legislation is expected to reduce emissions intensities even further by 2030. For economies in transition and regions with medium development,[12] current legislations imply most significant declines across all regions by 2030. This trend reflects tightening of policies particularly in the power sector (e.g., through application of flue gas desulfurization or DENOx) and for vehicles (e.g., catalytic converters). Today's low income regions are generally characterized by modest air quality controls. These regions show also the least pronounced declines in emissions coefficients to 2030, reflecting the lack of concrete plans for future legislation over the short term.

In RCP8.5 many regions exhibit a catch-up in economic levels beyond 2030 to income levels greater than 5000$/capita (Fig. 10). After this point the regions follow the EKC assumptions of declining emissions coefficients explained in Section 2.3.1. In addition, an important trend in RCP8.5 is the pervasive shift in the energy system towards cleaner fuels and advanced fossil technologies, which together with the EKC assumptions explain the long-term decline in pollutant emissions intensities (Fig. 10). For example in the case of SO_2 emissions in the power sector, tightening of legislation results in emissions reductions from end-of-the-pipe technologies, but at the same time a growing share of inherently cleaner coal technologies (e.g., through gasification processes) fosters additional emissions reductions through technology shifts.

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[12] The definitions of medium and low development are based on the GDP/capita assumptions of the modeled region, and do not consider more complex indices like for instance the HDI (Human Development Index.

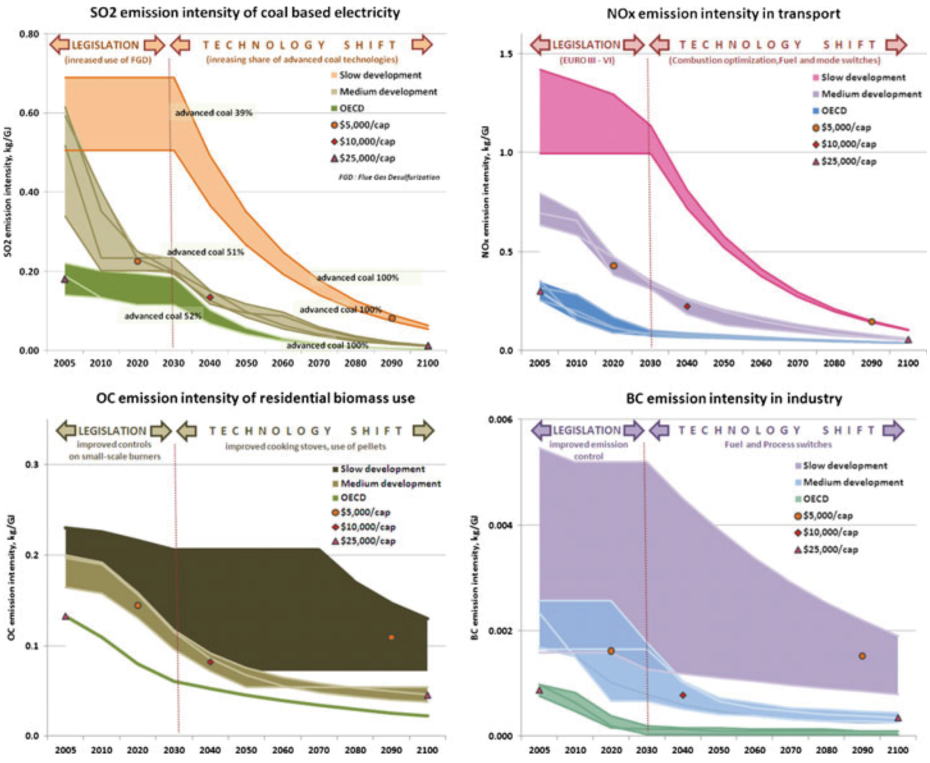

Fig. 10 Illustrative examples for the development of emissions intensities for different pollutant emissions and sectors. Current and planned environmental legislation drive improvements in emissions coefficients to 2030. Thereafter technology shifts and EKC assumptions explain further improvements. Colored ranges depict sub-regional differences between regions at similar economic development stages (slow development, medium development, and OECD)

Assumptions about environmental legislations in combination with ongoing structural and technological change imply thus in RCP8.5 that pollutant emissions decline significantly as seen in the example of SO_2 emissions in Figs. 11 and 12. Growing regional environmental concerns combined with the lack of a global climate change regime thus also imply a clear decoupling of CO_2 emissions from pollutants. For example, the power sector remains a major contributor to CO_2 emissions by the end of the century; although SO_2 emissions from this sector are almost negligible due to increasing use of advanced coal technologies. Also in the transport and residential sector, CO_2 emissions continue to rise globally while in most developing regions, there is either a slowing down of growth of pollutants from this sector or even a decline where air quality legislations are stringent enough to offset growing demand. This is important as the RCP8.5 while representing the highest levels of GHG emissions among the RCP set, is not necessarily a 'high pollution' case as well.[13]

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[13] An important caveat to note is that the RCP8.5 assumes the full implementation of present air quality legislation in all regions. However if we took into account the uncertainty in implementation of present plans for legislation, pollutant emissions might be higher than as depicted by the RCP8.5. In the longer term, uncertainty in technological availability and controls may also lead to a higher emissions profile than estimated here. For a sensitivity analysis of the impact of e.g., different EKC assumptions for long-term pollutant emissions see Rafaj et al. 2010.

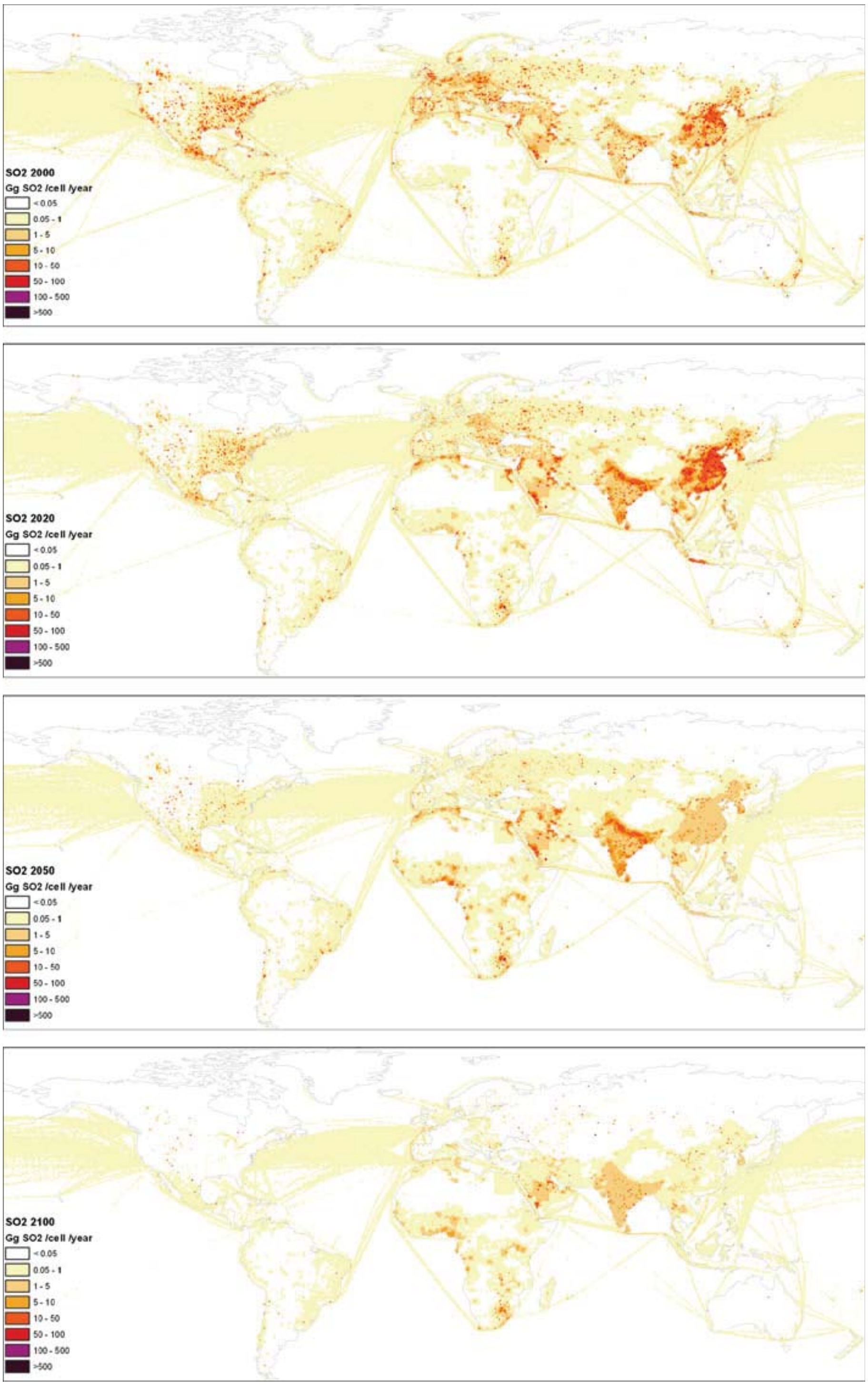
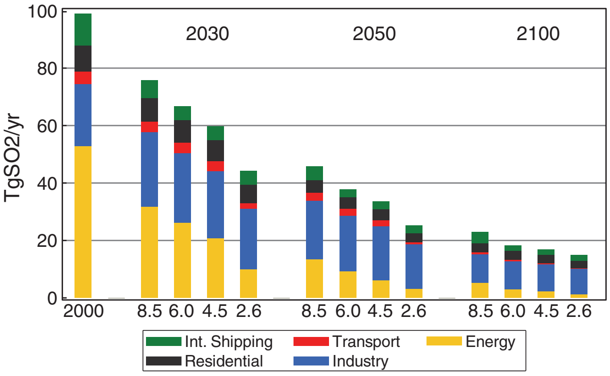


Fig. 11 Distribution of SO_2 Emissions in RCP8.5 for the years 2000, 2020, 2050, and 2100

Fig. 12 Global SO_2 Emissions by sector in the RCP8.5 baseline and the mitigation scenarios for 6, 4.5, and 2.6 W/m^2



While globally aggregated trends for pollutants show continues improvements and declines in emissions, there are pronounced regional and spatial differences with local implications for human health, environment, and climate change. The maps of Fig. 11 illustrate some of the main spatial dynamics for the evolution of SO_2 emissions in RCP8.5. The spatial dynamics are similar for other pollutant emissions and to large extent also for the mitigation scenarios. Initially, the majority of the reductions happen in OECD countries whereas developing regions, in particular Asia, continues to grow in terms of SO_2 emissions, mainly due to growing energy demands (see map for 2020). This clearly indicates that currently legislated environmental policies are most likely not sufficient in reducing pollution levels of emerging economies where growth in energy demands can offset the effects of control policies. This may particularly be the case in China and India. In the longer-term, however, increasing affluence and technological shifts in these regions (Fig. 10) imply in RCP8.5 that global emission levels decline significantly, leading to reduced impacts from pollutants at global scale.

3.5.2 Air pollutants in the mitigation scenarios

With respect to the mitigation scenarios, we observe significant co-benefits from climate mitigation for pollutant emissions. As explained earlier, the greenhouse gas emissions reductions in the mitigation scenarios lead to major improvements of the carbon-intensity and the energy-intensity compared to the RCP8.5 baseline. This switch to carbon-free and non-fossil technologies is generally associated with lower pollutant emissions. In addition, also the application of CCS requires cleaner combustion processes, and thus reduces pollutant emissions in the climate mitigation scenarios further. Perhaps most importantly, the higher rates of energy-intensity improvements in the climate mitigation scenarios leads to pronounced energy savings, and each unit of energy that is not consumed is obviously climate friendly as well as pollution free.

The co-benefit of climate mitigation for pollutants is particularly pronounced over the short to medium-term (Fig. 12). For instance, the 2.6 W/m^2 scenario reduces global SO_2 emissions by about 55% in 2030 compared to the year 2000. This steep decline corresponds to roughly a doubling of pollutant emissions reductions compared to the RCP8.5 baseline (25% reductions in 2030 compared to 2000). Or put in other words, stringent climate mitigation may reduce pollutant emissions by about the same order of magnitude as the entire legislated air pollution policy that is presently in the pipe.

4 Discussion and conclusions

RCP8.5 depicts, compared to the scenario literature, a high-emission business as usual scenario. Its socio-economic development pathway is characterized by slow rates of economic development with limited convergence across regions, a rapidly rising population to comparatively high levels, and relatively slow pace of technological change. The latter assumption is reflected also by the scenario's modest improvement rates of energy intensity, which drives energy demand towards the high end of the scenario literature. The primary energy mix of RCP8.5 is dominated by fossil fuels, leading to the extraction of large amounts of unconventional hydrocarbon resources well beyond presently extractable reserves. GHG emissions grow thus by about a factor of three over the course of the century, mainly as a result of both high demand and high fossil-intensity of the energy sector as well as increasing population and associated high demand for food. The resulting radiative forcing is the highest among the RCPs presented in this SI, with the emissions profile of RCP8.5 being representative of high GHG emissions scenarios in the literature.

For the development of RCP8.5 we employed new methodologies for the spatial representation of land-cover changes as well as the improved representation of pollutant emissions legislation, including spatial downscaling algorithms for exploring local implications of regional/global air pollution trends. Our results indicate that successful implementation of presently legislated pollutant control measures would reduce global pollutant emissions significantly over the short term (e.g. global reductions of about 25% of SO_2 emissions between 2000 and 2030). This trend occurs despite the high GHG intensity of RCP8.5, illustrating the possibility to decouple air pollutant emissions from greenhouse gases through end-of-the-pipe technologies. In the long term additional technological shifts to advanced fossil technologies reduce pollutant emissions further to very low levels in RCP8.5.

The results from the mitigation analysis indicate that it would be technically possible to reduce GHG emissions from RCP8.5 down to levels comparable to the other RCPs presented in this SI. In contrast to earlier studies we found that this was possible even for the most stringent radiative forcing target of 2.6 W/m^2. This finding is conditional, however, on the feasibility of massive changes in the energy system compared to the RCP8.5 development path, accelerating energy intensity improvements by a factor of two and carbon intensity even by a factor of about six over the entire century. The mitigation scenarios would thus require a pronounced departure from the original RCP8.5 storyline.

Finally, form the policy perspective, an important finding of our analysis is the significant potential of climate mitigation to further reduce pollutant emissions. In the case of the most stringent forcing target of 2.6 W/m^2 the co-benefit for air pollutants are globally of the same order of magnitude as the effect of presently legislated pollutant measures over the next two decades. The results thus indicate the importance of better integration of local policy priorities, such as health and air pollution into the global climate mitigation debate.

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Air-pollution emission ranges consistent with the representative concentration pathways

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The fifth phase of the Coupled Model Intercomparison Project[1] uses four representative concentration pathways[2] (RCPs) that span the literature range of total anthropogenic radiative forcing[2,3] but not necessarily of each single forcing agent. We here explore a wide range of air-pollutant emissions over the twenty-first century consistent with the global CO_2 paths of the RCPs, by varying assumptions on air-pollution controls and accounting for the possible phase-out of CO_2-emitting sources. We show that global air-pollutant emissions in the RCPs (including ozone and aerosol precursors) compare well to and are at times higher than cases that assume an extrapolation of current and planned air-pollution legislation in the absence of new policies to improve energy access for the poor. Stringent pollution controls and clean energy policies can thus further reduce the global atmospheric air-pollution loading below the RCP levels. When assuming pollution control frozen at 2005 levels, the RCP8.5-consistent loading of all species either stabilizes or increases during the twenty-first century, in contrast to RCP4.5 and RCP2.6, which see a consistent decrease in the long term. Our results inform the possible range of global aerosol loading. However, the net aerosol forcing depends strongly on the geographical location of emissions[4]. Therefore, a regional perspective is required to further explore the range of compatible forcing projections.

Representative concentration pathways (RCPs) were selected to be representative of a wide range of radiative forcing outcomes. They were developed with the support of different integrated assessment models (IAMs) and yield net forcing outcomes by the end of the century ranging from 2.6 to 8.5 W m^{-2}. Although anthropogenic greenhouse gas (GHG) emissions are the dominant driver of global mean warming[5,6], emissions of air pollutants can have important local and regional effects[4,7] including changes in local and regional circulation or precipitation patterns. RCPs did not intend to span the full uncertainty of future air-pollutant emissions, but present possible, internally consistent air-pollutant pathways (often using similar assumptions, see below). However, some studies have indicated that emissions of air pollutants can vary notably when varying air-quality policies for the same global CO_2 emissions[8,9]. Here we approach this question systematically and vary pollution control assumptions to explore a range of air-pollutant emissions consistent with each RCP in a single modelling framework. This provides a point of comparison for understanding the stringency of pollution controls implied by the original RCPs.

Emissions of air pollutants depend on the presence and activity of air-pollution sources, the stringency of air-pollution policies and eventual enforcement of related control technologies. CO_2 and several air pollutants are co-emitted by the same (fossil fuel) sources in the energy system. Measures to reduce CO_2 will thus also impact air-pollutant emissions[10–12], although some sources (such as biomass burning[13]) are only marginally affected because they are considered carbon neutral in IAMs. Likewise, other energy-system transitions will also influence the abundance of air-pollutant sources, independent of climate policies[14].

We develop consistent air-pollutant emission paths for the RCPs by estimating the relationship between global CO_2 and air-pollutant emissions at four distinct levels of air-pollution control stringency, starting from a large and diverse scenario set developed in a previous study[15] that was based on work from the Global Energy Assessment[16] (Methods). Our air-pollution control levels originate from another previous study[17] and range from no improvements relative to 2005 to very stringent reductions that push the frontier of end-of-pipe pollution control technologies (Table 1; ref. 17). We assume a total of four air-pollution control levels: a frozen legislation case (FLE), a current legislation case (CLE), a stringent legislation case (SLE) and a case assuming maximum feasible reductions (MFR). Our current legislation case assumes a further tightening of air-pollution legislation in developing countries throughout the century, in line with economic affluence (Table 1), leading to levels similar to our stringent legislation case in the long term. The scenarios that we use for the estimation of the relationships between global CO_2 and air-pollutant emissions assume middle-of-the-road population and economic projections[16] that are not varied across the scenarios. Varying these assumptions, in particular on the regional and sectorial scale, might further increase the ranges we present below. In the absence of climate policy, energy intensity improvement rates in these scenarios are consistent with what has been observed historically[16,18]. However, with increasing CO_2-emission reductions, energy intensity improvements increase also (for example, see ref. 18). Furthermore, assumptions about whether and when the poorest segments of society gain access to better living conditions[16] has a critical impact on residential air pollution. This is discussed further below, where we explore accelerated energy access policies[19]. We also explore implications of alternative assumptions of fundamental technological drivers, such as structural shifts in the way energy is provided (centralized versus more distributed).

Our discussion focusses on RCP4.5 and RCP8.5, which are part of the first tier of the Coupled Model Intercomparison Project (CMIP5) and have therefore been run by all participating climate modelling groups[1]. Furthermore, we discuss results for RCP2.6 (alternatively known as RCP3-PD), because major air-pollution co-benefits are expected in this scenario due to the phase-out of fossil fuels under stringent climate change mitigation. Figure 1

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Table 1 | Overview of air-pollution policy cases.

Policy case	Code	Description
Frozen legislation	FLE	Air-quality legislation is kept frozen at its 2005 level in all regions during the entire twenty-first century.
Current legislation	CLE	Present existing and/or planned legislation is enacted in every region, respectively. After 2030, air-pollution legislation in developing countries is further tightened throughout the century in line with economic affluence to levels consistent with present air-pollution legislation in the developed world[8,14,17].
Stringent legislation	SLE	Feasible, yet aggressive, air-quality legislation is enacted in all regions; in each region, the implementation level is about 70% of the theoretically achievable MFR potential (see below).
Maximum feasible reduction	MFR	Air-quality legislation is enacted globally at the level of best available technologies of today in every region by 2030; this case is used as a present theoretical limit to air-pollution control.

Based on refs 17,15. See Supplementary Table 1 for more background on energy access policy cases.

shows the resulting paths for black carbon (BC), organic carbon (OC), carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOC). Also, the original RCP trajectories, developed by the individual modelling teams within the original RCP exercise, are shown in red.

Applying our relationships to the RCPs helps to disentangle the effect of decarbonization over the twenty-first century from the effect of air-quality legislations on air-pollutant emissions. When assuming the same air-pollutant policies, consistent emissions for RCP4.5 and RCP2.6 are generally lower than in RCP8.5 in the long term, because of CO_2 mitigation in the lower RCPs. The more decarbonization (CO_2 mitigation), the more the consistent pollutant emissions ranges shift downwards.

The original RCP paths exhibit a strong decline in most air pollutants leading to a very similar level of air pollution in all RCPs in the medium to long term. This is mostly because of the shared assumption of the RCPs that air-pollution policies increase proportionally with income[9,14,20–22] (although exact assumptions vary per RCP). Also, our model set-up reproduces this general trend. However, although the reconstructed and original emissions in Fig. 1 are very consistent (orange/red lines), they are overall at the higher end of our air-pollution ranges. This indicates that although all RCPs do include some improvement of air-quality policies over the twenty-first century, consistent air-pollutant emissions can be both significantly higher and significantly lower. We explore this in more detail below.

The wide range of air-quality control enforcements assumed in our methodology[17] is one of the main reasons underlying the wide ranges presented here (grey areas, Fig. 1). Earlier studies generally explored smaller policy variations[9]. The range we present shows the maximum influence of shifting from a level in which future air-quality policy is unsuccessful and even rolled back to 2005 levels (FLE) to very ambitious global pollution controls assuming widespread implementation of the current best available technologies (MFR). We find that for almost all pollutants stringent air-quality legislation could further reduce emissions beyond the RCP levels during the first half of this century. However, significant increases in air pollution would be consistent only in a high CO_2-emission world, such as RCP8.5.

Our highest air-pollution estimates for RCP8.5 are consistent with other studies that provide baseline emission estimates until 2050 (refs 8,23), with differences depending on model structure and the modelled technological transitions in our scenarios. The Special Report on Emission Scenarios[24] (SRES) also provides baseline projections. Although the SRES scenarios included air-pollution legislation that was already implemented by 1990, the most pessimistic case available here is assuming air-pollution legislation frozen at its 2005 level. As air-pollution legislation became more stringent between 1990 and 2005, the highest air-pollution estimates here are lower than those of the SRES scenarios.

Furthermore, the underlying scenarios here use regional technology and fuel-specific emissions factors from which we derive global relationships between CO_2 and air pollutants (Methods). However, technological change can contribute to declining overall emission intensities over time, even if air-pollution policy remains the same. For example, technology and fuel-specific emission factors in the scenarios underlying our frozen legislation case (the most pessimistic case here) are frozen at their 2005 levels. However, even in absence of climate change mitigation, new technologies are adopted over the course of the century in the underlying scenarios, for example, for reasons of cost-effectiveness or because retired power plants are replaced by current technology. These new technologies result in overall improved and cleaner combustion processes and thus imply that, even in high emission scenarios and in the absence of any additional air-pollution controls, emission intensities of air pollutants at the sectorial level can decline over time. This approach differs from other studies, which use more aggregated sectorial emissions factors that are kept constant over time to create baseline emission estimates[23] (see also Supplementary Information).

Other drivers besides air-quality controls and GHG mitigation influence the quantity of air pollutants released to the atmosphere. First, policies that promote energy access for poverty eradication attempt to induce a shift in the energy use of poor populations, from traditional biomass burning to modern forms of energy. By doing so, they also significantly reduce certain air-pollutant emissions. The default assumption underlying our analysis is that modern forms of energy become available to the poorest parts of the population by the early second half of this century at the latest. When assuming that these efforts are accelerated[17,19]—resulting in universal energy access by 2030, as promoted by the United Nations Sustainable Energy for All initiative (www.se4all.org)—near-term air pollution is also reduced markedly in the residential and commercial sectors of the developing world (brown areas, Fig. 2). The RCPs here provide an excellent additional point of comparison. The scenario storyline underlying RCP8.5, for example, assumes a very heterogeneous world, with a continuously increasing global population and little convergence between high- and low-income countries[14,25]. Also, the other RCPs assumed storylines with a focus on local and regional solutions rather than global ones[20,21,26]. This suggests an underlying assumption in all RCPs that a significant share of the global population still lives with no access to modern and clean energy by the end of the century, albeit a smaller relative share than

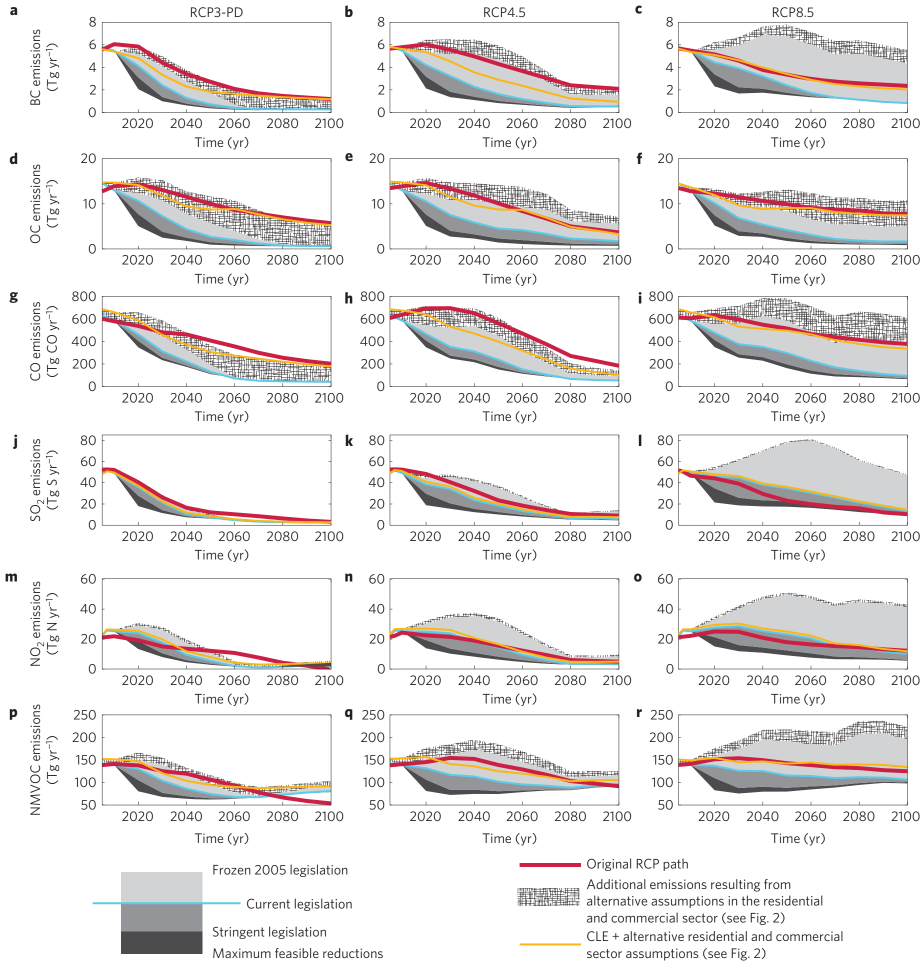

Figure 1 | Ranges of anthropogenic air-pollutant emissions consistent with the representative concentration pathways (RCPs). a–r, Results for RCP3-PD, RCP4.5 and RCP8.5 are shown in the left, middle and right column, respectively, and for BC (**a**–**c**), OC (**d**–**f**), CO (**g**–**i**), SO_2 (**j**–**l**), NO_2 (**m**–**o**) and NMVOC (**p**–**r**). Grey ranges are derived from our four air-pollution policy cases, with the blue line indicating the current legislation (CLE) case. The pollutant emission paths from the original RCPs are given in red. The hashed range illustrates the potential influence of energy access policies on the various air-pollutant species (see also Fig. 2). The orange path shows CLE emissions combined with the hashed ranges. See Methods for a definition of anthropogenic sources.

today. This is illustrated by the high OC, CO and BC emissions in the residential and commercial energy sectors in the original RCP scenarios (Fig. 2) and the differences with our scenario set assuming some level of energy access policies by the second half of the century (see hashed areas and blue versus orange lines in Fig. 1; Fig. 2). The absolute influence on SO_2 and NO_x is limited, because in most regions typical residential fuels (biomass, charcoal and liquefied petroleum gas) emit only low amounts of these species.

A second alternative driver of future air-pollutant emissions relates to assumptions about long-term energy efficiency improvements and technological change, two factors influencing the resulting energy mix. For example, the replacement of pulverized coal-fired power plants with much more versatile integrated gasification combined cycle (IGCC) plants will result in the removal of sulphur from the exhaust stream because of the thermodynamic design of IGCC plants and their need to avoid fuel impurities (see also ref. 16). Exploring such influences across a diverse set of technological drivers[16] shows that alternative technology mixes can indeed induce differences in pollutant emissions (given similar CO_2 emissions), but to a smaller degree than the other factors discussed above (Supplementary Fig. 7). These differences become more pronounced in the second half of the century, when energy systems can differ more substantially and can be more dependent on underlying model assumptions.

Land-use practices and land-use change are another important factor influencing the abundance of air pollutants. For example, in

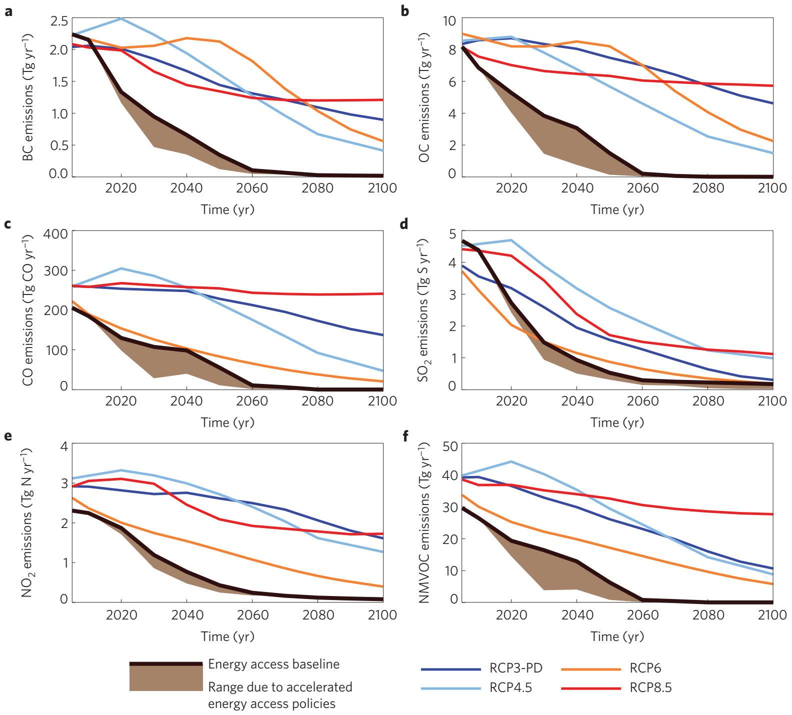

Figure 2 | Influence of energy access policies on air pollutants from the residential and commercial sector. a–f, Results are provided for BC (**a**), OC (**b**), CO (**c**), SO_2 (**d**), NO_2 (**e**) and NMVOC (**f**). Original representative concentration pathway (RCP) emissions are given in blue, orange and red (see legend). The reference pathways from ref. 15 are given in dark brown and assume gradual improvements in the access of poor populations to modern and clean energy carriers (moderate access in Supplementary Table 1). Brown ranges show estimated emission reductions when accelerating energy access policies (see refs 17,19; universal access in Supplementary Table 1). RCP8.5 (red) assumes no new policies throughout the century (Supplementary Table 1). Being produced by the same modelling framework, the difference between RCP8.5 and the brown ranges provides a consistent indication of how high an impact energy access policies can have on air pollutants by the end of the twenty-first century. The difference between the dark brown line and each RCP, respectively, is represented by the hashed area in Fig. 1.

2005, emissions from savannah and forest burning were responsible for 33, 64, 44, 14 and 36% of total global BC, OC, CO, NO_x and NMVOC emissions, respectively[27]. Regionally, contributions can be even higher. Supplementary Fig. 8 compares these contributions between the Global Energy Assessment[16] and the RCPs. The Global Energy Assessment assumed future land-use practices that limit emissions from forest fires (owing to sustainable forest management practices) and savannah burning (for public health reasons). Although these so-called natural sectors are important sources of air-pollutant emissions, here too the RCPs look rather conservative when compared with a scenario taking into account numerous aspects of sustainability[16]. In a world with an increasing population and therewith possible increase in global share of managed land, a scenario with increasing contributions of these natural sectors is not excluded but might become less plausible.

Our results affirm that the air-pollutant emissions of the original RCPs are comparable to futures with a continuation of current pollution control legislation throughout the remainder of the century (red versus blue/orange lines, Fig. 1). However, both higher and lower evolutions are possible when exploring a wide range of influencing factors. For RCP2.6 and RCP4.5, we find that air-pollutant emissions are at the high end of our ranges. This is different for RCP8.5, which has air-pollutant emissions that are mostly in the middle to lower range and for which significantly higher aerosol loadings could be technologically consistent. When energy access provisions and land-use practices are considered, all original RCPs seem to present a relatively high global aerosol loading (by both warming and cooling species, Fig. 2 and Supplementary Fig. 8).

For present legislated and planned air-pollution controls to materialize effectively over the coming decades, policy enforcement is key. Although this analysis assumes perfect enforcement at each level of policy stringency, real-world variations in implementation and technology performance might also lead to significant deviations, especially at a regional level. Also, improvements in energy access and land-use practices require dedicated policies. This corroborates earlier findings that highlight the important benefits of policies that aim at achieving many objectives—such as climate protection, clean air and energy access—concurrently instead of in isolation[15].

All variations in our assumptions notwithstanding, there are many alternative futures that could be imagined in addition to the ones underlying this study, and they can be modelled differently by different modelling teams. Alternative storylines can, for example, vary the anticipated challenges to climate change adaptation and mitigation, or air-pollution assumptions such as the global convergence of air-pollution legislation along with economic affluence. It is expected that such variations will affect the air-pollution emissions of scenarios with little to no CO_2 mitigation significantly more than those of stringent CO_2 mitigation scenarios, where reductions are driven by the requirement to decarbonize. Ongoing work in the framework of the shared socioeconomic pathways[28,29] is exploring a number of alternative storylines and will yield further invaluable results across a multitude of models in the coming years.

Methods

Based on a large ensemble of scenarios from ref. 15 (all of which are created with the linked MESSAGE-GAINS IAM framework[17,25,30,31] and in which both climate policy[10,15] and air-pollution control stringency[17] are varied), we develop relationships by means of non-parametric fits with piecewise polynomial cubic smoothing splines between the global level of anthropogenic CO_2 emissions from fossil fuel and industry in a given year and the corresponding global air-pollutant levels (Supplementary Figs 1–6; for detailed information and a lookup tool for these fits, see Supplementary Data).

Our estimates thus reflect technological changes that lead to the adoption of new technologies in the underlying scenarios. Such technological change often results in improved and cleaner combustion processes. Examples of such technologies include coal-based IGCC and polygeneration plants with gasification. These technologies have by design lower pollutant emissions (for example, for SO_2) compared with traditional coal-power generation technologies and, more generally, have more efficient combustion processes that emit lower amounts of CO, BC and OC. Global and sectorial intensities of air pollutants relative to CO_2 can thus improve over time even if legislation stays at a fixed level.

The coefficients of determination for the fits with species that share many common sources with CO_2 (BC, NO_x, SO_2) are usually larger than 0.9 (see background data in Supplementary Data). For species that are less subject to co-control by CO_2 mitigation (OC, CO), the coefficients of determination are much lower, indicating that their emission levels depend to a much larger degree on the stringency of air-pollution control instead of the presence of CO_2-emitting sources. We use the developed pollutant-by-pollutant relationships at a global level to create consistent air-pollutant emission paths for the CO_2 emissions of the RCP2.6, RCP4.5 and RCP8.5 scenarios and also include the influence of energy access policies at the residential and commercial sector level. The variations of air-pollutant controls in our set are based on a set of variants from ref. 17 and include short-term information from the GAINS (ref. 31) model. The scenario set of ref. 15 is supplemented by scenarios from ref. 32 that additionally vary assumptions on the drivers of technological development in terms of, for example, energy efficiency improvements and technological change, and alternative energy access scenarios from ref. 18, based on ref. 33.

Anthropogenic air-pollutant emissions here are the emissions from all sectors excluding savannah, grassland and forest burning that are referred to as natural sources. For the assessment of the possible influence of varying technological drivers, we base our study on the GEA-Efficiency, GEA-Mix and GEA-Supply scenario families of the Global Energy Assessment[16]. Energy access policy cases are based on ref. 19.

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Author contributions

J.R. and K.R. designed the research; J.R. carried out the research, using air-pollution policy variants from S.R. and scenario data from D.L.M.; J.R. wrote the first draft; all authors contributed to the analysis and discussion of the results, as well as to writing the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.R.

Competing financial interests

The authors declare no competing financial interests.

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Future aerosol emissions: a multi-model comparison

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Abstract This paper compares projections over the twenty-first century of SO_2, BC, and OC emissions from three technologically detailed, long-term integrated assessment models. The character of the projections and the response of emissions due to a comprehensive climate policy are discussed focusing on the sectoral level. In a continuation of historical experience, aerosol and precursor emissions are increasingly decoupled from carbon dioxide emissions over the twenty-first century due to a combination of emission controls and technology shifts over time. Implementation of a comprehensive climate policy further reduces emissions, although there is significant variation in this response by sector and by model: the response has many similarities between models for the energy transformation and transportation sectors, with more diversity in the response for the building and industrial sectors. Much of these differences can be traced to specific characteristics of reference case end-use and supply-side technology deployment and emissions control assumptions, which are detailed by sector.

1 Introduction

Aerosols, small particles in the atmosphere, are key climate-forcing agents, both positive and negative, with net aerosol cooling presently offsetting about 30 % of GHG warming (IPCC AR5 central values, Myhre et al. 2013). Aerosol emissions, therefore, form an essential component of

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projections used to explore future climate change (Taylor et al. 2012, Van Vuuren et al. 2011b). Climate mitigation strategies might also aim to manage future aerosols, such as reducing black carbon emissions, which have a positive contribution to warming. This can be a means of reducing short-term climate change (Unep 2011, Ramanathan and Xu 2010), although the scope for this may be more limited than previously thought (Smith and Mizrahi 2013, Rogelj et al. 2014).

It is important to understand the fundamental drivers of these emissions in future scenarios. Recently, Rose et al. (2014) examined the global aerosol forcing trends in projections from five integrated assessment models. This paper provides a more detailed sectoral examination of aerosol projections from three models, GCAM, IMAGE and MESSAGE, using projections produced for the Representative Concentration Pathway (RCP) scenarios process (Moss et al. 2010, Van Vuuren et al. 2011b). Understanding the emission trends in the RCPs is important as they have been widely used, including for CMIP5 climate model simulations (Taylor et al. 2012). Moreover, the current aerosol representations and model dynamics in these IAMs are similar to those in the model versions used to produce the RCPs (ESM §1, §2). We note that there have been new efforts by the IAMs to improve the representation of near-term pollution policies and linking efforts and degree of pollution control to socio-economic drivers. This is reflected in the recently developed SSP scenarios (Rao et al. 2016), which have a wider range of reference case emission pathways as compared to the RCP scenarios. However this range indicates the still substantial uncertainty in the future evolution of the key factors discussed here.

These IAM models simulate regional energy and land-use, their global interactions, and the greenhouse gas and pollutant emissions that result from these anthropogenic activities. They differ, however, in model structure and future assumptions for driving factors such as technology development and pollutant control levels. By comparing results from these three models in detail, we provide insight into how differences in model structure and assumptions impact pollutant emission projections. We examine both reference and corresponding climate policy scenarios from each model so that consistent changes due to climate policy can be examined. Further details on the scenarios and their development is provided in ESM §2.

This analysis focuses on century-scale emission projections for sulfur dioxide (SO_2), black carbon (BC), and organic carbon (OC), focusing on the energy and industrial emissions at the sectoral level. We single out these three compounds because these are the predominant sources and precursors of atmospheric aerosol particles.[1] For brevity, we will collectively refer to these as aerosol emissions below, noting that, physically, sulfur dioxide is an aerosol precursor.

The models and scenarios described elsewhere (Thomson et al. 2011, Riahi et al. 2011, Van Vuuren et al. 2011a), with a brief overview in the electronic supplementary material (ESM). Emissions in reference case projections that do not include a climate policy are examined in section 3. Section 4 examines how the projections change when a comprehensive climate policy is applied to the reference case scenarios. We conclude with a discussion and conclusions. The ESM contains comprehensive graphs of emissions and fuel use by sector, and regional emissions by sector.

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[1] Emissions of reactive gases such as nitrogen oxides, carbon monoxides, and volatile organic hydrocarbons also influence aerosol concentrations, however we focus here on SO_2, BC, & OC emissions.

2 Reference case emissions

2.1 Overall trends

We first consider emissions from the three reference case scenarios (solid lines in Figs. 1, 3, SM-3, SM-4, SM-7, etc.). Fossil energy use, one of the primary drivers of the emissions considered here, expands substantially in the reference cases. As a consequence, CO_2 emissions increase over the century in all three reference scenarios (ESM §5).

Global total anthropogenic emissions (exclusive of land-use) of SO_2, BC, and OC generally decline over the century (Fig. 1, ESM §7), as noted in previous work (Rose et al. 2014). SO_2 emissions trends are broadly similar in MESSAGE and GCAM, while the IMAGE emissions are much higher, which is largely due to different assumptions for the energy conversion sector. BC emissions are dominated by building and transport sectors. GCAM BC emissions increase until 2020, driven by increases in buildings and industry, and then decrease to around 3 Tg by the end of the century. MESSAGE BC emissions continuously decrease after 2005 to around 2 Tg, with near-term decreases in transportation offsetting flat or slightly increasing near-term emissions elsewhere. IMAGE BC emissions show a sharp decline in the last half of the century and decrease to very low values (< 1 Tg). These sectoral level details discussed further below.

Emission intensity tracks the aggregate sectoral impact of technology changes plus emission controls. BC and SO_2 emission intensity projections for each reference case are shown in Fig. 2. We define emission intensity as aerosol emissions per unit CO_2 emissions because a large portion of BC, OC, and SO_2 emissions originate from fossil-fuel combustion (there can be a slight bias in this metric depending on bioenergy accounting, but this is a small effect in most cases, see ESM).

Global emission intensity generally decreases by roughly an order of magnitude over the century (Fig. 2) as aerosol and precursor emissions progressively decouple from CO_2 emissions. BC emissions in GCAM and SO_2 emissions in IMAGE show the smallest intensity decrease, while SO_2 in MESSAGE and BC in IMAGE show the largest decreases. The divergence in emission intensity increases markedly in the second half of the century. The MESSAGE scenario has the lowest emission intensity values. In part, this is due to the MESSAGE scenario, broadly speaking, aiming to achieve similar air quality improvements

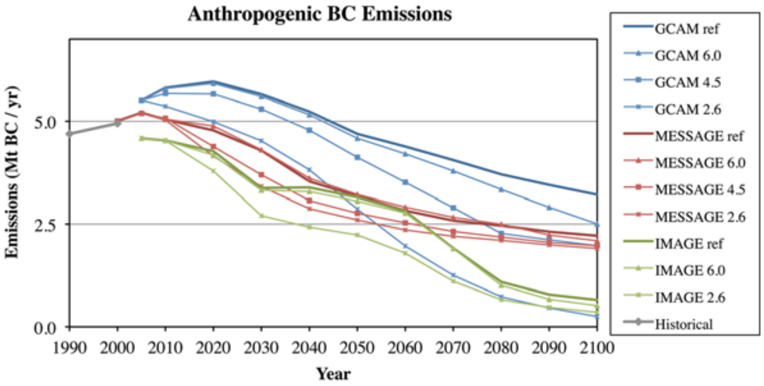

Fig. 1 Global anthropogenic black carbon (BC) emissions (*exclusive of land-use*). For each model, the thicker line is the reference scenario and the three thinner lines are the corresponding climate policy scenarios. The grey lines show historical emission estimates (Lamarque et al. 2010). Base-year emission differences are within estimated uncertainties are discussed further in the ESM

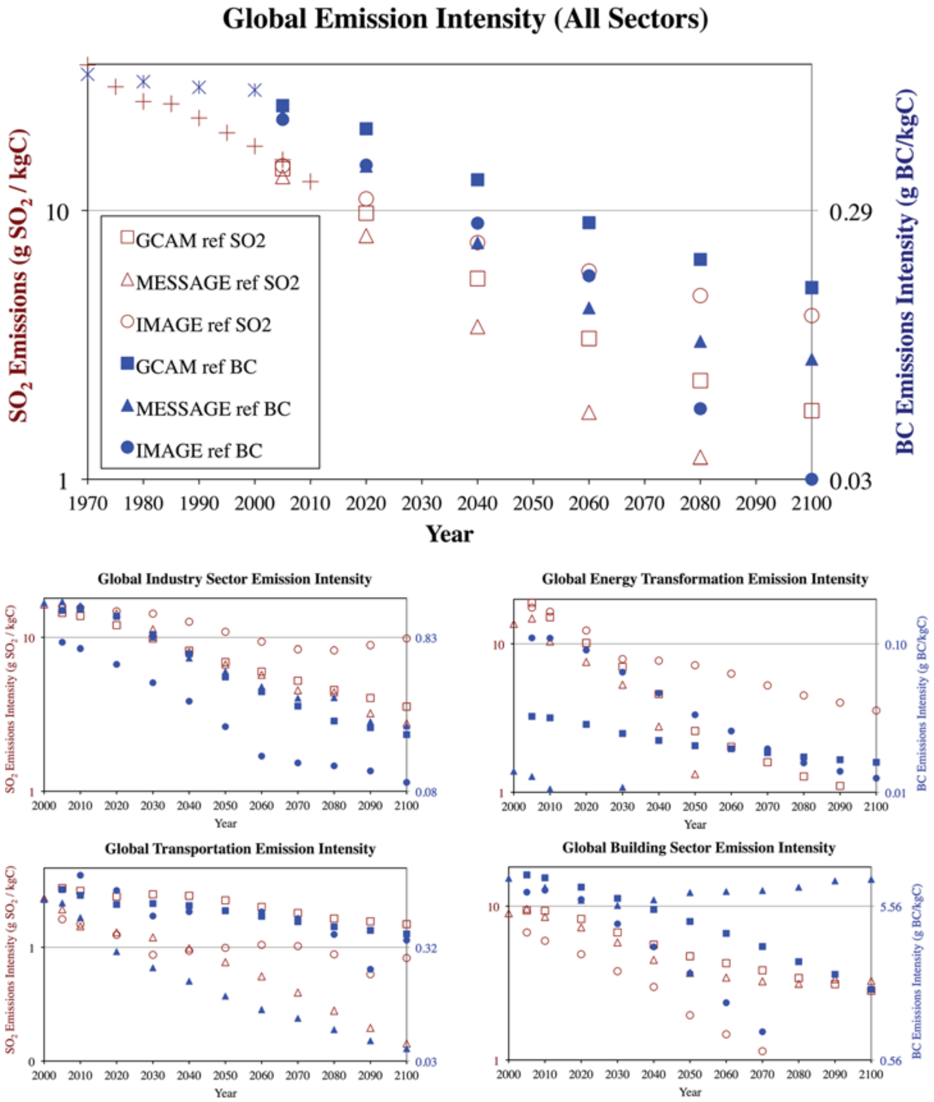

Fig. 2 BC and SO_2 emission intensities globally (*excluding land-use*) for reference (*ref*) scenarios. Top: for all sectors, and bottom: for the transportation, energy transformation, and industrial sectors separately. Intensities are in terms of reference scenario emissions per unit CO_2 emissions (in carbon units). Open, red symbols are for SO_2 (*left axis*), and closed, blue symbols are for BC (*right axis*). The vertical scale is logarithmic, and covers the same relative interval for BC and SO_2, although note the axis origin is different. Historical values from 1970 are also shown for global intensities. Note that non-combustion SO_2 emissions are included in the industrial sector, which increases this ratio (ESM §1.2). Building sector emission intensities are influenced by different accounting of CO_2 from biomass in the models

as in the other two models, in a scenario with higher fossil energy consumption, e.g. CO_2 emissions that are 30–40 % higher from 2050 to 2100. This requires a lower emission intensity to achieve a similar pollutant emissions outcome.

2.2 Emissions by sector

Figure 2 provides sectoral emission intensity trends, while the ESM provides comprehensive graphs for emissions and energy consumption by sector. The discussion below focuses on BC and SO_2. OC emissions at the sectoral level generally follow the trends for BC, and are briefly discussed in the supplement.

Transportation Transportation BC emissions and liquid fuel consumption are shown in Fig. 3. This sector is a substantial source of BC emissions through at least mid-century in all the models. By the end of the century transportation BC emissions in GCAM are only slightly lower than current estimates, while in MESSAGE these emissions have dropped substantially, and in IMAGE emissions are nearly zero by 2100. These differences are broadly reflected at the regional level as well (ESM §13). The end of century decrease in the IMAGE model is due to the widespread adoption of hydrogen-fueled vehicles. In GCAM, the global-average BC emission intensity falls by 60 % over the century (Fig. 2), which results in a modest reduction in total emissions from this sector given consumption increases. Transportation liquid fuel consumption in the MESSAGE model in 2100 is nearly twice that in the GCAM reference scenario (Fig. 3), however a much larger assumed decrease in emissions factors results in lower overall emissions. The MESSAGE scenario includes an increasing use of methanol in place of petroleum fuels, which is an inherently low sulfur fuel that would be compatible with the advanced particulate controls assumed in this scenario. These differences illustrate that assumptions about both technologies and the extent to which emission controls are implemented in the future can have a substantial impact on emission trajectories. See Riahi et al. (2012) and Chuwah et al. (2013) who examine how varying these assumptions impact future emission levels.

Buildings BC from this sector is primarily from residential buildings, and is initially higher in GCAM but then declines steadily after 2020. BC emissions in MESSAGE decline until mid-century mainly due to assumptions for fuel-shifting, but are then relatively constant to 2100 due largely to sustained use of traditional biomass in this scenario. The higher population and somewhat lower income levels in the MESSAGE scenario imply a larger rural population that continues to use traditional biofuels. Building BC emissions from IMAGE are lower in the base-year, and decline steadily over the century. Emissions from the buildings sector are driven more by assumptions about the penetration of modern energy forms, e.g., "energy access", than explicit pollution controls. Emissions, therefore, are closely linked to assumptions about the use of coal and traditional biomass fuels in residential buildings (ESM §8,9), which also impact sectoral emissions intensity. Regionally, these assumptions have the most impact in Africa and India (ESM §13).

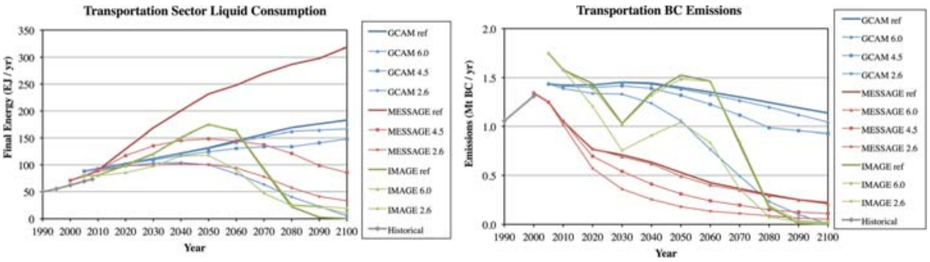

Fig. 3 Global liquid fuel use (*left*) and BC emissions (*right*) from the transportation sector

Industry The trajectory of industrial BC emissions is similar in all three models, flat or increasing initially, and then declining through the end of the century. Industrial BC emissions are largely from smaller, less efficient, industrial activities and would be impacted by both fuel substitution over time and emission factor assumptions. The global average emission intensity in this sector decreases substantially in all three models (Fig. 2). The assumed changes in emission factors in these models represent both general modernization of industries and implementation of explicit emission controls.

Energy transformation The energy transformation sector is currently dominated by electric power production. BC emissions from this sector are relatively low, at least for well-run modern power plants, while this sector is the dominant source of SO_2 emissions. Reference case total SO_2 emissions show substantial divergence, with the IMAGE reference scenario showing relatively constant global emissions after 2030 while emissions in the GCAM and MESSAGE scenarios gradually declining to 40 (GCAM) and 20 (MESSAGE) $TgSO_2$ by the end of the century.

These differences stem from assumptions for emission controls and technology choices. In the MESSAGE model, SO_2 emission trends in the near-term (to 2030) are derived from currently planned and legislated pollution limits (see SI) while in the long-term SO_2 emissions fall due to technology substitution processes, such as the installation of IGCC plants with inherently low pollutant emissions, which reaches 60 % of total fossil electric generation by 2050 and further increases to more than 80 % by the end of the century. IGCC penetration in the GCAM reference scenario reaches 50 % of coal-fired generation in 2050 and remains near that level throughout the century. Conventional coal plants in GCAM are assumed to be increasingly equipped with scrubbers over time as incomes increase.

The relatively high SO_2 emissions in the IMAGE scenario result from a rapid increase in the use of fossil fuels (in particular coal) that is only partially offset by a decline in emission factors (Fig. 2). It is possible that in some areas with high emissions (SE Asia, India, Africa; ESM §13), given the high population densities, surface air pollution levels would exceed recommended health guidelines (Smith et al. 2011, Rao et al. 2013). Long-term SO_2 emissions are lower in later versions of the IMAGE model. In all three models SO_2 emissions in 2100 are dominated by energy transformation and industrial sectors. Both emission control assumptions and technology assumptions, such as those for IGCC, can have a substantial impact on future emissions.

Land-use emissions of SO_2, BC, OC originate from natural and human-caused forest and grassland wildfires along with burning associated with deforestation. Reference case emissions from all three models are lower by 2100 than 2005 due to a reduction in deforestation and generally lower amounts of unmanaged land subject to wildfires. Emissions decline the most in IMAGE, with the decline largely complete by 2050 as a result of the land-use trends, while carbonaceous aerosol emissions in GCAM increase to 2050 due to increased deforestation before declining. Emissions in MESSAGE show a steady decline over the century reflecting a declining deforestation trend in combination with policies for fire prevention in the developing world in the long term. These different patterns reflect a diversity of underlying land-use trends and policies in the models.

These comparisons illustrate that future pollutant emissions pathways are a function of both assumptions about the evolution of pollutant emission controls and the evolution of technologies and energy systems. Ultimately, however, pollutant emission levels will be determined by preferences of future societies in terms of air pollutant concentrations, and the resources devoted to meeting these preferences.

3 Climate policy response

3.1 Overall response

The reference case is the background upon which climate policies are applied. In each model a comprehensive climate policy is implemented in which a carbon price, or equivalent policy, is implemented throughout the global energy system in order to meet the specified radiative forcing target.

Meeting a climate forcing goal will require some combination of increased energy efficiency, decreased fossil-fuel consumption, increased use of carbon capture and storage, and land-use strategies. All of these options will tend to decrease emissions of aerosols and precursor compounds, although emission increases are occasionally seen as well. In aggregate aerosol emissions decrease, with reductions increasing with more stringent climate policies.

The response by emission and sector are discussed in more detail below. The emission responses to a carbon policy can generally be traced directly to changes in fuel consumption. Graphs of both emissions and fuel consumption are, therefore, provided in ESM §8, §9. A discussion of the response of land-use and international shipping emissions is provided in ESM §10.

The impact of a climate policy on aerosol emissions is summarized in Fig. 4, which shows the SO_2 and BC emissions reduction relative to the reference case as a function of CO_2 reduction. The relative aggregate response of SO_2 emissions to a climate policy is similar in all three models. This is due largely to coal combustion being a common source of both SO_2 and CO_2, and a similar relative response to a climate policy in the electric generation sector.

The BC emissions reduction in response to a carbon policy is smaller and more variable between the models. At moderate climate policy levels, with CO_2 emissions reduced by up to about 50 %, BC emissions are generally only reduced by 10–20 %. The models differ more substantially on the response to a very ambitious carbon policy, whereby emissions of carbon dioxide are net negative by the end of the century. BC reductions in the 2.6 scenario, relative to reference, range from no more than 20 % for MESSAGE, up to 40 % for IMAGE, and up to 80 % for GCAM, which are examined in more detail below.

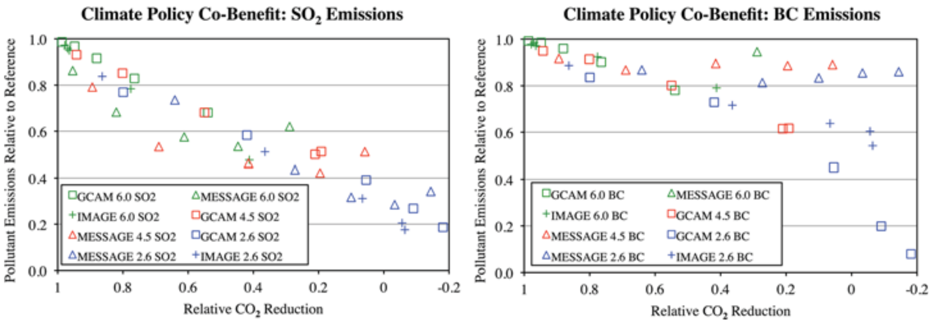

Fig. 4 Global SO_2 (*left*) and BC (*right*) climate policy co-benefit, shown as the aerosol emission level, relative to the reference scenario, as a function of CO_2 emissions reduction (also relative to the reference scenario). Note that net negative carbon dioxide emissions (negative reduction on the x-axis) are a feature of the most ambitious climate policy scenarios

3.2 Response by sector

Transportation All three models show a substantial reduction in BC emissions from the transportation sector. Liquid fuel consumption decreases relative to reference under a climate policy in all three models (Fig. 3), which decreases emissions. Transportation services shift to modern fuels: electricity in GCAM, hydrogen in IMAGE, and electricity, biomass-based liquids and hydrogen in MESSAGE. The level of the response in terms of fuel consumption also varies by climate policy target and the resulting carbon price. While GCAM has a relatively modest decrease in liquid fuel consumption in the 4.5 W/m^2 scenario, liquid fuel consumption for transport in MESSAGE is less than 1/3 of the reference case value in this scenario (due, in part, to the larger carbon price in MESSAGE, see ESM). Both GCAM and MESSAGE show large decreases in liquid fuel consumption and emissions in a 2.6 W/m^2 scenario by the end of the century. BC emissions in the IMAGE scenario are already small by the end of the century in the reference case due to the use of hydrogen in the transportation sector, with any climate response shifted upstream to the transformation sector.

A portion of these differences are due to baseline emission control assumptions. The much stronger transportation BC emission controls, coupled with substantial use of synthetic fuels, in the MESSAGE baseline scenario and resulting low emission levels, mean that, in absolute terms, there is less room for emissions to further decrease as liquid fuel consumption decreases under a climate policy. The larger reference case emissions in GCAM result in a potential for a larger relative reduction in the climate policy case.

Energy transformation The energy transformation sector is a relatively small source of BC emissions, and the response for BC and OC varies between the models. SO_2 emissions fall in all models as coal-fired electricity production either decreases or shifts to CCS technologies, which are assumed in all these models not to emit appreciable amounts of SO_2. Biomass energy with CCS (BECS) is included in all models. Similar to fossil power plants with CCS, BECS plants do not emit appreciable SO_2 or BC.

Industry IMAGE and GCAM have similar relative reductions in BC emissions, with the absolute reduction in GCAM larger due to larger initial emissions. There is only a very small response in the industrial sector BC emissions to climate policy in the MESSAGE model, due to the limited scope for reductions in this sector, the continued use of liquid fuels, and a requirement for some level of carbonaceous fuels.

The industrial sector is the second largest source of SO_2 at present, and emissions under a climate policy generally decrease in this sector, although the three models show different patterns. In absolute terms, the reduction in industrial SO_2 emissions is similar in IMAGE and GCAM, although overall emissions are lower in GCAM.

These differences in response in the industrial sector are due, in part, to different representations of industrial fuel demand in these models. Coal and liquid fuel consumption in the industrial sector shows a large response in GCAM and MESSAGE, with a much smaller response in IMAGE. Biomass consumption in the most stringent climate policy scenario increases in the near-term in GCAM and MESSAGE, but ultimately decreases to low levels by 2100 in both models, with a much smaller relative change in the IMAGE model.

Buildings The BC emissions response in the building sector is relatively small in IMAGE and MESSAGE, with a much more substantial response in the GCAM model. In all models a climate policy reduces coal and liquid fuel consumption, with this having a larger impact in GCAM due to higher reference scenario consumption. Most BC emissions, however, are associated with traditional bio-energy use. Traditional biomass consumption in the buildings sector is only mildly impacted by a climate policy in all of the models. Traditional biomass consumption increases slightly in IMAGE and GCAM under a climate policy as the cost of other fuels increases.

4 Discussion and conclusions

In this paper we document the state of three long-term integrated assessment models at the time the RCP scenarios were produced (Taylor et al. 2012, Van Vuuren et al. 2011b). Scenarios from all three models show two broad trends. As noted previously (Rose et al. 2014), aerosol emissions decline over the twenty-first century in the reference (no climate policy) scenarios as a result of combination of trends in energy technologies and air pollution policies. Emission intensity, measured relative to carbon dioxide emissions, decreases substantially in all three models, but the assumed rate of decrease varies by substance, sector, and model. These differences stem from different assumptions for pollution controls, technology characteristics, and model behavior at the sectoral level. Widespread adoption of inherently low emitting technologies, such as integrated gas combined cycle (IGCC) coal combustion or hydrogen fuel cell vehicles will result in low emissions, which can be an important factor motivating the adoption of such technologies.

Black carbon emissions are determined largely by assumptions in the transportation and buildings sectors. The higher black carbon emissions in the GCAM scenario are largely due to the assumption of less stringent emission controls for BC in the transportation sector. While there is significant uncertainty in the ability of many world regions to enforce emission controls. GCAM transportation emissions, for example, do not fall as rapidly as in recent more detailed projections (Yan et al. 2014), indicating that these projections might be too high. The somewhat modest decrease in BC emissions from MESSAGE in the last portion of the century is due to an assumption of continued reliance on traditional biofuels in developing countries in this scenario (See ESM).

SO_2 generally dominates the anthropogenic particulate fraction and is also the source of the largest aerosol climate forcing, the assumptions for sulfur dioxide emission controls in the electric power sector, and to a lesser extent in industry, are particularly important. The higher sulfur dioxide emissions in the IMAGE model, for example, are largely the result of an assumption of less stringent emission controls for energy transformation (Fig. 2).

A second common trend is a further reduction in emissions, relative to each model's reference case, under climate policy scenarios (Fig. 4). Reductions in sulfur dioxide and carbon dioxide are strongly coupled in all three models because coal combustion is a primary source of both SO_2 and CO_2. While reducing greenhouse gases also results in black carbon reductions, in general the reductions are smaller and there is a larger variation between the models in the response of BC emissions.

A number of trends in terms of aerosol reductions in response to a climate policy emerged at the sectoral level:

- In all three models, aerosol emissions from the *energy transformation* sector fall to low levels under a climate policy as energy transformation shifts to either renewable sources or technologies that use carbon capture and geologic storage (CCS), both of which have inherently low aerosol emission levels. This transition occurs relatively early, with energy sector emissions, particularly for SO_2, relatively low by mid-century under moderate (4.5 W/m^2) to strong (2.6 W/m^2) climate policies.

- For the *surface transportation* sector, projections vary between models due to different reference case assumptions. Under a stringent 2.6 W/m^2 scenario, however, the models agree that aerosol emissions become relatively small by the end of the century as liquid fuels are replaced by other options. Emissions by mid-century vary more substantially, even under a climate policy, with emission levels depending largely on reference-case emission control and fuel demand assumptions.
- There is considerable diversity in the climate policy response in the *industry* sector, driven in part by representations of this sector that are fairly aggregate (e.g., explicit technologies are often not represented), requiring styled assumptions to capture the relevant dynamics. Fossil-fuel use in the industrial sector comprises a wide range of uses, including process heat, internal combustion engines, and process-specific uses such as steel-making over a range of scales, from small plants and boilers to large manufacturing centers. In some models, off-road diesel consumption is also included in this sector. Historically, regulations on pollutant emissions can vary by industry, with inertia playing an important role. Fossil fuels can be difficult to replace in some industrial activities, such as those that need high temperature process heat. Some processes have quite specific requirements, such as steel making which requires a carbon-based input such as coal coke, which also differs in its pollutant emissions as compared to coal.
- *Building sector* emissions also show a range of responses. In all scenarios, aerosol emissions are lower by 2050 than in 2005, but the level varies substantially by model, even in the reference case. The response to policy also varies, with BC emissions changing little under a climate policy in two models, and reducing substantially in one model. Reference case assumptions can have a large impact in this sector. The MESSAGE reference case, for example, describes a world where a relatively large fraction of rural population in developing countries is still using traditional biofuels by the end of the century. The result is higher baseline black carbon emissions, from a sub-sector (traditional biofuels) that is also minimally responsive to climate policy.

In summary, the response of future aerosol emissions to the imposition of a comprehensive climate policy depends on both reference case scenario details and model structure (which is indicated by differences in sectoral climate policy response and carbon prices). A specific examination of the importance of model structure is given in the appendix, where comparable results are examined for a more recent version of the GCAM model that contains more end-use detail. Greater end-use detail results in a smaller aerosol emissions response to climate policy in this case (ESM §6).

Note that the analysis in this paper has focused on idealized model results. In all these scenarios, aerosol emissions factors and emission controls were assumed to be the same, at the level of individual technologies, in the climate policy scenarios as in the reference case. This simplifies the analysis but also implicitly assumes that additional reductions due to a climate policy would not result in relaxing pollutant emission controls elsewhere. In a pollutant cap and trade system, for example, at least some of the reductions in air pollutants resulting from a climate policy might be offset, at least in the near-term, by relaxed emission controls elsewhere. A recent health impact assessment (Rao et al. 2013), however, indicates that a combination of stringent policies on air pollution control, climate change mitigation and energy access would be important in achieving health objectives in the short-term for some regions. In the longer term (post 2050) climate policies result in large-scale technology shifts such that pollutant emissions from some sectors may become essentially zero. This trend is particularly strong in the electricity sector of all of the stringent mitigation scenarios assessed in this paper. Under strong climate policy mitigation scenarios, therefore, air pollutant control assumptions have a weaker impact in the long term.

5 Recommendations for future work

The relative sectoral contributions to future emissions are robust findings that will generally apply to all models, and points to the importance of analyzing future projections at the sectoral level. This also indicates where future model development could focus in order to better understand potential future pathways for aerosol emissions. These include how effective emissions controls will be in the transportation sector and how much traditional biofuel use might change in the future (often examined under the paradigm of energy access). Improving IAM resolution for the industrial sector, and off-road mobile emissions in particular, could also be a target for improvement.

While historical analysis should be used to improve future scenarios, there are data limitations. Assumptions for the use of traditional biomass, for example, have a large impact on black carbon emissions, however improvements here are particularly challenging since data on historical trends for these fuels are still quite uncertain (ESM §4). Historical emissions are also uncertain, particularly BC (Bond et al. 2007), and this uncertainty will also map directly to uncertainty in future projections.

Scenario development in these models has tended to focus on trends air pollution control policies and associated emissions, with pollutant control assumptions are informed by results from more detailed models (Amann et al. 2011, Chuwah et al. 2013). Instead of emissions, however, the ultimate policy objective is limiting impacts such as surface particulate concentrations and acidification. Research to incorporate more of the real-world tradeoffs, for example between pollution control costs and human exposure outcomes, while challenging, are needed. Improved application of methods that allow a connection between emissions and surface concentrations are need to improve the consistency of future scenarios (Smith et al. 2011, Rao et al. 2012, Chuwah et al. 2013). Additional challenges to modeling future air pollution policies include burgeoning megacities across the developing world and the increasing importance of long-distance pollutant transport, which makes achieving regional air pollution goals increasingly tied to actions elsewhere.

Finally, the impact of a climate policy on aerosol emissions depends on the sectoral level technology and service shifts. A better understanding of the reasons why models differ in this respect would be helpful. The industrial sector stands out in this analysis for such differences, and further examination of the potential response of the industrial sector to climate policies, particularly under stringent climate policies, seems warranted.

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Environmental Modeling and Methods for Estimation of the Global Health Impacts of Air Pollution

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Abstract Air pollution is increasingly recognized as a significant contributor to global health outcomes. A methodological framework for evaluating the global health-related outcomes of outdoor and indoor (household) air pollution is presented and validated for the year 2005. Ambient concentrations of PM2.5 are estimated with a combination of energy and atmospheric models, with detailed representation of urban and rural spatial exposures. Populations dependent on solid fuels are established with household survey data. Health impacts for outdoor and household air pollution are independently calculated using the fractions of disease that can be attributed to ambient air pollution exposure and solid fuel use. Estimated ambient pollution concentrations indicate that more than 80% of the population exceeds the WHO Air Quality Guidelines in 2005. In addition, 3.26 billion people were found to use solid fuel for cooking in three regions of Sub Saharan Africa, South Asia and Pacific Asia in 2005. Outdoor air pollution results in 2.7 million deaths or 23 million disability adjusted life years (DALYs) while household air pollution from solid fuel use and related indoor smoke results in 2.1 million deaths or 41.6 million DALYs. The higher morbidity from household air pollution can be attributed to children below the age of 5 in Sub Saharan Africa and South Asia. The burden of disease from air pollution is found to be significant, thus indicating the importance of policy interventions.

Keywords Air pollution · Atmospheric PM2.5 · Health impact methodology · Solid fuels · Household health

1 Introduction

The relation between ambient air pollution and health has been well discussed (see [1] for a detailed literature survey of the health impacts of outdoor air pollution) and a number of epidemiological studies (including, for example, [2–4]) have reported significant effects of exposure to fine particles (particulate matter with aerodynamic diameter smaller than 2.5 μm) on long-term mortality due to cardiopulmonary disease and lung cancer in adults, while controlling for smoking, diet, occupation and other factors. There is also evidence of significant mortality and morbidity losses associated with household air pollution caused by the inefficient combustion of solid fuels [5].

This has led to increasing recognition of the need for policies that can sufficiently control for the health impacts from air pollution. An integrated air quality policy approach

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will require adequate knowledge base and analytical tools that combine information on expected trends in anthropogenic activities that relate to air pollution and information on atmospheric dispersion of emissions including representation of urban areas (see [6] for discussion). Limited measurement data for air pollution and the absence of dispersed and advanced air pollution sensors makes it difficult to obtain accurate measurements of air pollutants in general. Recent advances in satellite measurements are helping to improve the availability of information on air pollutants, in particular fine particulate matter (see, for example, [7]). In addition, atmospheric models are increasingly being deployed to understand the spatial distribution of air pollutants (see [8]) and additionally compute health impacts (see [9]). Finally, integrated assessment models have also recently been updated to include more information on air pollutants to examine in particular the implications for a range of radiative forcing implications [10].

Growing concern for the serious health and environmental impacts of enduring dependence on dirty cooking fuels is also driving efforts to better understand household fuel choices, to set new targets for access to modern fuels, and design policies that facilitate a swifter transition to cleaner fuels and stoves [11, 12, 13, 14]. Undertaking consistent measurements of pollution concentrations and direct exposure levels within households at a global scale requires a much larger effort and has still not been attempted. In the absence of consistent household exposure datasets, information on populations dependent on biomass and other solid fuels is being used as a proxy for exposure. Recently, there have been more regular efforts to provide globally comprehensive estimates of the numbers of populations dependent on solid fuels [15, 14, 16].

Based on these recent developments, this paper describes a methodological basis that can be applied to specifically evaluate the atmospheric implications and health impacts of energy policies. Based on state-of-the-art modeling tools and an assessment of methodologies, it provides a template for quantifying the global health impacts of ambient and household air pollution. The results are validated for 2005. The health impact assessment approach used is similar to recent studies like [9] but updates include the link to an energy model for detailed sector based estimation of emissions and an accounting of urban and rural exposures at a spatial level.

2 Methodology

The Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE; [17–19]) is used for representing the underlying global energy system (see Fig. 1 for regional definitions in MESSAGE) and resulting greenhouse gas (GHG) and air pollutant emissions. In addition to the energy system, the model covers all GHG-emitting sectors, including agriculture, forestry, energy, and industrial sources for a full basket of greenhouse gases and other radiatively active gases (see [19–21]).

A similar set-up was used as in [20] in terms of representation of air pollutants and emissions for 2005 including open burning are consistent with [22]. Global spatially explicit emissions at a sector level (at a 1°×1° resolution) for 2005 were derived based on data described in [23].

In order to estimate the impacts of the spatially explicit emissions, atmospheric concentrations of PM, and aerosols were derived using the TM5 model. The TM5 model is an

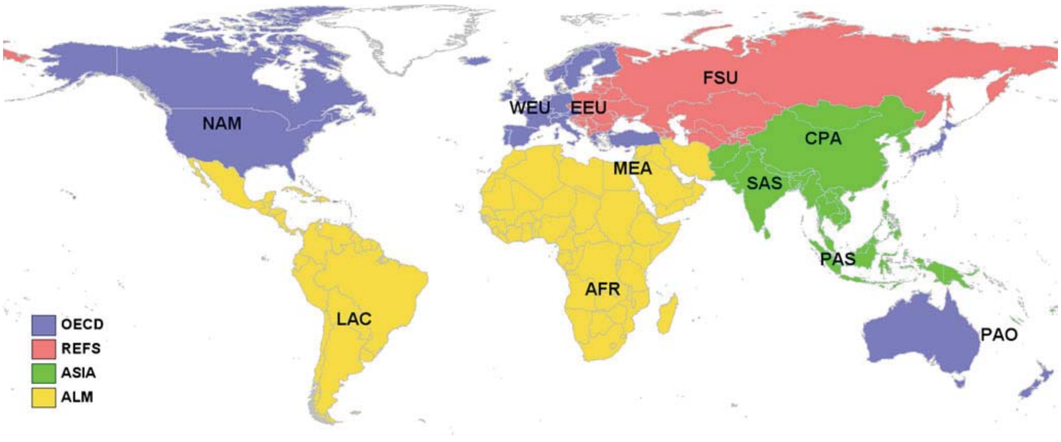


Fig. 1 Illustration of world regions in MESSAGE

off-line global transport chemistry model [24] that uses meteorological fields, including large-scale and convective precipitation and cloud data, from the European Centre for Medium Range Weather Forecast. For this work, a similar set-up in terms of model resolution has been selected as used [25]. The model has been used in a number of recent inter model comparisons [24, 26–29]. For PM2.5, TM5 includes contributions from (a) primary PM2.5 released from anthropogenic sources, (b) secondary inorganic aerosols formed from anthropogenic emissions of SO_2, NO_x, and NH_3 (including water vapor), (c) particulate matter from natural sources (soil dust, sea salt, biogenic sources). The spatial resolution of 1°× 1° used is state-of-the art for capturing the global features of long-range transported pollutants for the current mega regional scale analysis at which we calculate health impacts. However, given that ambient concentrations of some air pollutants may show strong variability at a much finer scales (e.g., in urban areas, at hot spots close to industrial point sources of emission, etc.), and could thus result in variable impacts on populations, we also separately estimate for all regions, an urban increment at the grid cell according to population density and the area over which they are emitted. The urban and rural population fractions are estimated by setting a threshold on the population density in high-resolution sub-grids (see Appendix I for details).

Household solid fuel dependence was independently estimated for the five MESSAGE regions of Sub Saharan Africa (AFR), Pacific Asia (PAS), South Asia (SAS), Centrally Planned Asia (CPA) and Latin America (LAM) in 2005 using nationally representative health and socio-economic surveys from key countries [30, 31, 32] and comparing these with other existing estimates of solid fuel dependence from [16] and the [33].

Health impacts from outdoor and household air pollution based on mortality and disability adjusted life years (DALYs) were further estimated using available World Health Organization (WHO) Comparative Risk Assessment methodologies [34] as described below:

Outdoor air pollution (OAP) The population-attributable fraction (PAF) approach based on the gradient of risk between the theoretical minimum level of air pollution exposure and the estimated observed exposure as detailed in [34] is used. This involved the estimation of attributable fractions (see Appendix II for details) which were further combined with population weighted average PM2.5 concentrations for the MESSAGE regions (2005 population estimates are based on [35]). Health impacts are estimated based on total PM2.5 concentrations. We do not estimate the health-related impacts of ozone, although recent evidence suggests that this could be significant (see, for example, [36]). We use cause-specific risk rates globally for selected risk categories based on [37] and as applied in [38] as regionally specific RRs are not available. We limit the analysis to adults over 30 years of age as detailed in Table 1 and use a concentration threshold range of 7.5–50 μg/m^3 based on [38] and later discussed in [39]. However, as discussed in many studies (including [38, 39]), whether or not there is a threshold makes a large difference to the estimate of attributed deaths, and the linearity or otherwise of the dose-response association is important and will have a significant impact on the results. There have been some recent studies suggesting a nonlinear relationship between estimated inhaled doses of PM2.5 (at higher levels) from ambient air pollution exposure. To-date, however, systematic non linear concentration response functions have not been published (see [40] for discussion on the implications of non-linearity and existing gaps).

Household air pollution (HAP) Health impacts attributable to solid fuel use in homes are estimated using methodology described in [41] and is described in detail in Appendix II. We use household dependence on solid fuels (biomass and coal) as a proxy for actual exposure to household air pollution. We are cognizant of the fact that this method neglects the large variability of exposures within households using solid fuels (e.g., due to differences in ventilation levels, etc.). However, the lack of comparable national or regional quantitative data on exposures within households, made the use of this method necessary. Estimates of relative risks for household air pollution as obtained from [41] and [42] and summarized in Table 2 were used to estimate the burden of those diseases with strong epidemiological evidence for an enhanced risk due to solid fuel use. While there is some evidence of increased incidence of cataracts and other eye diseases and perinatal effects as a consequence of exposure

Table 1 Relative risk rates for outdoor air pollution

Health outcome	GBD Category, WHO 2009	Group (sex, age in years)	Relative risk (per 10 μg/m^3)	Confidence Interval (CI)
Cardiopulmonary (infectious and chronic respiratory diseases and selected cardiovascular outcomes for adults)	39, 40, 106–109, 111	Men and women ≥30	1.059	1.015–1.105
Lung cancer	333	Men and women ≥30	1.082	1.011–1.158

Table 2 Relative risks for household air pollution

Health outcome	GBD category, WHO 2009	Group (sex, age in years)	Mean relative risk	Confidence interval (CI)
ALRI	39	Children <5	2.3	1.9–2.7
COPD	112	Women ≥30	3.2	2.3–4.8
Lung cancer (from exposure to coal smoke)	333	Women ≥30	1.9	1.1–3.5
Ischemic Heart Disease (IHD)	107	Women ≥30	1.2	n.a
COPD	112	Men ≥30	1.8	1.0–3.2
Lung cancer (from exposure to coal smoke)	333	Men ≥30	1.5	1.0–2.5

to smoke from solid fuel combustion, we do not include these in our analysis. In addition to adult-related diseases, we include here acute lower respiratory infections (ALRI) in children for which household air pollution from solid fuel use is a significant risk factor.

As seen in Tables 1, 2, considerable overlap exists between the underlying disease categories and populations at risk for outdoor and indoor air pollution. As discussed in [38], human exposure to air pollution occurs both indoors and outdoors and an individual's exposure to ambient urban air pollution depends on the relative amounts of time spent indoors and outdoors, the proximity to sources of ambient air pollution, and on the indoor concentration of outdoor pollutants. We cannot estimate the exact extent of the overlap in terms of the resulting impacts, but expect that in some developing nations it could be significant. This implies that the outdoor air pollution health impacts and household health impact estimates are not additive. We do not correct for this. There is also recent literature which suggests that the a more detailed component-wise estimation of PM2.5 could potentially have implications for the magnitude of health impacts (see, for example, [43, 44]) but we do not examine this issue in detail here.

We use baseline data from [45] on mortality and DALYs. This data is available at (http://www.who.int/healthinfo/global_burden_disease/projections/en/index.html) and was sampled to the MESSAGE regions based on underlying population shares of the countries. We base our estimates for 2005 on the 2004 and 2008 data which is available.

3 Results

Estimates of global emissions of SO_2, NO_x and PM2.5 are shown in Fig. 2. The power, industry, and transportation sectors are major emission sources globally. In addition, the residential sector is a large contributor to energy related PM emissions, especially in Asia and Africa due to the use of biomass and coal in cooking. In some regions like Africa and Latin America, non-energy sources, in particular open biomass burning are a dominant source of PM emissions.

Table 3 presents the resulting population weighted average annual PM2.5 concentration for the year 2005 aggregated from the gridded values to MESSAGE regions. The calculations were performed with a near-final version of the emissions. In order to ensure that these concentrations are completely consistent with emissions corresponding to the RCP inventories, some amount of rescaling was necessary. Appendix III shows the differences in PM2.5 concentrations

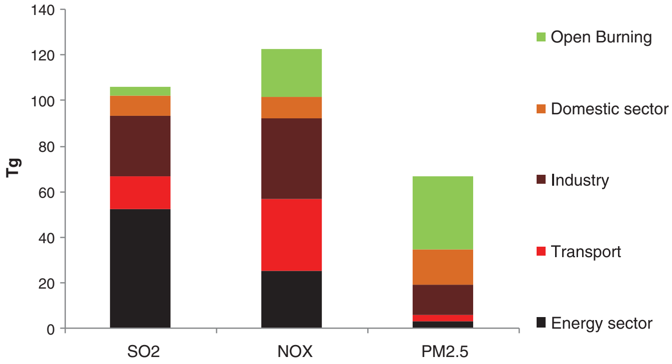


Fig. 2 Global emissions of SO_2 (T_g SO_2), NO_x (T_g NO_x) and PM2.5 (Tg PM2.5). Open burning includes agricultural waste burning, savannah and deforestation related emissions

Table 3 Regional average population weighted mean PM2.5 concentrations (including dust, sea salt and secondary organic aerosols, SOA), 2005, in micrograms per cubic meter

Region	Total	Comparison with other available studies
World	31.4	27 [7]
Europe (includes WEU, EEU and FSU)	21.8	16–17 [46]; 15–17 [7]
North America (NAM)	15.6	11–13 [7]; 13.8 (estimate for Eastern US; [47])
Pacific OECD (PAO)	21.2	
Centrally Planned Asia (CPA)	60.9	
South Asia (SAS)	31.5	
Pacific Asia (PAS)	19.5	
Latin America (LAM)	9.9	7 (estimate for South America, [7])
Sub Saharan Africa (AFR)	15.6	
Middle East and North Africa (MEA)	18.4	26 (estimate for North Africa [7])

Table 4 Fractions of population dependent on solid fuels, 2005, %

Region	Rural		Urban	
	Coal	Biomass	Coal	Biomass
SAS	0.5	97.8	4.5	53
PAS	0	82.4	0	31
AFR	0	97.5	0	88
CPA	30	50	28	10
LAM	2	60	1	6

before and after the scaling. Global PM2.5 concentration was estimated at 31.4 μg/m^3. Our estimates are quite comparable to a recent study by [7] who determined global estimates of population weighted PM2.5 concentrations of 20–27 μg/m^3 using a combination of total column aerosol optical depths from satellite instruments and models.

We compare the resulting PM2.5 concentrations with WHO Air Quality Guidelines (AQGs) and the three interim targets (IT 1–3) set for long-term exposure to PM2.5 [48]. As seen in Fig. 3 more than 80% of the world's population is estimated to exceed the WHO AQG for PM2.5 of 10 μg/m^3 while more than 30% also exceed the WHO Interim Target-1 of 35 μg/m^3.

We estimate the populations dependent on solid fuels in 2005 based on national level household survey data in three regions—around 3.26 billion, specifically in Sub Saharan Africa, South Asia, and Pacific Asia. Our estimates of populations dependent on solid fuels are slightly higher for all regions than other recent estimates including for example [16, 33]. This is mainly because of the inclusion of multiple fuels as our estimates are based on national level household survey data assuming all households that report some positive consumption of any of the solid fuels (unprocessed biomass, charcoal and coal) as dependent on solid fuels, even if they use these only as secondary or tertiary sources of cooking energy or are using these for other thermal purposes such as heating. Table 4 presents our estimates of the share of population using solid fuels in rural and urban areas.

We estimate that outdoor air pollution results in 2.7 million annual deaths or 23 million annual (DALYs) worldwide in 2005 as seen in Table 5 (also indicated are the ranges based on uncertainties in RRs). This represents around 5% of all deaths, 2% of all DALYs and around 12% of the total burden that can be attributed to cardiovascular, respiratory and lung cancer related causes. More than 70% of this burden is felt in Asia (CPA+SAS+PAS) alone. These results can be compared to other recent studies, including [9] who estimate 2.4–3.7 million deaths globally from exposure to PM2.5. Reasons for the higher estimates from our analysis as compared to for instance that estimated by previous GBD studies (see, for example, [34]

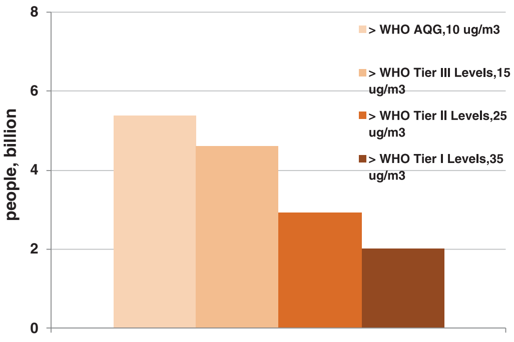


Fig. 3 Global population exposed to ambient concentrations of PM2.5 exceeding long-term WHO AQG and three IT Levels in 2005

Table 5 Annual mortality and DALYs from outdoor air pollution, 2005 (in parenthesis are the ranges of impacts from low and high confidence intervals of risk rates)

	Total population, million>30 years	Annual mortality (millions)	Annual DALYs (millions)
OECD	616	0.37 (0.07–0.58)	2.4 (0.44–3.68)
REFS	238	0.26 (0.07–0.42)	1.97 (0.52–3.18)
CPA	782	1.05 (0.29–1.57)	7.98 (2.2–11.8)
SAS	585	0.69 (0.19–1.09)	6.93 (1.94–10.91)
PAS	230	0.12 (0.03–0.19)	1.12 (0.29–1.84)
LAM	244	0.04 (0.01–0.07)	0.38 (0.1–0.64)
AFR	208	0.14 (0.04–0.23)	1.56 (0.42–1.58)
MEA	142	0.05 (0.01–0.08)	0.48 (0.13–0.18)
World	3,061	2.7 (0.72–4.23)	22.83 (6–35.5)

Table 6 a Health impacts of household air pollution (HAP) based on mean RRs, mortality, Millions (in parenthesis are the ranges of impacts from the low and high confidence intervals of risk rates). b Health impacts of household air pollution based on mean RRs, DALYs, millions (in parenthesis are the ranges of impacts from low and high confidence intervals)

Disease, sex and age	SAS	PAS	AFR	CPA	LAM
a Annual HAP-related mortality (million)					
ALRI, children <5	0.22 (0.18–0.25)	0.05 (0.04–0.06)	0.50 (0.42–0.56)	0.03 (0.02–0.03)	0.01 (0.00–0.01)
COPD, women >30	0.19 (0.16–0.23)	0.1 (0.08–0.12)	0.03 (0.02–0.03)	0.26 (0.18–0.34)	0.02 (0.01–0.03)
Lung cancer, women >30	0	0	0	0.02	0
COPD, men >30	0.16 (0.00–0.25)	0.06 (0.00–0.11)	0.03 (0.00–0.05)	0.12 (0.00–0.25)	0.01 (0.00–0.02)
Lung cancer, men >30	0	0	0	0.03	0
Ischemic heart disease, women >30	0.11	0.03	0.02	0.02	0.01
Ischemic heart disease, men >30	0.08	0.02	0.02	0.01	0.01
b Annual HAP-related DALYs (million)					
ALRI, children <5	7.94 (6.56–8.92)	1.83 (1.46–2.12)	17.58 (14.65–19.65)	0.98 (0.79–1.13)	0.28 (0.21–0.35)
COPD, women >30	2.23 (1.80–2.62)	0.90 (0.69–1.10)	0.27 (0.22–0.31)	1.6 (1.14–2.10)	0.27 (0.18–0.38)
Lung cancer, women >30	0.005	0.00	0.00	0.22	0.005
COPD, men >30	1.76 (0.00–2.83)	0.67 (0.00–1.19)	0.37 (0.00–0.58)	1.19 (0.00–2.37)	0.14 (0.00–0.30)
Lung cancer, men >30	0.007	0	0	0.3	0.004
Ischemic heart disease, women >30	1.05	0.26	0.21	0.16	0.06
Ischemic heart disease, men >30	0.82	0.2	0.17	0.11	0.05

and [38]).include the representation of both urban and rural exposures (thus including effects of industrial sources and other hot spots typically located outside urban areas) and the increase in global population since previous estimations. However, it is important to stress that health impact estimations from ambient air pollution exposures are subject to a number of uncertainties. The upcoming Global burden of Disease report [49] is expected to review a number of the underlying uncertainties based on latest epidemiological evidence.

Our estimates in Table 6 indicate that more than 2.1 annual million deaths or alternatively the loss of 41.6 annual million DALYs could be attributed to solid fuel use and related indoor smoke in 2005. In terms of shares, these results correspond to 23% of deaths and 35% of DALYs from combined causes (ALRI, COPD, lung cancer, and IHD). The HAP DALY estimates are higher than those from OAP due to the very high incidence of the morbidity burden among children less than 5 years of age which accounts for more than 68% of the total, with the largest fraction of these occurring in Sub Saharan Africa. HAP related premature child deaths are seen to exceed those due to HIV/AIDS and malaria [45].

We can compare these estimates to that of [50] who estimate globally 1.6 million deaths and 38.5 million DALYs were lost in the year 2000 as a result of exposure to indoor smoke from SFU. Two main reasons for the increased impacts are the higher estimates of populations dependent on solid fuels and the inclusion of ischemic heart disease, a risk category, which has not been included in household (indoor) impact estimates to date.

4 Summary

This paper provides a framework that combines energy and atmospheric models and uses available methodologies to estimate the global health impacts from outdoor and household air pollution. Global population weighted mean average ambient PM2.5 concentration for the year 2005 was estimated at 31–35 μg/m^3. More than 80% of the world's population is seen to currently exceed the WHO AQG for PM2.5 of 10 μg/m^3 while more than 30% also exceed the WHO Interim Target-Tier 1 level of 35 μg/m^3. Ambient concentrations in developing countries, particularly in Asia, are seen to be high due to large populations and significant emissions from the industrial and transportation sectors. In addition, 3.26 billion people were estimated to use solid fuel for cooking in 2005 in Sub Saharan Africa, South Asia, and Pacific Asia, leading to high exposures to household air pollution.

We estimate health impacts of 2.7 million annual deaths and 23 million annual DALYs from outdoor air pollution in 2005. This represents around 5% of all deaths, 2% of all DALYs and around 12% of the total burden that can be attributed to cardiovascular, respiratory and lung cancer related causes. We also estimate 2.1 million annual deaths and 41.6 million annual DALYs lost due to solid fuel use and related indoor smoke in developing countries. The significantly higher morbidity impacts of HAP as compared to OAP are primarily due to large populations of children below the age of 5 who are at a large risk from indoor cooking, especially in Sub Saharan Africa and South Asia.

Our estimates are consistent with recent studies that suggest that air pollution is a more significant contributor to the global burden of disease than previously estimated. This can be explained by high ambient concentrations of combined urban and rural outdoor air pollution especially in Asia and the increases in population since previous estimates. Additionally, given regional disparities in fuel use and development, while household air pollution is the primary problem for instance in Sub Saharan Africa, regions in Asia face high levels of exposure due to both outdoor and household air pollution.

Pollution-related impacts are found to be significant when compared to other major causes of disease and death in developing countries. This indicates the need for effective air pollution-related policies that can improve health and wellbeing in such regions. This paper provides a methodological basis that can be used for assessing future policy impacts in terms of exposures and health related impacts of OAP and HAP.

Expert assessments from the upcoming Global Burden of Disease study are expected to evaluate and significantly update the most recent information on health impacts from a range of causes-including indoor and outdoor air pollution. Future analysis will need to take this into account.

Appendix I: Representing Urban/Rural Fractions of PM2.5 in TM5

TM5 model simulations were performed at a spatial resolution of 1°×1° longitude–latitude, corresponding to a nominal longitudinal resolution of ca. 111 km at 0° latitude (tropics), 79 km at 45° latitude, and 56 km at 60° latitude (latitudinal resolution is always 111 km). Ambient concentrations of some air pollutants may show strong variability at a much finer scales (e.g., in urban areas, at hot spots close to industrial point sources of emission, etc.), and could thus result in variable impacts on populations. We also separately estimate for all regions, an urban increment at the grid cell resulting from anthropogenic primary aerosol emissions, assuming that the model calculations are sufficient to cover aerosols from natural and secondary sources. The sub-grid increment parameterization attributes calculated primary aerosol concentrations according to population density and the area over which they are emitted. Population density is derived from the high (0.1°×0.1°) resolution CIESIN population dataset provided by Columbia University (http://www.ciesin.org/). The urban increment of primary aerosol concentration at the 1°×1° grid cell is calculated according to population density and the area over which they are emitted.

Assuming that the concentration of Primary PM in each 1°×1° grid cell of the model is given by

$$\mathrm{CTM5} = \frac{\mathrm{E}}{\lambda} \tag{1}$$

With E=in-cell emission intensity of BC+PPOM (primary emissions of black carbon and particulate organic matter), λ=in-cell mixing rate, including dilution.

If we distinguish rural from urban emissions, we can define the rural concentration as

$$C_{\mathrm{RUR}} = \frac{E_{\mathrm{RUR}}}{\lambda} = \frac{1 - f_{\mathrm{up}}}{1 - f_{\mathrm{ua}}} \frac{E}{\lambda} \tag{2}$$

With f_{up}=urban population fraction in the 1°×1° grid cell derived from 0.1°×0.1° population statistics, f_{ua}=urban area fraction in the grid cell.

The urban and rural population fractions are estimated by setting a threshold on the population density in high-resolution sub-grids. To conserve the grid-average concentration, after the calculation of C_{RUR}, the urban concentration must fulfill the requirement that:

$$f_{\mathrm{ua}} C_{\mathrm{URB}} + (1 - f_{\mathrm{ua}}) C_{\mathrm{RUR}} = \mathrm{CTM5} \tag{3}$$

where according to Equations 1 and 2,

$$C_{\mathrm{RUR}} = \frac{1 - f_{\mathrm{up}}}{1 - f_{\mathrm{ua}}} \mathrm{CTM5} \tag{4}$$

C_{URB} follows immediately from Eq. (3)

Equation 4 basically rescales the sub-grid concentration of primary emitted components according to population density and the area over which they are emitted.

In order to avoid very spiky artifacts associated with a small fraction of the grid occupied by a densely populated sub-area, we introduce empirical limitations to the ratio $C_{\mathrm{RUR}}/C_{\mathrm{URB}}$ and to CTM5/C_{RUR}:

1. *Primary BC and POM (C_{RUR})* should not be lower than 0.5 times the TM5 grid average. This is based on observations in Europe [51, 52]
2. Urban primary BC and POM should not exceed the rural concentration by a factor 5.

Finally, the concentration edges between urban and rural areas are smoothed numerically (linear interpolation over the 0.1°×0.1° sub-grid cells at the rural–urban border to avoid artificial gradients).

Appendix II: Methodology for Estimation of Health Impacts from Outdoor and Household Air Pollution

We estimate health impacts from ambient air pollution using the PAF approach based on the gradient of risk between the theoretical minimum level of air pollution exposure and the estimated observed exposure [34]. We apply an approach similar to that detailed in [50] which involved: (1) estimating total population exposures to PM2.5; (2) choosing appropriate exposure-response factors for PM2.5 as discussed earlier in the text; (3) determining the current rates of morbidity and mortality in the population of concern using data from [45] and (4) estimating the attributable number of deaths and diseases.

The population-attributable fraction to exposure is calculated based on [53] and is estimated as:

$$\mathrm{PAF} = \frac{P \times (\mathrm{RR} - 1)}{[P \times (\mathrm{RR} - 1) + 1]} \tag{5}$$

where P=exposure expressed in PM2.5 concentrations, and RR = relative risk for exposed versus non-exposed populations. Once the fraction of a disease that is attributed to a risk factor has been established, the attributed mortality or burden is simply the product of the total death or DALY estimates for the disease and the attributed fraction.

We estimate the effects by combining information on the exposed population and the fraction of current disease levels attributable to solid fuel use. The approach utilizes relative risk estimates for health outcomes that have been associated with exposures to household pollution due to indoor smoke from solid fuel use and uses the population dependent on solid fuels as an exposure surrogate. In contrast to the pollutant based approach, which focuses on PM2.5 concentrations from combustion, the fuel-based approach takes advantage of the large number of epidemiological investigations conducted primarily in rural areas of developed countries that treat exposure to household air pollution from SFU as a single category of exposure and appears to be the most reliable method for assessing the environmental burden of diseases from SFU in developing countries [50].

The attributable fraction to SFU, $\mathrm{AF}_{\mathrm{sfu}}$, can be estimated as:

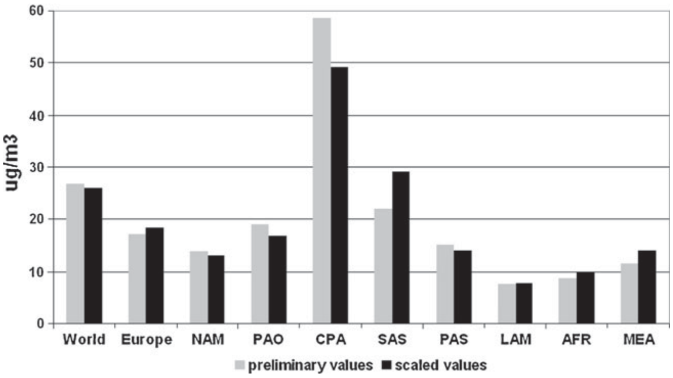
$$\mathrm{AF}_{\mathrm{sfu}} = \left[\frac{P_{\mathrm{e}}(r_{\mathrm{r}} - 1)}{P_{\mathrm{e}}(r_{\mathrm{r}} - 1) + 1}\right] \tag{6}$$

where p_{e} represents the population exposed to the solid fuels and r_{r} the relative risk due to SFU.

Similarly, attributable burden due to the solid fuel, $\mathrm{AB}_{\mathrm{sfu}}$ use can be estimated as

$$\mathrm{AB}_{\mathrm{sfu}} = \mathrm{AF}_{\mathrm{sfu}}\mathrm{CDL} = \left[\frac{P_{\mathrm{e}}(r_{\mathrm{r}} - 1)}{P_{\mathrm{e}}(r_{\mathrm{r}} - 1) + 1}\right]\mathrm{CDL} \tag{7}$$

Appendix III: Comparison of Preliminary and Scaled Values of Average PM2.5 Concentrations (Neglecting the Effects of Dust, Sea Salt and SOA, Without Urban Increment)



Rescaling involved calculating for each grid cell, the ratio of change in concentrations to changes in emissions for each component separately and scaling for the change in emissions. This assumes no regional transfer of emissions but assuming that emission changes are not at the grid level but rather at country/state/province level, the relative change in emissions within the cell is similar to the relative changes of the surrounding cells. Shown above are the comparisons of PM2.5 estimates before and after scaling. The differences were found not to impact the health impacts significantly due to the further truncation of the response above 50 $\mu g/m^3$.

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Better air for better health: Forging synergies in policies for energy access, climate change and air pollution

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ABSTRACT

Air pollution and its related health impacts are a global concern. This paper addresses how current policies on air pollution, climate change and access to clean cooking fuels can effectively reduce both outdoor and household air pollution and improve human health. A state of the art modeling framework is used that combines an integrated assessment model and an atmospheric model to estimate the spatial extent and distribution of outdoor air pollution exposures. Estimates of household energy access and use are modeled by accounting for heterogeneous household energy choices and affordability constraints for rural and urban populations spanning the entire income distribution. Results are presented for 2030 for a set of policy scenarios on air pollution, climate change and energy access and include spatially explicit emissions of air pollutants; ambient concentrations of PM2.5; and health impacts in terms of disability adjusted life years (DALYs) from both ambient and household air pollution. The results stress the importance of enforcing current worldwide air quality legislation in addressing the impacts of outdoor air pollution. A combination of stringent policies on outdoor air pollution, climate change and access to clean cooking fuels is found to be effective in achieving reductions in average ambient PM2.5 exposures to below World Health Organization recommended levels for a majority of the world's population and results in a significant decline in the global burden of disease from both outdoor and household air pollution.

1. Introduction

Adverse health effects of air pollution (both outdoor (ambient) and household related) have drawn considerable attention over recent years with increasing epidemiological evidence for cardiovascular, asthmatic and other health related outcomes (Dockery et al., 1993; Pope et al., 2002). In spite of legislated air pollution policies in many countries, recent studies estimate that 80% of the world's population continue to be exposed to ambient pollution that far exceeds the WHO recommended Air Quality Guideline (AQG) of 10 $\mu g/m^3$ for long-term PM2.5 concentration levels (particulate matter with aerodynamic diameter smaller than 2.5 μm) (Van Donkelaar et al., 2010; Rao et al., 2012; Brauer et al., 2012). In addition, while evidence of the high pollutant emissions and exposures resulting from the poor combustion efficiency of traditional biomass systems is well established as a major contributor to household (indoor) air pollution in developing countries (Smith and Haigler, 2008), recent studies also indicate potentially significant implications for ambient air quality (Zhang et al., 2000). More recent estimates indicate that outdoor and household air pollution are globally among the leading causes of mortality and morbidity related outcomes (Lim et al., 2012).

As a policy response to growing concern over air pollution, OECD countries have already implemented stringent air quality controls for ambient air quality and many large developing countries are increasingly following suit (Klimont et al., 2013). Economic growth has also led to an improvement in the quality of available fuels and technologies in developing countries (Stern, 2006; Dasgupta et al., 2001; Smith et al., 2005). However, emissions from cooking stoves continue to be a major component of global anthropogenic particulate matter (e.g., (UNEP/WMO, 2011)) in particular in developing countries, for e.g., in Africa and South Asia where emissions from cooking stoves are well over 50% of anthropogenic sources (Bond et al., 2004a, 2013). Improved access to modern energy services including cleaner-combusting and more efficient cooking fuels like LPG, biogas, natural gas and

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advanced biomass stoves for developing country households is also on the policy agenda of many countries and has received an impetus through the newly launched initiative of the Secretary-General of the United Nations toward "Sustainable Energy for All" (http://www.sustainableenergyforall.org/) and the Global Alliance for Clean Cookstoves (http://www.cleancookstoves.org/). Several measurement campaigns have evaluated the performance of improved stoves and fuels, including the evaluation of climate relevant species (e.g., (Maccarty et al., 2007, 2010)), and the potential health benefits of their introduction (e.g., (Anenberg et al., 2012)). In addition to resulting in significant health benefits, recent assessments suggest that such residential cooking fuel and stove switching, may also have a greater potential to curb global warming by reducing black carbon emissions (Bond et al., 2013; Shindell et al., 2012). Climate change and energy efficiency related policies are additionally being undertaken in many countries and these are likely to cause energy transformations that will impact air pollution and health related outcomes in the future.

A number of recent studies have focused on co-benefits of reducing short-lived aerosols and the associated reduction in climate and health related impacts (see for example (Anenberg et al., 2010; UNEP/WMO, 2011; Shindell et al., 2012). There is also a growing body of research focusing on the public health and potential climate co-benefits of improving access to modern cooking fuels and stoves in developing countries (Bond et al., 2004b; Haines, 2007; Smith and Balakrishnan, 2009). This new scientific research is resulting in increasing public attention on these issues and pressure to forge synergies in these traditionally separate policy domains. Also highlighted by current research is the limited assessment of policy impacts and potential co-benefits, lack of integration of the short-term benefits of related policies, and a growing need for integrated analysis that combines sophisticated modeling of policies, behavior of regulated entities, atmospheric transport chemistry, climate science and health effects (see (Jack and Kinney, 2010; Bell et al., 2008) for discussion).

In this context, we examine scenarios of outdoor and household air pollution and related health impacts in 2030, given different sets of policies on air pollution, climate change and energy access which are presented in detail in the recently published Global Energy Assessment (Riahi et al., 2012). The specific goal of this paper is to assess how effective such policy combinations could be in delivering improved air quality and health related outcomes. The climate change related outcomes of these scenarios in terms of long-term radiative forcing and associated temperature change are presented in detail in (Riahi et al., 2012) and (Mccollum et al., 2013) and are not discussed here. We do not examine here the direct impacts of climate change on human health although this is an important area of research. The underlying modeling framework used in this paper has been presented in detail in (Rao et al., 2012) and combines an integrated assessment model and an atmospheric chemistry transport model for the spatial distribution of outdoor air pollution exposures globally. We explicitly model future household energy access and use by accounting for heterogeneous household energy choices and affordability constraints for rural and urban populations spanning the entire income distribution based on (Pachauri et al., 2013). We use WHO Comparative Risk Assessment methods (Ezzati et al., 2004) and include a number of updates to methodology based on recent literature to estimate both ambient and household health related outcomes of the chosen policies. Global results are presented for 2030 and include spatially detailed emissions of air pollutants, ambient concentrations of PM2.5, health impacts in terms of disability adjusted life years (DALYs) from both ambient and household air pollution, and the associated costs of policies.

2. Materials and methods

We use the IIASA integrated modeling framework similar to (Riahi et al., 2011), including the Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) (Messner and Strubegger, 1995; Rao and Riahi, 2006; Riahi et al., 2007) for deriving global scenarios of air pollutants. Sectors included are power plants, industry (combustion and process), road transport, households, waste, agriculture, and large-scale biomass burning. Estimates of a number of GHGs and air pollutants including methane (CH_4), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC) and organic carbon (OC) are derived from the MESSAGE model and further spatially detailed at a 1×1 degree resolution. We use inventory data described in (Granier et al., 2011) and an exposure-driven algorithm for the downscaling of the regional air-pollutant emissions projections based on (Riahi et al., 2011). We include in the MESSAGE model, a detailed representation of a number of air pollution policies and costs of such policies until 2030 (methodology described in (Riahi et al., 2011, 2012). We estimate global PM2.5 emissions based on the black and organic carbon emissions in the MESSAGE model, and include in addition, non-carbonaceous components from fly-ash; production; and building sources (see (Rao et al., 2012) for details).

Atmospheric concentrations of particulate matter, in particular PM2.5, are calculated with the off-line global TM5 chemistry-transport model (Dentener et al., 2005, 2006a,b; Bergamaschi et al., 2007, 2009; Fiore et al., 2009). The models and methodology and validation of the results for 2005 are explained in detail in (Rao et al., 2012; Brauer et al., 2012) and references therein. In short, TM5 uses a set of nested grids; with a state-of-the art 1×1 resolution over the continental source regions. TM5 calculates emissions of natural origin, and uses a set of gridded emissions of primary and secondary aerosols from the MESSAGE model. Gas phase chemistry is calculated in the TM5 model using a modified CMB4 (Carbon Bond Mechanism 4) mechanism, and used to compute the formation of sulfate and nitrate, which are assumed to be in thermodynamic equilibrium following the EQSAM2 (Equilibrium Simplified Aerosol Model version 2) module. Secondary organic aerosol formation is parameterized using the AEROCOM recommendations in (Dentener et al., 2006a). Using parameterizations of wet and dry removal based on (Huijnen et al., 2010), output generated for this publication consists of primary (e.g. black carbon and organic carbon) and secondary (e.g. SO_4, NH_4 and NO_3) aerosol concentrations. As outlined in (Brauer et al., 2012) and (Rao et al., 2012), aerosol concentrations in urban regions are likely to be elevated compared to rural regions within a 1×1 degree TM5 grid cell. To compute aerosol concentrations relevant for exposure of populations, an urban increment is calculated on the basis of the contribution of primary particulate matter emissions from transport, energy and industry, and high resolution information on the fraction of population living in urban regions and the underlying land area. This is similar to the approach used in other recent studies (for e.g., (Brauer et al., 2012; Rao et al., 2012)) and includes a representation of both urban and rural exposures (thus also representing effects of industrial sources and other hot spots typically located outside urban areas) in assessing total PM2.5 concentrations and related health impacts on a global scale.

Health impacts from outdoor air pollution in terms of disability adjusted life years (DALYs) are further estimated using methodology detailed in (Rao et al., 2012). We use WHO baseline scenario data (WHO, 2008) on DALYs until 2030 based on a 5% discount rate. We limit the analysis to adults over 30 years of age and use a concentration threshold range of 7.5–50 $\mu g/m^3$ for PM2.5 in this study based on (Cohen et al., 2005) and (Krewski et al., 2009) although there is now evidence of health impacts at also higher concentrations (see (Lim et al., 2012). Central estimates of cause-specific relative risk rates (RR) were based on (Cohen et al., 2005) and are as applied in (Krewski et al., 2009) (see Appendix B for definition and summary of risk rates used in this paper). We do not estimate the health related impacts of ozone, as it is generally assumed that they are an order of magnitude smaller than those of particulate matter. We exclude here the impacts of outdoor air pollution on children although there is recent evidence of increased acute lower respiratory infection (ALRI) from outdoor air pollution in children below the age of 5 years (Lim et al., 2012). We also note here that the outdoor and household related health impacts are not independent, i.e. we do not adjust for the share of outdoor air pollution that can be attributed to household burning of solid fuels. While recent evidence indicates that this fraction is quite significant in many developing countries and is estimated at around 16% globally (Lim et al., 2012), we do not correct for this due to inherent uncertainties in estimation. There is also recent literature which suggests that the composition of PM2.5 could potentially have implications for the impacts on health (see for example (Ostro et al., 2006, 2009) but we do not examine this here. Appendix C summarizes the methodology for estimating health impacts.

We use one of the core WHO health and development indicators, "proportion of population using solid fuels," as a proxy for actual exposure to household air pollution. We interpret this as those populations relying on all solid fuels including coal, charcoal, wood, crop, or other agricultural waste, dung, shrubs, grass, and straw. Future scenarios regarding household dependence on solid fuels are assessed using the MESSAGE-Access modeling framework (Riahi et al., 2012; Pachauri et al., 2013). Estimates of relative risks for disease due to household air pollution from (Desai et al., 2004; Wilkinson et al., 2009) are used to estimate the burden of those diseases with strong epidemiological evidence for an enhanced risk due to solid fuel use (see also Appendix B for definition and summary of risk rates). Similar to outdoor air pollution, we use mortality and morbidity related outcomes for adults over the age of 30 years but additionally include children below the age of 5 years, given long-standing evidence that household air pollution from solid fuel use is a leading risk factor for ALRI in young children (Smith et al., 2004; Lim et al., 2012). We estimate health effects by combining information on the exposed population and the fraction of current disease levels attributable to solid fuel dependence, using the methodology described in (Rao et al., 2012) and summarized in Appendix C.

We use a baseline scenario of global energy and GHG emissions described in detail in (Riahi et al., 2012) as the underlying basis for estimation of pollution related emissions. The scenario includes detailed estimates of solid fuel use in the household sector based on (Pachauri et al., 2013). This scenario combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand (global energy demand is projected to increase to 460 Exajoules (EJ) in 2030) and a long-term climatic response similar to the RCP 8.5 described in (Riahi et al., 2011). This scenario thus provides a good basis for estimating the impacts of stringent transformational policies on the energy system and related impacts in pollutant emissions.

In this paper, we focus on selected combinations of climate change, energy access and air pollution policies as shown in Table 1 to specifically examine the impacts of such scenarios on outdoor and household air pollution levels and related health impacts in 2030. A more in-depth description of such policies is provided in (Riahi et al., 2012). Appendix A describes in detail the air pollution control measures assumed.

Table 1
Policy scenarios.

Scenario	Air pollution	Climate change	Energy access*
a	No improvement in air quality legislations beyond 2005	No policies. Annual energy intensity (EJ/GDP) growth of 3% per year. 72 Gt CO_2 eq GHG emissions in 2030	No policies.
b	All current and planned air quality legislations until 2030 (fuel standards, emission limits, technology standards). (See Supplementary Online Material for detail.)	Same as "a"	Same as "a"
c	All current and planned air quality legislations until 2030	Limit on global temperature change to 2 °C in 2100 based on the Conference of Parties agreement in Copenhagen. Annual energy intensity reduction of 2.6% until 2050. Replacement of fossil-fuels; and increase in zero-carbon electricity production). 42 Gt CO_2 eq GHG emissions in 2030.	Access to modern cooking fuels for 0.5 billion additional people in Sub-Saharan Africa, Pacific and South Asia by 2030 compared to a no new access policies scenario. This would be achieved by means of fuel subsidies on modern fuels and microfinance to households for new stove purchases.
d	Stringent air quality legislations (end-of pipe controls and fuel improvements) corresponding to 70% of maximum technologically feasible reduction levels. (See Appendix B.)	Same as "c"	Same as "c"
e	Same as "d"	Same as "c"	Aspirational scenario reflecting universal availability of cooking fuels in Pacific & South Asia, sub-Saharan Africa based on the United Nations (UN) call for universal access to modern energy services by 2030. This would be achieved by means of fuel subsidies on modern fuels and microfinance to households for new stove purchases. All households switch to either cleaner combusting fuels such as LPG or biogas or advanced biomass stoves with emissions and efficiency characteristics similar to cooking with LPG.

[*] The current framework does not consider specific access policies in Centrally Planned Asia (CPA) and Latin America (LAM) where use of coal and biomass is prevalent in the household sector. However economic growth is assumed to lead to a decline in such fuel use. We also do not consider here the impacts of electrification but recent analysis indicates that the GHG and pollutant emissions of such a policy are not likely to be significant (see (Riahi et al., 2012)).

3. Results

3.1. Emissions and concentrations

Fig. 1 shows population (>30 years) weighted ambient concentrations of PM2.5 (including an urban increment factor, excluding dust, secondary organic aerosols and sea salt) in 2005 and 2030 for scenarios (a–e). This represents the average PM2.5 concentrations derived by weighting each underlying grid cell value by the underlying population over 30 years of age. Also shown (as insets) are global anthropogenic emissions of SO_2, NO_x, and PM2.5. We compare the estimated PM2.5 concentrations to the WHO AQG of 10 $\mu g/m^3$ for long-term PM2.5 concentrations and WHO Tier I–III levels of 10–35 $\mu g/m^3$ still associated with significant health risks but shown to be achievable with successive and sustained abatement measures (WHO, 2006).

Assuming no additional air quality legislation beyond those committed globally by 2005 as in scenario (a), is seen to lead to an overall increase in both pollutant emissions and PM2.5 concentrations of more than 50% by 2030 compared to 2005 levels, thus indicating the key role of air quality policies to control growing outdoor air pollution in the future. Assuming a full implementation of all currently planned air quality legislation in the 2010–2030 period as in scenario (b) is found to lead to a slight decline in global SO_2 and PM2.5 emissions of around 2% while NO_x emissions increase by 15% compared to 2005 levels. Global population-weighted anthropogenic PM2.5 concentrations in 2030 are estimated to rise to 34 $\mu g/m^3$ compared to 26 $\mu g/m^3$ in 2005. The globally modest impacts of currently legislated air quality policies are similar to findings in (IEA, 2011), and can be explained in particular by increased NO_x and PM2.5 emissions from the transportation sector in developing countries, which offset the reductions resulting from the implementation of air pollution policies in OECD countries. Additionally, there is an increase in the population dependent on solid fuels for cooking, which grows from 2.2 billion to 2.4 billion in South Asia, Pacific Asia and sub-Saharan Africa between 2005 and 2030, in the absence of new policies to improve access to clean cooking fuels. These trends are similar to those in (IEA, 2011) that estimate an initial increase in the number of people dependent on biomass fuels globally, and despite a drop in the share of population dependent on solid fuels, almost no change in the numbers by 2030.

The implementation of global climate mitigation policy and a partial energy access policy in scenario (c) lead to reductions of outdoor air pollution related emissions of SO_2, NO_x and PM2.5 of around 40% compared to scenario (b). The reductions derive mainly from resulting improvements in energy efficiency; substitution of fossil fuels; adoption of advanced energy technologies; and an overall increase in the share of zero-carbon electricity. Additionally, the population dependent on solid fuels is reduced by 0.5 billion in 2030 as a result of energy access policies (see Table 1 for details). The associated population-weighted global PM2.5 concentrations are estimated at 26 $\mu g/m^3$ in 2030. However, large fractions of the population are still exposed to ambient concentrations of PM2.5 above WHO recommended levels in many parts of the world. Also, around 1.9 billion people still remain dependent on solid fuels in 2030, and related cooking emissions continue to contribute significantly to both ambient and household pollution. It is necessary to note that we exclude here the contributions from dust and sea salt, which are significant in many parts of the world.

Increasing further the stringency of outdoor air pollution policies as in scenario (d), yields significant emission reductions compared to scenario (c), particularly in industrial and transportation sectors. As climate change and energy access policies are the same as in scenario c, the additional reductions in emissions derive primarily through a number of additional pollution controls on these sectors (see Appendix A for details). While in OECD regions, this results in up to 80% of the population below the WHO AQG level for PM2.5, in Asia and Africa, concentration levels remain high. A major contributor is the continued use of biomass for cooking in these regions, as a result of which household related PM2.5 emissions are high (40–50% of total PM2.5 emissions in 2030). Further inclusion of an energy access policy that eliminates the use of solid-fuels in the household sector as in scenario (e), is thus particularly effective in regions with high solid fuel use, and

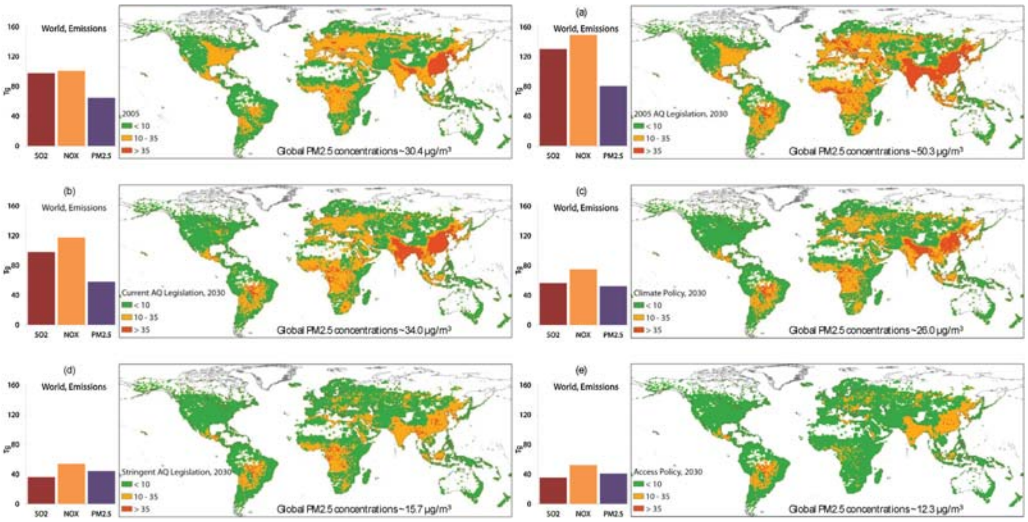

Fig. 1. Global population-weighted average anthropogenic PM2.5 concentrations (excluding dust, sea salt and secondary organic aerosols, including large scale biomass burning), and emissions of SO_2, NO_x and PM2.5 in 2005 and across scenarios in 2030 (a–e). The ranges for concentrations reflect the WHO recommended AQG value (10 $\mu g/m^3$), the attainment of which is expected to significantly reduce the health risks and the three interim targets defined for long-term PM2.5 concentration (10–35 $\mu g/m^3$).

results in 100% of the global population below 35 $\mu g/m^3$, and more than 50% of the global population at levels below 10 $\mu g/m^3$.

Our results thus lend further support to current evidence that currently legislated outdoor air pollution policies, while necessary to control growing air pollution, will be inadequate in meeting WHO recommended levels for long-term PM2.5 globally in 2030. Stringent pollution policies are found to be necessary in this context and can lead to significant improvements in global air quality when supplemented by policies on climate change and energy access.

3.2. Health impacts

Fig. 2 summarizes the health impacts for 2005 and in 2030 for the different policy packages (see also (Rao et al., 2012) for discussion of 2005 impacts). For 2005, we estimate 23 million DALYs from outdoor air pollution and 46 million DALYs from household air pollution. This can be compared to the most recent estimates from (Lim et al., 2012) of 76 million DALYs from outdoor air pollution and 116 million DALYs from household air pollution in 2010. Differences in both sets of estimates can be attributed to a number of reasons. While a difference in base-years is one component, inclusion of more disease categories in (Lim et al., 2012) compared to our study is another factor. These include in particular ALRI in children less than 5 years also for outdoor air pollution and cerebrovascular disease and lung cancer from biomass use as risk categories for household air pollution. Another important reason for differences is that (Lim et al., 2012) postulates non-linear concentration response functions and assumes continued risk of disease also at concentrations above 50 $\mu g/m^3$. Including these updates would affect our numbers, but there is unlikely to be changes in the relative health impacts of the scenarios.

If outdoor air pollution legislation remained frozen at 2005 levels (scenario a), this would lead to a global increase of nearly 50% in outdoor air pollution related DALYs in 2030 compared to 2005. Current outdoor air quality legislation (scenario b) results in lower health impacts as compared to scenario (a) in 2030, but DALYs still increase by more than 30% as compared to the 2005 level. While this is partly explained by the increase in PM2.5 concentrations, an additional factor for increased health impacts is the growth in population above 30 years of age, especially in developing countries, where large increases can be expected in these age cohorts in the next two decades. It is also necessary to note that the underlying share of cardiopulmonary disease and lung cancer related causes in the overall burden of diseases increases significantly from current levels in many developing countries in 2030, reflecting a baseline shift from infectious diseases to chronic ones, thus also contributing to the increased health impacts from outdoor air pollution. We further estimate that in the absence of any significant policies on energy access, 22 million DALYs can still be attributed to household air pollution in 2030. The reductions in household pollution related DALYs from 2005 levels accrue from a shift in underlying baseline mortality as DALYs attributable to ALRI among children are expected to decline between 2005 and 2030 even in the absence of any access policies (see (Riahi et al., 2012) for details).

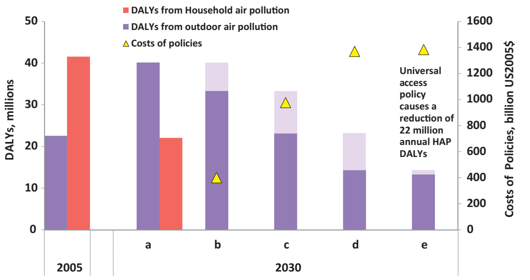

Fig. 2. Global Health Impacts (million DALYs) of outdoor and household related air pollution in 2005 and 2030 and Combined Annual Costs (US2005$), of air pollution, climate change and access policies in 2030. Household air pollution DALYs (red bars) only estimated for limited set of scenarios. Purple bars indicate impacts from outdoor air pollution. Shaded or lighter areas specifically indicate the savings in terms of outdoor air pollution related DALYs due to policies. Policy costs shown here on the right-hand axis are additional to annual energy system costs of US$1630 billion in 2030. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Additional inclusion of climate change and partial energy access policies (scenario c) lead to a reduction of more than 7 million DALYs compared to scenario (b) as a result of lower PM2.5 concentrations due to the transformational changes in the energy system associated with these policies. Increased stringency of air pollution controls and universal energy access (scenario e), while eliminating the remaining household air pollution related DALYs (22 million DALYs saved from reduced household air pollution), also leads to a reduction of 20 million DALYs in outdoor air pollution impacts or more than a 50% reduction as compared to (c). The additional outdoor air pollution related health related impacts of the universal access policy, while small in global terms, are particularly significant for sub-Saharan Africa and South Asia, where as seen in Fig. 1, large declines in ambient concentrations are observed. The associated global burden of disease from outdoor air pollution reduces to less than 5% of the DALYs associated with cardiovascular, respiratory, and lung cancer related disease in 2030.

Our results provide further evidence that policies on climate change and energy access could potentially provide significant benefits in terms of outdoor air pollution related health outcomes. It is important to acknowledge that health impacts as estimated here are subject to a number of uncertainties and are used mainly to provide a comparative basis for the scenarios. Future work will need to take into account a number of recent updates in methodology and estimation as postulated by the new GBD study (Lim et al., 2012).

3.3. Costs

The costs of individual policies vary significantly based on the underlying type and stringency assumed. Air pollution policies result in total annual control costs in 2030 ranging from 400 billion US$ (scenario (b) up to 800 billion US$ per year (scenario (d)) (all economic values are expressed in 2005 US $). Climate change policies as in scenario (c) result in substantial additional energy system cumulative investments (including supply and demand) of 830 billion US$ per year in 2030. These estimates are similar to other recent studies (see for example (IEA, 2011). The costs of energy access policies (the investments needed for providing LPG or advanced biomass stoves to new users as well as the subsidy costs to lower prices of LPG) are estimated at between 3.5 billion US$ per year (partial access to modern cooking fuels as in scenario (d)) to 17 billion US$ per year (universal access to modern cooking fuels as in scenario (e)), most of which would be required in Sub-Saharan Africa and South Asia. Further details on the costs of individual policies are found in (Riahi et al., 2012).

Fig. 2 indicates the costs of the combined policy packages. We find that significant cost related co-benefits exist from viewing policies in combination. For instance, the direct costs of outdoor air pollution control are significantly reduced in scenarios (c) and (d) (up to 40% reduction in pollution control costs in 2030) due to the fuel shifts and efficiency improvements associated with climate change policies which limit the need for costly end- of- pipe controls. These findings are similar to other studies that also estimate a reduction in air quality control costs from the implementation of climate mitigation policies (see for example (Amann et al., 2011; Mccollum et al., 2013). Energy access policies are also seen to bring significant benefits in outdoor air pollution, at very little additional costs.

4. Discussion

Our results demonstrate the application of an extensive knowledge base and analytical tools that combine information on anthropogenic activities relating to air pollution and spatial dispersion of emissions, in order to examine how combined policies on air pollution, climate change and energy access could improve outdoor air quality and related health outcomes.

We underline the relevance of integration across multiple policy domains for improvements in outdoor air quality and the role that health related indicators can play in the evaluation and choice of such policies. We find that in many regions current air quality policies may be insufficient to achieve reductions in global air pollution. Beyond more stringent air pollution control, policies on climate change and energy access could promote important structural changes in the energy system which not only contribute to improvements in air quality in the shorter-term, but may also have potential impacts on outdoor air pollution levels and related health impacts in the longer-term. Energy access policies will also simultaneously lead to a corresponding decline in household air pollution and related health impacts. We find that a full suite of policies on air pollution, climate change and energy access results in more than 50% of the world's population below WHO recommended levels for long-term PM2.5 exposure in 2030.

Our results also provide support to the notion that the substantial and immediate health related benefits associated with climate change policies could potentially accelerate low carbon energy choices in the first place. The inclusion of outdoor air pollution related health benefits could further provide an additional impetus to energy access policies which are primarily focused on the issue of household air pollution.

We highlight the need for multi-criteria methodologies for evaluating the costs and benefits of combined policies, which could have significant impacts on the choice and evaluation of such frameworks. While we focus here on the avoided or reduced costs for pollution control, it is important to acknowledge that given the inherent difficulties in valuing human life in economic terms, the analysis does not attempt to quantify, for instance, the additional benefits associated with such policies, including for example reduced health expenditure. Further, we do not discuss the uncertainties in estimating the climate impacts of particulate matter reductions, which could significantly affect the evaluation of the co-benefits of such policies. It is also important to acknowledge that policy frameworks as discussed here presume the effective implementation of subsidies, regulation, enforcement and increased capacity building. The choice of policies, the stringency of the targets, and the exact combination of clean fuels and technologies will be specific to each country or region and are likely to be associated with significant uncertainties with regards to their design, costs and implementation. However, the analysis presented here clearly highlights the importance of potential air quality and health benefits from better coordination across policy domains that have traditionally been assessed in isolation from each other.

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Appendix A. Policies and measures for air pollution control

	Transport	Industry and power plants	International shipping	Other
Current legislation (CLE)				
Sulfur dioxide (SO_2)	OECD: EU fuel quality directive (2009/30/EC) and national legislation on the sulfur content in liquid fuels; non-OECD: national legislation on the sulfur content in liquid fuels and coal.	OECD: for EU, emission standards from the LCPD (2001), IED (2010), NEC (1991), UNECE (1999). National legislation elsewhere. Non-OECD: increased use of low-sulfur coal, increasing penetration of flue gas desulfurization (FGD) after 2005 in new and existing plants according to national legislation.	MARPOL Annex VI revisions from MEPC57.	Limiting open burning of agricultural waste (if legislation exists).
Nitrogen oxides (NO_x)	OECD: emission controls for vehicles and off-road sources up to the EURO-IV/EURO-V standard (vary by region). Non-OECD: National emission standards equivalent to approximately EURO III–IV standards (vary by region).	OECD: for EU, emission standards from the LCPD (2001), IEC (2010), NEC (1991), UNECE (1999). National legislation elsewhere. National emission standards on stationary sources – if stricter than in the LCPD. Non-OECD: primary measures for controlling of NO_x.	MARPOL Annex VI revisions from MEPC57.	Limiting open burning of agricultural waste (if legislation exists).
Carbon monoxide (CO)	As above for NO_x.			Limiting open burning of agricultural waste (if legislation exists).
Volatile organic compounds (VOC)	Measures as described above for NO_x; legislation on fuel quality and evaporative losses.	A number of directives for the EU: e.g., solvent directive of the EU (1999), stage I directive (1995), NEC (1991), UNECE (1999).		Limiting open burning of agricultural waste (if legislation exists).
Ammonia (NH_3)		End-of-pipe controls in industry (fertilizer manufacturing).		NEC (1991) and UNECE (1999).

Appendix A (*Continued*)

	Transport	Industry and power plants	International shipping	Other
PM2.5 (including BC and OC)	As for NO_x.	For the OECD like for SO_2, NOx; for the non-OECD, improving enforcement of PM control with end of pipe measures required by national legislation; often linked to FGD requirements.		Limiting open burning of agricultural waste (if legislation exists).
Additional measures in stringent legislation (SLE): corresponding to 70% of maximum technologically feasible reduction levels				
SO_2	As in CLE.	High-efficiency flue gases desulfurization (FGD) on existing and new large boilers. Use of low-sulfur fuels and simple FGD techniques for smaller combustion sectors. High-efficiency controls on process emission sources.	Same as CLE.	Reduction in agricultural waste burning.
NO_x	OECD and non-OECD: EURO-5 and EURO-6 for light duty vehicles.	Selective catalytic reduction at large plants in industry and in the power sector. Combustion modifications for smaller sources in industry and in the residential and commercial. sectors. High-efficiency controls on process emission sources.	Same as CLE.	Reduction in agricultural waste burning.
CO	As in CLE.			Reduction in agricultural waste burning.
VOC	As in CLE.	Regular monitoring, flaring, as well as control of the evaporative loses from storage. Solvent use: full use of potential for substitution with low-solvent products in both “do it yourself” and industrial applications, modification of application methods and introduction of solvent management plans.		Reduction in agricultural waste burning.
NH_3		End-of-pipe controls in industry (fertilizer manufacturing).		Substitution of urea fertilizers, rapid incorporation of solid manure, low nitrogen feed and bio-filtration.
PM2.5 (including BC and OC)	As in CLE.	High-efficiency electrostatic precipitators, fabric filters, new boiler types, filters, good practices.	Revised MARPOL Annex VI (2005) regulations.	Reduction in agricultural waste burning.

1. LCPD, 2001: Council Directive 88/609/EEC of 24 November 1988 on the limitation of emissions of certain pollutants into the air from large combustion plants.
2. IED, 2010: Industrial Emissions Directive (2010/75/EU) http://ec.europa.eu/environment/air/pollutants/stationary/ied/legislation.htm.
3. NEC, 1991: National Emission Ceiling Directive (2001/81/EC).
4. UNECE, 1999: The 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone; http://www.unece.org/env/lrtap/multi_h1.html.
5. Solvent Directive of the EU, 1999: 1999/13/EC Council Directive 1999/13/EC on the limitation of emissions of volatile organic compounds due to the use of organic solvents in certain activities and installations.
6. Stage 1 Directive, 1995: 1994/63/EC aims to prevent emissions to the atmosphere of volatile organic compounds (VOCs) from off-road sources.
7. MARPOL: International Convention for the Prevention of Pollution From Ships, 1973 as modified by the Protocol of 1978; Annex VI entered into force in 2005.

Appendix B. Risk rates[a] for outdoor and household air pollution

Relative risk rates for outdoor air pollution.

Health outcome	GBD category, WHO 2009	Group (sex, age in years)	Relative risk (per 10 $\mu g/m^3$)	Confidence Interval (CI)
Cardiopulmonary (infectious and chronic respiratory diseases and selected cardiovascular outcomes for adults.)	39,40,106–109, 111	Men and Women ≥ 30	1.059	1.015–1.105
Lung cancer	333	Men and Women ≥ 30	1.082	1.011–1.158

Relative risks for household air pollution from solid fuel use.

Health outcome	GBD category, WHO 2009	Group (sex, age in years)	Mean relative risk	Confidence interval (CI)
Acute lower respiratory infection (ALRI)	39	Children < 5	2.3	1.9–2.7
Chronic Obstructive Pulmonary Disease (COPD)	112	Women ≥ 30	3.2	2.3–4.8
Lung cancer (from exposure to coal smoke)	333	Women ≥ 30	1.9	1.1–3.5
Ischemic Heart Disease (IHD)	107	Women ≥ 30	1.2	n.a
Chronic Obstructive Pulmonary Disease (COPD)	112	Men ≥ 30	1.8	1.0–3.2
Lung cancer (from exposure to coal smoke)	333	Men ≥ 30	1.5	1.0–2.5

[a] The concept of risk rate (RR) relates to the relative risk of exposure that is associated with specific disease outcomes. In the case of household air pollution, the exposure is typically assumed to be based specifically on 24-h kitchen concentrations of PM2.5 typically in the range of 500–1000 $\mu g/m^3$, with 24-h personal exposures for cooks and young children around 200–500 $\mu g/m^3$, with short periods of peak exposure that are many times higher than these concentrations. In the case of outdoor air pollution, response functions for long-term exposure are based on 10 $\mu g/m^3$ increase in ambient PM2.5.

Appendix C. Methodology for estimation of health impacts from outdoor and household air pollution

We estimate health impacts from ambient air pollution using the population-attributable fraction (PAF) approach based on the gradient of risk between the theoretical minimum level of air pollution exposure and the estimated observed exposure (WHO, 2002). We apply an approach similar to that detailed in (Smith et al., 2004; Cohen et al., 2005) which involved: (1) estimating total population exposures to PM2.5; (2) choosing appropriate exposure-response factors for PM2.5; (3) determining the current rates of morbidity and mortality in the population of concern using data from (WHO, 2008) and (4) estimating the attributable number of deaths and diseases.

The population attributable fraction to exposure is calculated based on (Murray et al., 2003) and is estimated as:

$$\mathrm{PAF} = \frac{P * (RR - 1)}{[P * (RR - 1) + 1]}$$

where P = exposure expressed in PM2.5 concentrations, and RR = relative risk for exposed versus non-exposed populations. Once the fraction of a disease that is attributed to a risk factor has been established, the attributed mortality or burden is the product of the total death or DALY estimates for the disease and the attributed fraction.

For household air pollution impacts, we estimate the effects by combining information on the exposed population and the fraction of current disease levels attributable to solid fuel use. The approach utilizes relative risk estimates for health outcomes that have been associated with exposures to household pollution due to indoor smoke from solid fuel use and uses the population dependent on solid fuels as an exposure surrogate. The fuel-based approach takes advantage of the large number of epidemiological investigations conducted primarily in rural areas of developed countries that treat exposure to household air pollution from solid fuel use (sfu) as a single category of exposure (Smith et al., 2004). Recent studies propose an integrated concentration-response curve that draws from studies on indoor air pollution, outdoor air pollution, and tobacco smoke (Lim et al., 2012) but we do not apply this here.

The attributable fraction (AF) to sfu, $\mathrm{AF}_{\mathrm{sfu}}$, can be estimated as:

$$\mathrm{AF}_{\mathrm{sfu}} = \left[\frac{p_e(r_{rr} - 1)}{p_e(r_r - 1) + 1}\right] \qquad (1)$$

where p_e represents the population exposed to the solid fuels and r_r the relative risk due to sfu.

Similarly, attributable burden due to the solid fuel, $\mathrm{AB}_{\mathrm{sfu}}$ use can be estimated as

$$\mathrm{AB}_{\mathrm{sfu}} = \mathrm{AF}_{\mathrm{sfu}}\mathrm{CDL} = \left[\frac{p_e(r_r - 1)}{p_e(r_r - 1) + 1}\right]\mathrm{CDL}$$

where CDL is the current disease level estimated from (WHO, 2008).

Appendix D. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.gloenvcha.2013.05.003.

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LETTER

A multi-model assessment of the co-benefits of climate mitigation for global air quality

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Abstract

We present a model comparison study that combines multiple integrated assessment models with a reduced-form global air quality model to assess the potential co-benefits of global climate mitigation policies in relation to the World Health Organization (WHO) goals on air quality and health. We include in our assessment, a range of alternative assumptions on the implementation of current and planned pollution control policies. The resulting air pollution emission ranges significantly extend those in the Representative Concentration Pathways. Climate mitigation policies complement current efforts on air pollution control through technology and fuel transformations in the energy system. A combination of stringent policies on air pollution control and climate change mitigation results in 40% of the global population exposed to PM levels below the WHO air quality guideline; with the largest improvements estimated for India, China, and Middle East. Our results stress the importance of integrated multisector policy approaches to achieve the Sustainable Development Goals.

Introduction

The recent Sustainable Development Goals (SDGs) provide a possible policy platform for linking action on air pollution and climate change. Effective action on the SDGs will require that the connections between the goals and targets be better understood and the local vs global scale synergies and trade-offs evaluated [1]. Here, we present the first multi-model study on the co-benefits of climate policies for regional air quality. Our goal is to provide critical information to the ongoing policy debate on aligning global and national actions to achieve key SDGs related to air pollution and climate change.

Integrated assessment models (IAMs) project economic growth, population, energy consumption, land-use and agriculture along with associated GHG and pollutant emissions. Scenarios developed using IAMs reflect plausible future pollutant emissions based on socioeconomic, environmental, and technological trends. The Representative Concentration Pathways (RCPs) [2], were the first set of long-term global air pollution scenarios developed across multiple IAMs. These scenarios were primarily developed for use by climate modelers and are based on a set of long-term radiative forcing targets. They reflect assumptions on the successful implementation of emissions controls in the next few decades and as a result show significant declines in particulate matter (PM) and ozone precursor emissions over the 21st century [3, 4]. Recent studies have pointed to the importance of a systematic assessment of future air quality across a wide range of uncertainties related to the enforcement of pollution control and alternative policies and developments in the underlying energy systems [5, 6].

Standard model inter-comparison projects (MIPs) in which, IAMs implement a common study protocol, and highlight conclusions that are robust to different models' specifications, have been used to gain a better understanding of future structural transformations related to long-term climate change . Here, we use a set of global climate policy scenarios from a recently concluded MIP [7] to assess the co-benefits of climate policies across a set of IAMs for varying levels of implementation of air pollution control. We present results in terms of emissions of a number of air pollutants for key sectors across 10 global regions. We also calculate regional concentrations of fine particulate matter (PM2.5) using a reduced-form global air quality source-receptor model (AQ-SRM) and assess them in relation to the World Health Organization (WHO) air quality guidelines [8].

Through this effort, we respond to the need for comprehensive modeling that accounts for multiple uncertainties to increase the policy relevance of the co-benefits of climate policies [9] and extend a number of studies [10, 11] in this regard. The methods and insights developed here, are expected to inform scenario development processes in the Shared Socio Economic Pathways (SSPs), which are part of a new framework that the climate change research community has adopted to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation [12].

Data and methods

Six IAMs participated in this study. The models differ in their economic, technological and sectoral representation and in the way they are solved, with some models maximizing an intertemporal objective function (such as economic activity) and others simulating a set of equilibria. Moreover, the models differ in their representation of GHG emissions and their sources, energy demand and supply sectors, population and GDP baselines, and assumptions about techno-economic parameters.

All models implemented a common set of scenarios. These include:

- *REF*: counterfactual baseline development without climate policy against which climate policy scenarios are evaluated. This includes assumptions on median GDP and population projections and does not explicitly include any climate policies.
- *MIT*: climate policy scenario that includes emissions reduction targets for the year 2020 as laid down in the Copenhagen pledges with inclusion of some plausibility considerations of the pledges; and a long-term 450 ppm carbon-di-oxide equivalent (CO2e) concentration target.

For this study, all models represented a number of air pollutants over the 2000–2100 period. Emissions for the base year (2000) were based on a common historical emissions inventory [13]. For the 2000–2030 period, we sourced data on pollution control across multiple regions and sources from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model [14–16]. Pollution abatement as defined here specifically included end-of-pipe controls removing pollutants without affecting the emission-producing activity itself. We aggregated data by source from the GAINS model for all energy-related combustion (supply and demand), conversion, and transformation sectors, and applied them in the respective IAMs using emission factors (emissions per unit energy). This approach allows for a relatively simplistic method to represent quantitatively, concepts related to the speed and degree of implementation of pollution control [17].

In order to reflect uncertainty related to future pollution control, we developed three air pollution policy variants across the REF and MIT scenarios:

- *FLE: 'fixed legislation'; no further emission controls beyond those in place in 2010.*
- *CLE: 'current legislation'; full and timely implementation of all existing and planned air pollution legislation until 2030; full implementation of the best available emission control technologies as exists today by 2100 (independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions).*
- *SLE: 'stringent legislation'; rapid pollution control with 75% full implementation of the best available emission control technologies by 2030 and full implementation by 2050.*

The emission outcomes from all IAMs were further linked to the TM5-FASST model, a global AQ-SRM [18, 19]. The TM5-FASST model calculates 1° × 1° resolution grid maps of PM2.5 surface

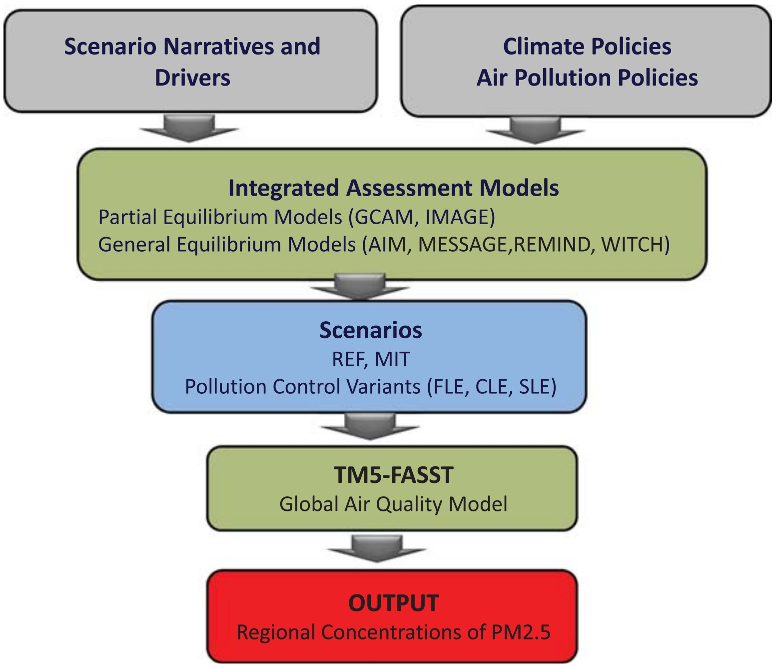

Figure 1. Description of modeling and scenario framework.

concentrations taking as input annual emission rates of pollutants for 56 regions. For population exposure calculations, the resulting PM.5 grid maps were interpolated to 7.5′ × 7.5′ to match high resolution population grid maps [20].

Figure 1 shows the systems and scenario framework for this study. Further information on model types, scenario descriptions, sector definitions, and air quality modeling is available in the supplementary information (SI).

Results

A complete description of the energy and GHG transitions underlying the scenarios used in this study are available in [7, 21]. Key results with regards to the achievement of stringent climate targets that have been highlighted include the importance of fossil fuel combustion for achieving stringent climate mitigation targets; and the need for the phase out of global greenhouse gas (GHG) emissions by 2100. SI figure 1 further summarizes the development of primary energy in the REF and MIT scenarios.

In figure 2, we now review emissions of sulfur dioxide (SO_2), nitrogen oxide (NO_X) and black carbon (BC) in the REF and MIT scenarios for the CLE, SLE and FLE pollution policy variants. We focus here on the implications of changes in energy supply and demand sectors. See SI figure 7-2 for similar results on remaining pollutants.

The first important robust conclusion we make is regarding the comparison to the RCP scenarios in terms of air pollutant emisison ranges. While the scenarios used in this study span a similar range of long-term radiative forcing as the RCP set, assumptions on alternate developments in the energy system and the enforcement of pollution control; result in a wider range of emission outcomes as compared to RCP. These results are important in qualifying the uncertainty related to future air pollution development, particularly in a long-term scenario context.

Climate policies lead to significant reductions in near-term emissions of air pollutants, while simultaneously resulting in large declines in GHG emissions (see SI figure 7-3 for a comparison of reductions in pollutants and GHG emissions in the MIT scenario). The technological transitions entailed by climate policies are effective in controlling for the increases in pollutant emissions in the REF scenario, even with full implementation of current and planned air pollution controls (CLE). With lax implementation of direct pollution control (FLE), climate policies are seen to lead to larger reductions in air pollutants while with more stringent implementation of direct controls (SLE), reductions are more limited. The largest reductions in air pollutant emissions in 2030 occur in the MIT SLE scenario. Thus, comprehensive policies that

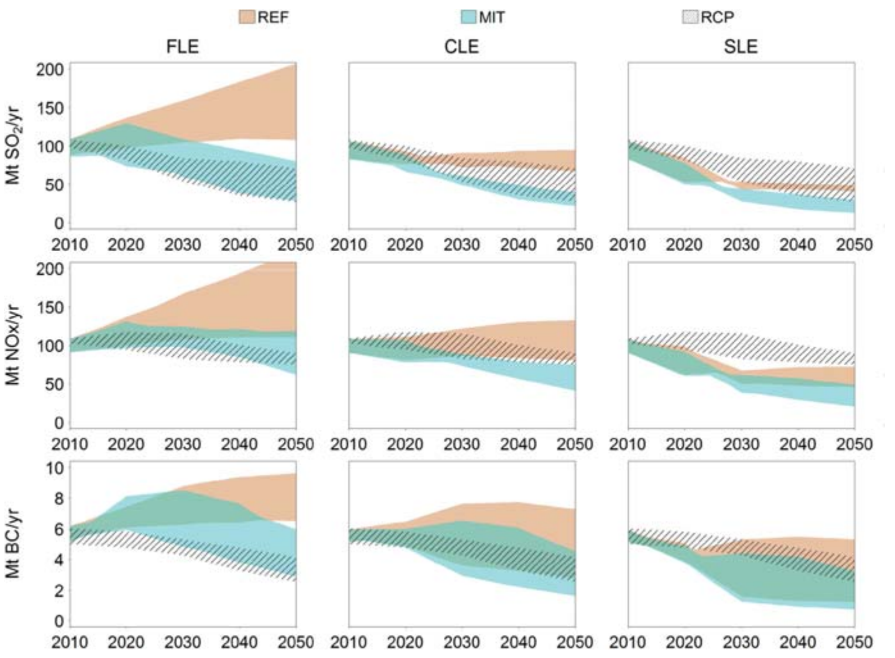

Figure 2. Global emission ranges for REF and MIT scenarios across IAMs for selected air pollutants (SO_2, NO_X and BC) from energy supply and demand activities until 2050 in FLE, CLE and SLE air pollution control variants respectively. Shaded area shows the range of emission outcomes from similar sectors in the RCP scenario set.

include multiple approaches to air pollution control could be most effective in delivering maximum reductions in air pollution in the near-term.

We note that assumptions on the technological limits of direct emission controls are an important factor in terms of the ability of climate policies to afford further reductions in air pollutants. Thus, we may possibly over-estimate co-benefits for the pathways and regions with high penetration of advanced pollution control technologies. On the other hand, given the current low rates of application of these technologies, technological progress in the scenarios can be expected to mature their use over the longer-term.

Even with similar assumptions on the levels of direct pollution control, there is a wide spread across scenario realizations, in terms of the extent of the co-benefits from climate policies. The differences reflect choices of modelers on the technological development and alternative policies in the reference scenarios; as well as the timing and extent of mitigation technologies in the MIT scenarios. A more extensive analysis of these differences is important for the appropriate placing of the co-benefits argument in a policy context.

A closer look at the distribution of reductions in air pollutants across sectors is indicated in figure 3. It is important to note that that though we use consistent definitions of sectors in this study, the aggregate nature of the IAMs means that the results also depend on the assumed level of technological detail in a particular model. While we focus here on the energy supply and demand sectors, SI figure 7.4 indicates clearly that assumptions on land-use and other sectors could imply additional differences across the range of model realizations of the respective scenarios.

We find that current and planned air pollution controls have uneven impacts across different sectors and pollutants in the REF CLE scenario. For SO_2 emissions, adequate pollution controls in the electricity generation sector and the penetration of advanced coal facilities implies that emissions decline significantly in most models in this sector. However, relatively poor controls in other sectors like industry and a growing use of fossil fuels could result in an increase in emissions. For NO_X emissions, the differences across models in the medium term are larger due to a number of factors including, a lag in controls in the industrial sector in many countries; the high pollutant intensity in processes such as steel and cement; and the increasing use of liquid fuels in the transportation sector. Fossil based liquids comprise on average 92% of total transportation final energy in 2050 in all scenarios here, with assumptions on the relative costs of fuel substitution and infrastructure development being a common constraint. For BC emissions, assumptions on biomass use in developing countries is seen to have a major impact on the reductions from current air

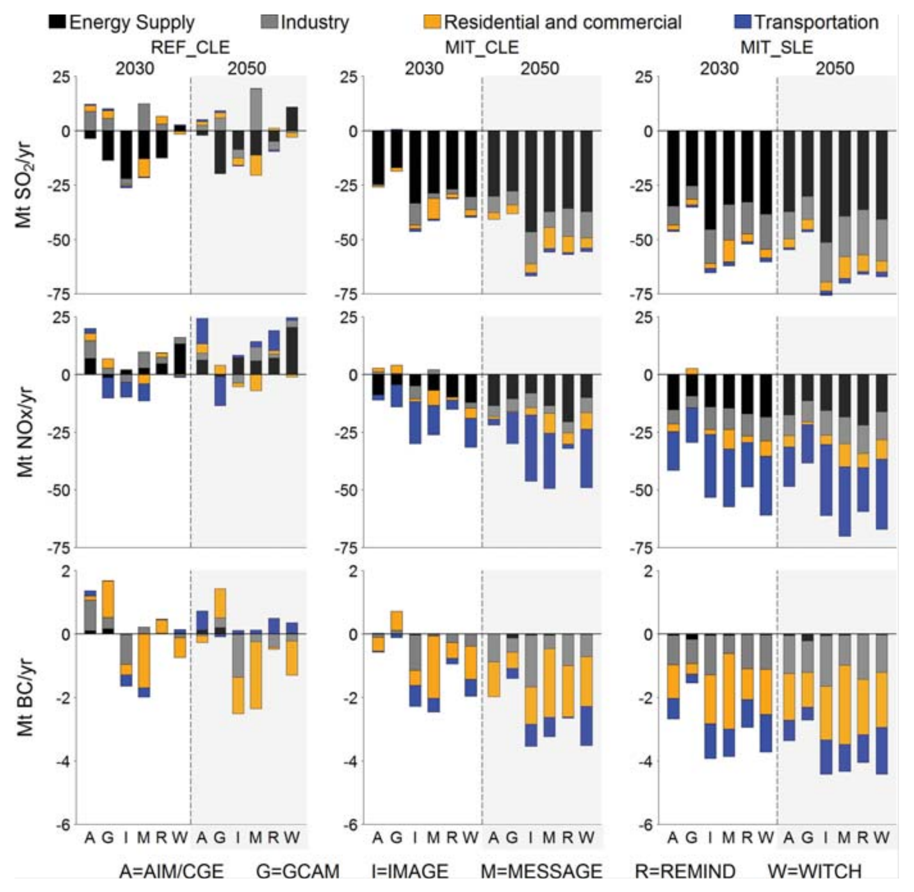

Figure 3. Sector disaggregation of emissions reductions across IAMs in 2030 and 2050 compared to 2010 in REF CLE, MIT CLE and MIT SLE respectively.

quality controls. With the continued use of solid fuels for cooking and in small industries, BC emissions are seen to increase significantly in the short-term in these sectors.

With climate policies, we see a convergence in the distribution of the reductions in air pollutant emissions across the different scenario realizations. Air pollutants decline due to increased non-fossil electricity production; penetration of advanced fossil electricity technologies; switch in process heating from coal to gas; a shift to natural gas and electricity based transport; accelerated energy efficiency improvements: and the replacement of coal use for cooking. The co-benefits from climate policies clearly depend on the extent to which such energy related transformations are already part of the respective reference scenarios. In cases, where favorable socio-economic and technological conditions imply low pollutant emissions in the underlying reference scenarios, the co-benefits from specific climate mitigation policies are correspondingly lower. An important finding is that potential tradeoffs from climate policies could occur from an increase in the use of traditional biomass in the residential sector in the near-term due to high fossil fuel prices and the relatively high costs of more advanced cooking technologies. Thus, effective ambient air pollution control in developing countries will require additional policies on access to clean energy for cooking.

Given the different atmospheric and chemical nature of the pollutants, they can be expected to have varying impacts on regional air quality. In figure 4, we show how the change in man-made fine particulate matter (PM2.5) from 2010 to 2050 is spatially distributed for the different scenarios. By 2050, the REF-CLE results in lower annual ambient PM2.5 concentrations compared to 2010 levels in regions where legislation is already stringent, e.g., North America (average over all models: -2.4 ± 0.8 μg m^{-3}) and Europe (-4.2 ± 1.0 μg m^{-3}). For other regions, concentrations increase compared to 2010 (for example, India: $+12 \pm 4.7$ μg m^{-3}). Alternative developments in the reference scenarios across the emission models

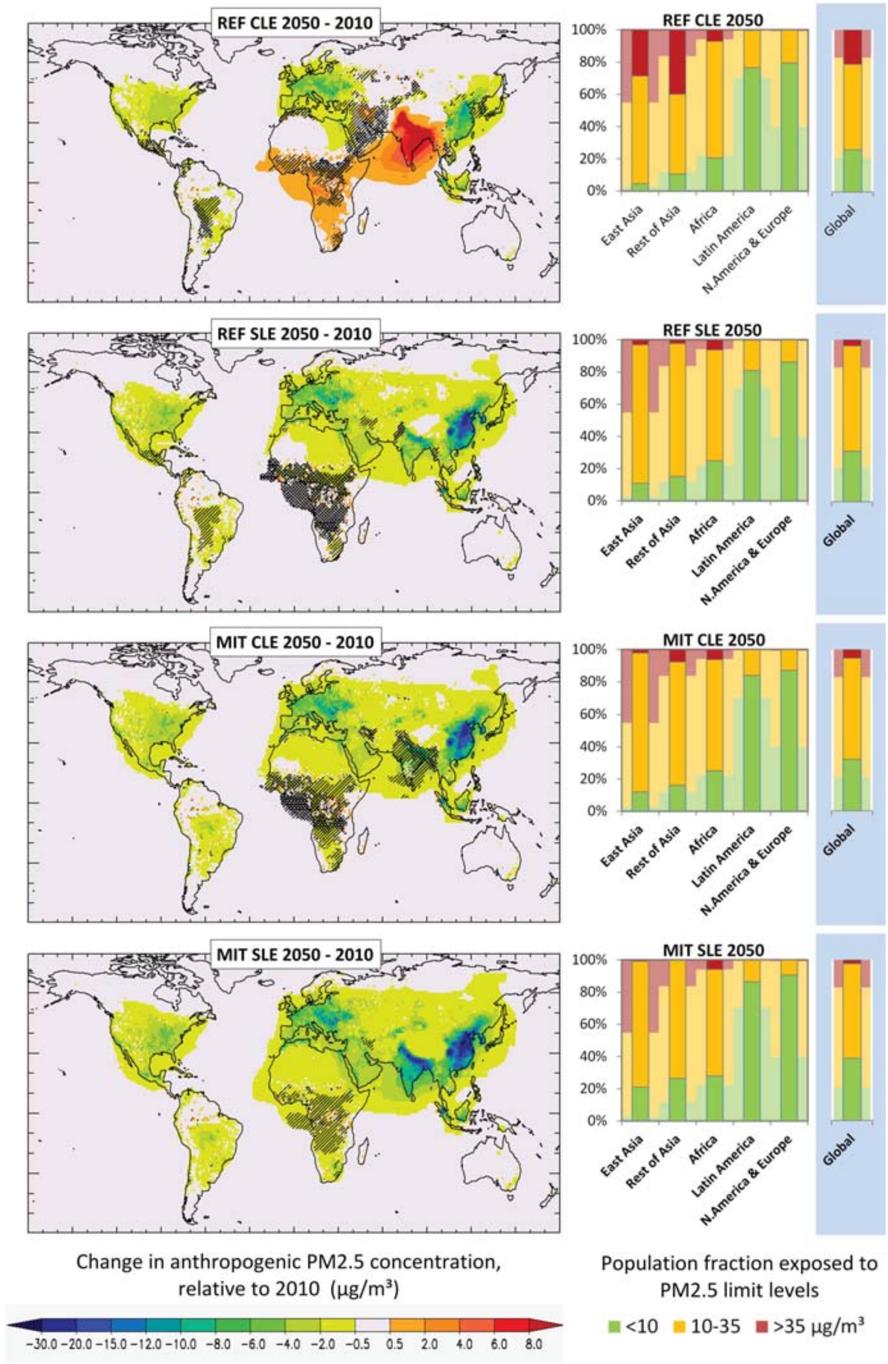

Figure 4. Left column; average difference in annual PM2.5 concentrations (includes primary PM components [BC, OC] and PM precursors [SO_2, NO_X, NMVOCs, CO, NH3) from all sources) between selected scenarios across the six models in 2050 and year 2010. Hatched areas indicate grid cells where at least one model has a different sign than the other models and where the standard deviation for the six models is larger than 0.5 $\mu g\ m^{-3}$. Right column: regional and global fraction of population exposed to anthropogenic PM2.5 levels below 10, between 10 and 35 and above 35 $\mu g\ m^{-3}$ for the scenario couples compared in the maps. Foreground: 2050 scenario; background: year 2010.

lead to a wide variation in PM2.5 trends in some regions, in some cases even with opposite trends, marked as hatched areas on the map. Differences in land-use emissions across scenarios are another important factor, especially in regions like Africa with large scale forest burning. The regional averages and standard deviation for ten world regions are available in the SI.

By 2050, the REF-CLE scenario leaves 21% of global population (17% in 2010) above the WHO highest recommended Tier 1 values for long-term average PM2.5 concentrations of 35 μgm^{-3}. Between 2010 and 2050, the whole Asian region experiences the most significant further deterioration, increasing from 28% to 36% the population fraction exposed to air pollution levels above Tier 1 levels. Stringent air quality policies (REF-SLE) reduce the fraction of global population exposed to anthropogenic PM2.5 levels above WHO Tier 1 value to 4% (Asia: 3% of population). The combination of climate policies with CLE controls results in a comparable reduction of pollutant levels (global exposure above Tier 1 level: 5%, Asia: 6%), although models show more diverging results over India and Africa than for the SLE scenario. The largest improvements in air quality, with most converging results of all models, result from a combination of air pollution and climate policies (MIT-SLE). By 2050, MIT-SLE results in less than 3% of global population (less than 0.5% in Asia) above Tier 1 values and 39% of the global population (25% in Asia) below the WHO AQG level of 10 $\mu g\ m^{-3}$. The potential health impacts of such combined policies, although not calculated here are expected to be significant in Asia where the large increase in populations in the next few decades and the established nonlinearity in dose-response functions [22] implies that the types of relative shifts highlighted above could lead to significant declines in air pollution related mortality.

Discussion

Our findings support the notion that the co-benefits of climate mitigation policies can be useful in structuring action on the achievment of key SDGs related to air pollution and climate change.

The results emphasize the critical role of climate policies in complementing direct efforts on air pollution control. The use of multiple instruments that include technology-advancement policies in addition to direct emission controls could potentially offset uncertainty related to potential market failures [23]. However, with current policies, we find that many regions may only be partially capitalizing on the potential to achieve appreciable improvements in air quality and health. Traditional 'end-of pipe' pollution control may have less of a role in reducing emissions than the effects of socio-economic growth and related fuel and technological shifts, especially over longer time frames [24]. Thus 'pollution control' itself should be carefully designed to include a wide range of multi-sector efforts targeted at appreciable improvements in air quality and health [25, 26]. In developing countries, this will imply a need for additional policies on access to clean energy for cooking. This could potentially reduce household air pollution and afford additional improvements in health [27, 28].

In spite of the favorable environment that the SDGs may create, policy integration will not happen automatically. Integration of strategies across sectors and policy advice represents a challenge to the way development work is usually conducted, and will require a paradigm shift [29]. By increasing the robustness of climate policy to uncertain damages, abatement costs, and discount rates, the co-benefits of climate mitigation could potentially support more aggressive near term climate action even in the face of large uncertainty. In practice damages are, either implicitly or explicitly, balanced against the economic costs of pollution control, for which technology characteristics, particularly costs of pollution control or lower emission alternatives are a key driver [30, 31]. Other studies that have looked at the climate benefits of air pollution control have highlighted that their assessment could also be important in policy formulation [32–34].

This study has used a standard model inter-comparison under a common set of assumptions on policies with a goal to determine robust conclusions on the co-benefits of climate mitigation for air pollution. This approach allows us to capture the complex interactions between policy outcomes; and assess both model and scenario related uncertainty in qualifying the impacts of climate policies [35, 36]. We have dealt with the inherent uncertainties related to short-term trends in the drivers of emissions and the relatively large time steps underlying the models, through a specific focus on longer-term (multi-decade) scale trends. We acknowledge that innovative risk management approaches that explicitly account for structural uncertainties can be further useful in deriving robust policy conclusions, but these have not been implemented in IAMs so far [37].

The methods and findings from this study have important implications for the development of long-term scenarios of air pollution. Future efforts on modeling and scenario development will benefit from integrated narratives that are multi-dimensional and encompass social, economic and environmental factors, thus allowing for informed and relevant policy choice.

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Future air pollution in the Shared Socio-economic Pathways

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ABSTRACT

Emissions of air pollutants such as sulfur and nitrogen oxides and particulates have significant health impacts as well as effects on natural and anthropogenic ecosystems. These same emissions also can change atmospheric chemistry and the planetary energy balance, thereby impacting global and regional climate. Long-term scenarios for air pollutant emissions are needed as inputs to global climate and chemistry models, and for analysis linking air pollutant impacts across sectors. In this paper we present methodology and results for air pollutant emissions in Shared Socioeconomic Pathways (SSP) scenarios. We first present a set of three air pollution narratives that describe high, central, and low pollution control ambitions over the 21st century. These narratives are then translated into quantitative guidance for use in integrated assessment models. The resulting pollutant emission trajectories under the SSP scenarios cover a wider range than the scenarios used in previous international climate model comparisons. In the SSP3 and SSP4 scenarios, where economic, institutional and technological limitations slow air quality improvements, global pollutant emissions over the 21st century can be comparable to current levels. Pollutant emissions in the SSP1 scenarios fall to low levels due to the assumption of technological advances and successful global action to control emissions.

1. Introduction

Despite efforts to control atmospheric pollutant emissions, ambient air quality remains a major concern in many parts of the world. Air pollution has significant negative impacts on human health (Pope et al., 2002; Dockery et al., 1993; Jerrett et al., 2009).

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More than 80% of the world's population is exposed to pollutant concentrations exceeding the World Health Organization (WHO) recommended levels (Brauer et al., 2012) and around 3.6 million deaths can be attributed to ambient air pollution with another 4 million from household related sources (Lim et al., 2012). Moreover, air pollution can alter ecosystems, damage buildings and monuments, as well as influence earth's energy balance and therefore climate change.

Long-term global scenarios for air pollutant emissions have been used for atmospheric chemistry and Earth system model simulations intended to examine future changes in climate, air, and water systems. These scenarios reflect plausible future emissions based on socioeconomic, environmental, and technological trends. These scenarios are generally produced by integrated assessment models (IAMs) (Moss et al., 2010), which project economic growth, population, energy consumption, land-use and agriculture along with associated GHG and pollutant emissions. Recent examples include in particular, the Representative Concentration Pathway (RCP) scenarios (van Vuuren et al., 2011a), which were the multi-model global scenarios of greenhouse gases and air pollutants used in the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2011). The RCPs were developed to span a range of climate forcing levels and were not associated with specific socio-economic narratives. These scenarios reflected the prevailing view that air quality policies will be successfully implemented globally and that emissions control technology will continue to evolve and as a result show significant declines in particulate matter (PM) and ozone precursor emissions over the 21st century at a global level (Amann et al., 2013; van Vuuren et al., 2011b). More recent scenarios have included alternative assumptions on pollution control, in an effort to better understand the role of air pollution control in terms of reference scenario development and the co-benefits from climate policies (see for example Rogelj et al., 2014; Rao et al., 2013; West et al., 2013; Chuwah et al., 2013) . While providing a wider range of pollution futures, the assumptions on air pollution control in these scenarios are, however, still largely independent of underlying scenario narratives.

It is generally assumed in long-term scenarios, implicitly, that pollutant concentration goals will continue to be more ambitious over time, once incomes become sufficiently large. However, the time, stringency, and enforcement success of future targets for a particular region cannot generally be known and must ideally be treated as scenario variable. In a long-term scenario context, it is further necessary that assumptions on air pollution control are consistent with the underlying challenges to climate change mitigation and adaptation. Pollution outcomes in such scenarios can then be expected to be a cumulative result of a range of variables including socio-economic development, technological change, efficiency improvements and policies directed at pollution control as well as alternative concerns including climate change, energy access, and agricultural production.

The Shared Socio Economic Pathways (SSPs) (Kriegler et al., 2012) are a new generation of scenarios and storylines primarily framed within the context of climate change mitigation and adaptation. The SSP narratives (van Vuuren et al., 2014; O'Neill et al., 2014) comprise a textual description of how the future might unfold, including a description of major socio-economic, demographic, technological, lifestyle, policy, institutional and other trends. In this paper, our overarching goal is to develop plausible ranges of future air pollutant emission development pathways in the SSP scenarios, which are based on internally consistent and coherent assumptions on the degree and implementation of future air pollution control. Other papers in this Special Issue summarize parallel efforts in terms of elaboration of developments in the energy system, land use and greenhouse gas emissions in the SSP scenarios (Bauer et al., 2016; Popp et al., 2016).

The structure of the paper is as follows. We first describe the development of a set of alternative assumptions on the degree and implementation of 'pollution control' in the SSP scenarios. These assumptions then reflect historical evidence and prevailing attitudes and progress on pollution control and potential attitudes to the health and environmental impacts of air pollution in the future. We further postulate a link between these alternative development pathways for pollution control and a specific SSP narrative. We also describe quantitative guidance with regards to implementation of these assumptions in IAMs. Finally, the paper summarizes key results from different IAM interpretations of the SSP scenarios in terms of air pollutant emissions and regional ambient air quality.

2. Methodology

In the following sections, we first summarize the overall description of the SSP scenarios. We next describe the development of a set of qualitative assumptions on pollution control that can be linked to the overall SSP narratives and present a quantitative proposal for implementation of these assumptions in IAMs.

2.1. Description of SSP scenarios

The SSPs depict five different global futures (SSP1–5) with substantially different socio-economic conditions. Each SSP is described by a qualitative narrative (Kriegler et al., 2012). Four of the narratives (SSP1, SSP3, SSP4, and SSP5), are defined by the various combinations of high or low socio-economic challenges to climate change adaptation and mitigation. A fifth narrative (SSP2) describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme in any of the dimensions, but rather follow middle-of-the-road pathways. As part of the scenario development process, consistent and harmonized quantitative elaborations of population; urbanization and economic development have been developed for all the SSPs. The quantitative elaborations of the SSP narratives are then referred to as 'baseline' scenarios.

The SSP narratives themselves do not include explicit climate policies. However, additional climate mitigation runs have been developed that include for each SSP baseline, additional long-term radiative forcing targets of 2.6, 4.5 and 6.0 W/m^2 in 2100. Climate mitigation scenarios in the SSP framework further include a number of additional assumptions on specific issues related to the level of international cooperation; the timing of the mitigation effort over time; and the extent of fragmentation (particularly in the short-to medium-term). These are characterized as shared policy assumptions (SPAs) which describe for each SSP narrative, the most relevant characteristics of future climate mitigation policies, consistent with the overall SSP narrative as well as the SSP baseline scenario developments. The mitigation effort of the SSP scenarios is then a function of both the stringency of the target and the underlying energy and carbon intensities in the baselines. This could result in some cases in infeasibilities in terms of meeting mitigation targets (for a complete overview of the SSP baseline and climate mitigation scenarios (see Riahi et al., 2016).

A number of IAMs ran the elaborations of SSP scenarios. These include IMAGE (van Vuuren et al., 2016); MESSAGE-GLOBIOM (Fricko et al., 2016); AIM/CGE (Fujimori et al., 2016); GCAM (Calvin et al., 2016); REMIND-MAgPIE (Kriegler et al., 2016); and WITCH-GLOBIOM (Emmerling et al., 2016). Detailed information on the models can be found in the Supplementary Information (SI). For simplification, for each of the five SSPs, one marker IAM has been identified (representative of a specific SSP from a single IAM). The selection was guided by consideration of internal consistency

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Table 1
Summary of scenarios.

Identifier	Descriptor	Marker IAM	Also computed by (non-marker IAMs)	Central SPA assumptions for Climate Mitigation
SSP1	Sustainability	IMAGE (van Vuuren et al., 2016)	All	Early accession with global collaboration as of 2020
SSP2	Middle-of-the-road	MESSAGE-GLOBIOM (Fricko et al., 2016)	All	Some delays in establishing global action with regions transitioning to global cooperation between 2020 and 2040
SSP3	Regional rivalry	AIM/CGE (Fujimori et al., 2016)	IMAGE, GCAM, MESSAGE-GLOBIOM, WITCH-GLOBIOM	Late accession – higher income regions join global regime between 2020 and 2040, while lower income regions follow between 2030 and 2050
SSP4	Inequality	GCAM	AIM/CGE, WITCH-GLOBIOM	Same as SSP1
SSP5	Fossil-fuelled development	REMIND-MAgPIE	AIM/CGE, GCAM, WITCH-GLOBIOM	Same as SSP2

across different SSP interpretations as well as the ability of a model to represent the specific storylines. This helped to ensure also that the differences between models were well represented in the final set of marker SSPs. Additional replications of the SSPs from 'non marker' models then provide insights into possible alternative projections of the same storyline. The multi-model approach was important for understanding the robustness of the results and the uncertainties associated with the different SSPs.

Table 1 summarizes the SSP scenario set.

2.2. Pollution control in the SSP narratives

In this section, we now describe the development of a set of assumptions on pollution control that can be used to guide the interpretation of SSP narratives.

While there is no unique relationship between either pollutant levels or emission controls and income (Stern, 2005; Carson, 2010; Smith et al., 2005), a continued tightening of pollution targets can be considered a consequence of growing attention given to health outcomes with increasing income, or perhaps also as a result of new research that ties additional morbidity and mortality modalities to air pollution. The adverse impacts of air pollution are well documented and costs of control technologies have generally declined over time. This means that developing countries can benefit from past experience and have often implemented pollution controls well in advance, relative to income, as compared to historical experience in currently more affluent regions. Countries have, however, different physical, economic and institutional circumstances that impact both the amount and effort needed to achieve pollution goals. Pollutant emission densities in the developing world are sometimes quite high and, even with more advanced technology, reaching pollution targets may be more difficult. The same level of pollution control will result in different concentration levels in different locations.

Policies to control the adverse impacts of air pollution are numerous and regionally diverse. They are generally aimed at avoiding exceeding specified targets for concentration levels (for example, sulfur-di-oxide, ozone, and particulate matter) but goals for ecosystem protection (e.g., from acidification and eutrophication) have also been pursued in several regions. Pollution targets are periodically revised at both the global level (e.g. WHO) and by national and regional bodies. Levels of pollution control are also often different across sectors. Further, in some circumstances, traditional 'end-of pipe' pollution control may have less of a role in reducing emissions than the effects of socio-economic growth and related fuel and technological shifts (Rafaj et al., 2014). Thus 'pollution control' itself could refer to a wide range of policies and developments. For example, policies addressing climate change often, as a co-benefit, reduce atmospheric emissions, thus improving ambient air quality (McCollum et al., 2013; van Vuuren et al., 2006; Bollen, 2008) . Conversely, policies targeting air pollution will have also climate impacts, e.g., (Carmichael, 2008; Shindell et al., 2012), although climate co-benefits may be smaller than previously expected (Smith and Mizrahi, 2013; Stohl et al., 2015). Technological availability can also be a key influence on the degree of pollution control, especially if few or only costly options are available. In practice damages are, either implicitly or explicitly, balanced against the economic costs of pollution control, for which technology characteristics, particularly costs of pollution control or lower emission alternatives are a key driver.

We cannot capture all these complexities within current integrated scenarios. We first simplify our approach by identifying three characteristics for air pollution narratives:

1. Pollution control targets (e.g. concentration standards), which we specify relative to those in current OECD countries.
2. The speed at which developing countries 'catch up' with these levels and effectiveness of policies in current OECD countries.
3. The pathways for pollution control technologies, including the technological frontier that represents best practice values at a given time.

Based on these characteristics, we developed three alternative assumptions for future pollution controls (strong, medium and weak), which are further mapped to specific SSP scenarios. This terminology follows the same convention as other studies used to inform the SSP scenario design process (KC and Lutz, 2016; Crespo Cuaresma, 2016).

The *medium pollution control* scenario (SSP2) envisions a world that continues following current trends. Due to the diffusion of technology and knowledge, there is some 'catch-up', where countries achieve levels of emission control and policy efficacy in advance, in terms of income levels, of the historical record in current OECD countries. Pollution concentration targets become more ambitious over the century as income grows, the commitment to set and enforce pollution targets becoming increasingly effective, and more value is placed on health and environment protection. To reach these targets, some regions will ultimately require implementation of very efficient technologies, some perhaps requiring advances over current technology levels. Regions with large population densities or adverse physical conditions (e.g. geographic features that lead to frequent high pollution episodes) may not achieve their desired outcomes.

The *strong pollution control* scenarios (SSP1 and SSP5) assume that increasing health and environmental concerns result in successful achievement of pollutant targets substantially lower

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than current levels in the medium to long term. Associated with this scenario is a faster rate of pollution control technology development, with greater effectiveness as compared to current technologies. The ambitious air quality goals in the strong pollution control scenario would require, in some regions, implementation of current best available technology (and perhaps even beyond) and assure overall enforcement of environmental laws supported by efficiently operating institutions.

Weak pollution control scenarios (SSP3 and SSP4) assume that the implementation of pollution controls is delayed and less ambitious in the long-term compared to the *medium* scenario. This may be due to the large challenges several regions face, including, high emission densities in developing countries' megacities, failure to develop adequate air quality monitoring, and/or weaker institutions resulting in poor enforcement of respective legislation. The problems are aggravated by the assumption that international cooperation is weaker resulting in low ambition or slow development of international laws that also leads to slower rates of technological improvements and *trans*-boundary pollution contributes to higher background concentrations in many regions.

These pollution control storylines are matched to the SSP scenario narratives as shown in Table 2. The strong pollution control narrative is assumed for the SSP1 and SSP5 scenarios due to their high levels of development, focus on human capital, and reduced inequality. Conversely, we associate the low pollution control narrative with the SSP3 and SSP4 scenarios due to their lower levels of development and greater inequality. The SSP2 scenario is mapped to the medium pollution control narrative. The speed and absolute value to which country groups converge is differentiated across the SSPs. While we qualify three sets of assumptions on pollution control that are mapped to the five SSP scenarios, we note that even with similar assumptions on pollution control, pollution outcomes in specific SSP scenarios will differ due to varying assumptions on economic and population growth, energy consumption patterns, and other scenario characteristics.

2.3. Implementation in IAMs

For quantitative interpretation of the storylines, there is a further need to bridge the gap between the complexity in estimating pollution emissions and their impacts, the ability of available measures, such as emission controls, to mitigate these impacts, and the need for simplified representations of these processes in IAMs. Given that IAMs do not generally represent explicit air pollution control technologies on a detailed level, we detail below an approach where scenario parameters are broadly represented in terms of changes in emission factors derived from a more detailed air pollution model. This approach has been used in a number of recent studies (Riahi et al., 2012) and allows for a relatively simplistic method to represent quantitatively, concepts related to the speed and degree of implementation of pollution control developed and described earlier.

We base our quantitative guidance on a dataset of regional emission factors (i.e., emissions per unit of energy) for energy-related combustion and transformation sectors until 2030 based on current policies and technological options derived from the GAINS model (Amann et al., 2011,Klimont et al., in Preparation). This dataset includes emission factors for 26 world regions for sulfur dioxide (SO_2), nitrogen oxides (NO_x), organic carbon (OC), black carbon (BC), carbon monoxide (CO), non-methane volatile organic carbons (NMVOC), and ammonia (NH_3) from all energy combustion and process sources. The detailed emissions factor data was processed to accommodate the aggregate structure and resolution of the IAMs (see supplementary information (SI) Section 1 for further details). The emission factors used include:

CLE: 'current legislation' – These emission factors assume efficient implementation of existing environmental legislation. It thus describes a scenario of pollution control where countries implement all planned legislation until 2030 with adequate institutional support. The CLE emission factors are "fleet average" values that are the aggregate emission factor of all ages of equipment operating in the given year.

MTFR: 'maximum technically feasible reduction' – These emission factors assume full implementation of 'best available technology' as it exists today by 2030 independent of their costs but considering economic lifetime of technologies and selected other constraints that could limit applicability of certain measures in specific regions. While, the full penetration of MTFR measures in the near-term is not a feasible scenario, these values serve rather as ultimately achievable air pollutant emission factors for conventional technologies considered being available at the present time.

In order to develop trajectories for emission factors that could be consistent with the SSP storylines, we draw on experience and results from a number of existing and forthcoming studies including (Rao et al., 2013; Riahi et al., 2012) where similar sets of emission factors have been used in a single IAM in conjunction with a full scale atmospheric chemistry model, thus providing an indication of the implication of such emission factor development in terms of resulting atmospheric concentrations of PM2.5 and corresponding health impacts in the medium-term. We identify two main components in terms of emission factor development:

Table 2
Qualitative framework for pollution control in the SSPs.

Policy strength	Policy targets		Technological innovation	SSP link	Key relevant characteristics of SSPs
	High Income countries	Medium and Low income countries			
Strong	Policies over the 21st century aim for much lower pollutant levels than current targets in order to minimize adverse effects on population, vulnerable groups, and ecosystems.	Comparatively quick catch-up with the developed world (relative to income)	Pollution control technology costs drop substantially with control performance increasing.	SSP1, SSP5	Sustainability driven; rapid development of human capital, economic growth and technological progress; prioritized health concerns
Medium	Lower than current targets	Catch-up with the developed world at income levels lower than when OECD countries began controls (but not as quick as in the strong control case).	Continued modest technology advances.	SSP2	Middle of the road scenario
Weak	Regionally varied policies.	Trade barriers and/or institutional limitations substantially slow progress in pollution control.	Lower levels of technological advance overall.	SSP3, SSP4	Fragmentation, inequalities

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Until 2030, emission factors assumed in the different SSP scenarios reflect assumptions on the attitudes to health and environment and the institutional capacity to implement pollution control in the near-term. They include full implementation of CLE pollution control measures in the medium scenario but allow for partial and additional control in the weak and strong pollution control scenarios.

After 2030, the trajectories are assumed to depend on the extent to which economic development implies that lower-income regions catch-up to OECD levels in terms of implementation (e.g. emission factor reductions) and the extent of technological change, i.e., the progress towards MTFR levels of emission factors. The MFTR values are assumed to be static themselves and do not change with time and we do not speculate about impact of innovation on further improving the reduction efficiency of the best measures we included. Thus, while in some sense, we may be conservative for the pathways and regions with high penetration of MTFR equivalent technology, on the other hand, given that most MFTR values here are based on current small-scale applications, we assume that technological progress in the scenarios will mature these technologies and allow for wide application over the longer-term.

Fig. 1 shows a conceptual representation of the development of pollution control policy and associated emission factor change in the different SSPs. A more detailed illustration of how the emission factors in the dataset can be used to emulate the above guidelines is presented in section 1.2 of the SI.

The IAMs use the emission factor data provided and quantitative guidelines described to individually develop the SSP scenarios. The emission factors are implemented in the baseline scenarios describing the SSP narratives, while the climate mitigation scenarios then describe the additional impacts of climate policies on air pollution emissions and air quality, compared to the baselines. Thus, the climate mitigation scenarios do not include further policies on air pollution control compared to the baseline scenarios. It is important to note that the models use different inventories for the 2000–2010 periods, and are not benchmarked to a single source. The differences across models in this period then reflect the uncertainty in inventory data and to some extent, the regional and sector aggregation of the IAMs. For land-use, international shipping, and other sectors not covered in the emission factor dataset, additional assumptions are made (see SI [3943] for more details on inventories and drivers for emissions across the IAMs.). The assumptions for methane (CH_4) from energy, waste and land-use sectors are separately described in Bauer et al. (2016) and Popp et al. (2016) and summarized in the SI.

3. Results

In this section, we summarize key results for the SSP scenarios in terms of air pollution emissions and regional air quality. We describe the full range of marker and non-marker ranges for the SSP scenarios. In terms of climate mitigation, we only focus on central SPA case for each SSP.

Results are mainly presented at a global scale and further discussed for five aggregate regions:

- OECD90 countries and new EU member states and candidates (OECD);
- reforming economies of Eastern Europe and the Former Soviet Union (excluding EU member states) (REF);
- countries of the Middle East and Africa (MAF);
- countries of Latin America and the Caribbean (LAM); and
- Asian countries (with the exception of the Middle East, Japan and Former Soviet Union states) (ASIA).

3.1. Emissions of selected air pollutants

Fig. 2 shows potential emissions futures across the SSP scenarios in the 2005–2100 period for selected pollutants. Results for remaining pollutants are summarized in the SI. We include emission ranges from the RCP scenario set as well as the entire range of scenarios from the IPCC Fifth Assessment Report, in order to place the SSP scenarios in context. Differences in historical emissions between the models (2000–2010) are due to use of different inventories by IAMs (Table S1 and individual model descriptions) and are within uncertainty ranges (Granier et al., 2011; Lamarque et al., 2010). For example, for SO_2, historical global emissions uncertainty has been estimated at about 10%, with larger uncertainties for some regions (Smith et al., 2010). Uncertainty is much larger for black carbon emissions, estimated to be a factor of two (Bond et al., 2004). Beyond uncertainties in activity data and emissions factors, additional aspects include the relatively aggregate representation of sectors in IAMs and the large uncertainties in land-use and land-use change emissions (see Popp et al., 2016 for full description of land-use sector).

The SSP3 baseline shows an increase in future emissions over the short-term across all pollutants examined here, due to large population growth and relatively slower and heterogeneous economic growth. At a global level, emissions continue increasing for the next two to three decades and by 2100 show only a slight decline from current levels. The SSP4 baseline, which has identical assumptions on pollutant controls, shows lower emissions than

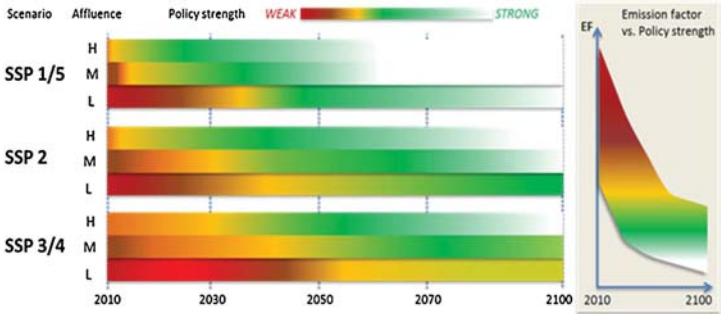

Fig. 1. Proposed Pathways for Air Pollution Policy in SSPs over time. Right hand inset shows schematic development of emission factors. We use here identical definitions of income country groups (low income (L) countries, middle income (M) countries, and high income (H) countries) as used in the SSP process for development of economic projections, based on recent World Bank classifications. https://secure.iiasa.ac.at/web-apps/ene/SspDb/static/download/ssp_suplementary%20text.pdf.

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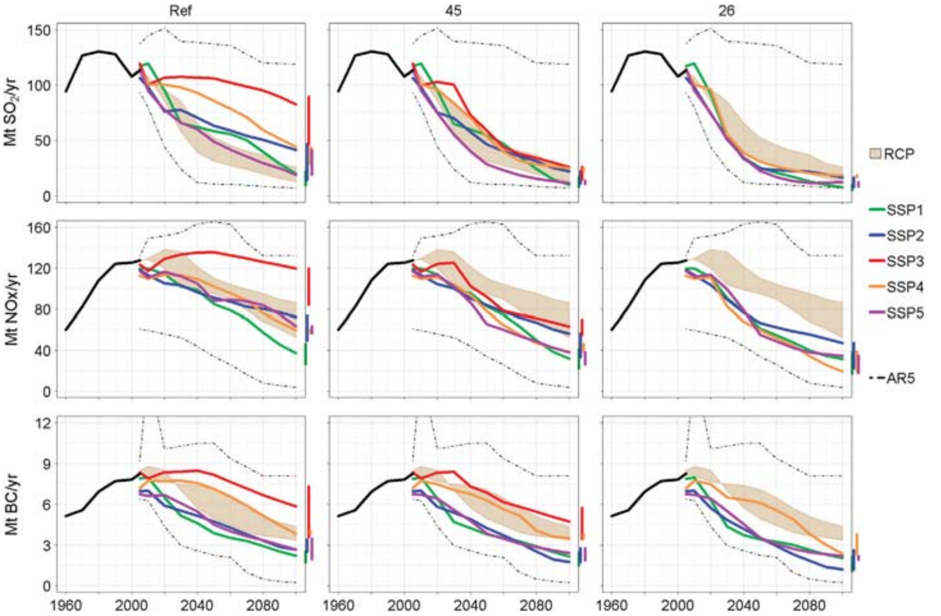

Fig. 2. Emissions of SO_2, NO_X and BC in SSP marker baselines (Ref) and 4.5 (labeled as 45) and 2.6 (labeled as 26) W/m^2 climate mitigation cases. Shaded area indicates range of total emissions from RCP scenario range from (van Vuuren et al., 2011a). Assessment Report (AR5) range refers to the full range of scenarios reviewed in the Fifth Assessment Report (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC) https://tntcat.iiasa.ac.at/AR5DB/; Historical values are derived from (Lamarque et al., 2010); Colored bars indicate the range of all models (markers and non-markers) in 2100.

SSP3 for all pollutants as a result of different evolution of the energy system (see text below). The SSP2 shows a consistent decline in all pollutants throughout the century while SSP1 and SSP5 exhibit a more rapid decline as a result of more effective pollution control and lower fossil fuel intensities resulting in lowest emissions in the second half of the century.

Pollutant emissions in the SSP scenarios span across a much wider range than the RCP scenarios. In general, baseline SSP3 emissions are significantly higher than the largest RCP values, with NO_x and BC emissions in the SSP1 baseline case lower than the lowest RCP value. While scenario dynamics and assumptions on transportation and access to clean energy for cooking in developing countries are major drivers of emission outcomes of NO_x and BC, respectively, another aspect is the updated set of pollutant control assumptions and the emission factors used in this study. Results for remaining pollutants show similar trends (see SI).

The climate mitigation scenarios (Fig. 2 illustrates 4.5 W/m^2 (45) and 2.6 W/m^2 (26) cases) result in most cases in co-benefits in terms of lower pollutant emissions than the baselines. The largest co-benefits from climate policy occur in the weak pollution control, SSP3 scenario, which also has the highest corresponding baseline emissions, while the SSP1/5 scenarios show more limited reductions in air pollutants from climate policies. While SO_2 and NO_x emissions show the largest reductions and the model ranges within the SSPs are much smaller than in baseline cases, BC emissions do not decline as much as a result of assumptions on fuel-substitution in the residential sector (see discussion in Section 3.3).

3.2. Emission intensities

Fast economic growth and high emission intensities (emissions per unit of energy used) in many Asian countries have led to severe pollution episodes across the continent. In spite of the efforts to cut air pollutant emissions from key sources, the intensities remain well above those observed in OECD countries (Fig. 3) where air quality standards are presently the highest. Emission intensities in the OECD are thus already low, and planned legislation is expected to reduce these even further by 2030.

In the SSP baselines, emission intensities in ASIA decline significantly by 2050 in all SSPs. Economic growth and the average income in ASIA in 2030 differs significantly across SSPs, with a low value of 10 billion US2005$ in SSSP3 and a high value of 28 billion US2005billion$ in SSP5 (see also (Crespo Cuaresma, 2016) for details on economic assumptions in SSPs). Thus, countries could be expected to adopt pollution controls with varied schedules, depending on individual institutional, financial and technological capacities (see previous discussion in Section 2).

The relative contribution of pollutant control measures in terms of actual reductions in air pollution will depend on the SSP baseline pathway. Major energy transitions in the SSP scenarios occur gradually and assumptions for pollution control can be assumed to be particularly important in the first few decades in terms of reducing emission intensities. For example, coal based electricity evolves relatively similarly until 2050 across the SSPs and consequently the differences in development of emission intensities in ASIA within this time frame is a direct reflection of pollution control.

Over the longer term, the scenarios diverge significantly in terms of energy and fuel structures. The SSP1 and SSP5 baselines

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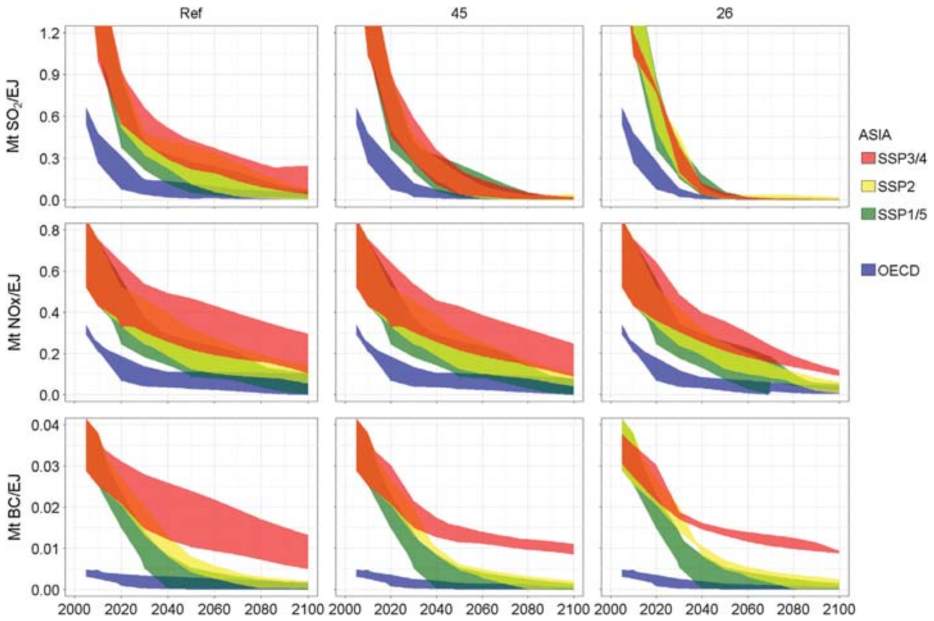

Fig. 3. Emissions intensities for major pollutants in ASIA and OECD in SSP baselines and 26 and 45 mitigation scenarios (both marker and non-marker scenarios included). Emission intensities defined differently for pollutants; SO_2 intensity is in reference to energy supply, NOx and BC in reference to final energy from respective sectors.

show a transition towards less polluting fuels and technologies, and thus result in a rapid and sustained reduction in emission intensities in ASIA. Conversely in the SSP3 and SSP4 worlds, relatively weaker technological change and higher fossil fuel intensities in the energy system lead to higher levels of pollutant emissions. The SSP2 scenario shows large-scale electrification- for example, electrification in ASIA grows rapidly and by 2030 has a similar share of final energy as current OECD levels. In the transportation sector, liquid fuels are the major fuel until mid-century in all SSP scenarios. The SSP1 shows only a slight decline in liquids while, SSP5 shows the largest increase. This reflects alternative narratives of future mobility resulting from differences in lifestyles, preferences and technology.

We note that for BC emissions from the residential sector in ASIA, emission intensities remain high throughout the century in the SSP3 and SSP4 baseline scenarios mainly because of continued biomass use. In the SSP3 scenario, for example, biomass use in ASIA is close to 20 EJ in 2100, almost the same as today's levels. In the SSP1, the assumption of rapidly increasing access to cleaner cooking fuels means that BC emissions decline substantially and by 2030 emission intensities converge to OECD levels.

Assuming proper enforcement of air pollution policies in the OECD region, climate policies have very little impact in terms of pollutant emission intensities. In ASIA, climate policies decrease emission intensities for SO_2 and NO_x, with more limited impact on BC, in fact, a slight increase is indicated in the SSP3 scenario (see discussion on sector impacts of climate policies and co-benefits in Section 3.3).

3.3. Sector emissions

The SSP scenarios offer a wide diversity of future growth patterns and how they relate to regional energy demand convergence and modernization of energy use (see Bauer et al., 2016 for details). In order to understand the impacts of alternative energy developments, we look at broad developments of pollutants across sectors (Fig. 4).

3.3.1. Baseline scenarios

The energy sector emissions are dominated by electricity production, which currently contributes a major share of SO_2 and in the developing countries also of NO_x. Both emission control assumptions and technology assumptions, such as those for clean coal or non-fossil technologies, can have a substantial impact on future emissions.

The industrial sector remains an important source of SO_2 emissions in all SSP baselines and climate mitigation scenarios throughout the century. Fossil-fuel use in the industrial sector comprises a wide range of uses, including process heat, internal combustion engines, and process-specific uses such as steel-making over a range of scales, from small plants and boilers to large manufacturing centers. This sector has significant diversity in regulations on pollutant emissions depending on the type of industry. Experience so far has shown that industrial legislation lags behind energy or transportation sector in developed and developing countries. Another factor is that fossil fuels can be difficult to replace in some industrial activities, such as those related to high temperature process heat. Some processes such as steel making require specific fuels like coking coal, which also differ in pollutant intensity as compared to coal. In the SSP baseline cases, SSP2 and SSP3 show a continuously increasing coal use in this sector while it declines in SSP1 and SSP5, especially towards the end of the century resulting in strong reduction of emissions of SO_2 and NO_x. Coal use in small boilers, coke and brick production industry can be significant sources of BC (Bond et al., 2004). In the long term, a transition to more efficient and cleaner technologies

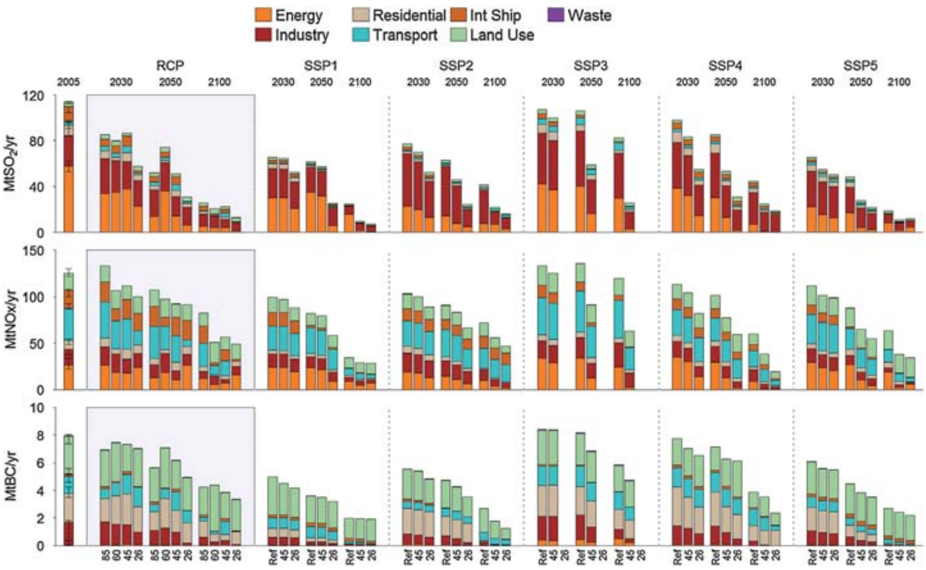

Fig. 4. World, Emissions by sector, Baselines and Climate Mitigation cases. RCP scenarios indicated for reference. Only marker SSP scenarios represented. Values for 2005 are from RCP8.5 while error bars show uncertainty across whole range of SSP and RCP scenarios.

will result in decline in emissions; in the SSP3 scenario this sector has a significant share of BC emissions until mid-century.

The transportation sector is a major source of NO_x and BC emissions through at least mid-century in nearly all SSP scenarios. As discussed earlier, continued use of liquid fuels means that NO_X emissions from the transport sector remain relatively high and only decline in the second half of the century. These differences are broadly reflected at the regional level as well (SI). The end of century decrease in the SSP1 is due to the widespread adoption of hydrogen-fueled vehicles. In the next decades, however, NO_X and BC emissions still remain relatively high even in the SSP1 scenario, mainly due to the large increase in liquid fuel use offsetting the increasing stringency of legislation, particularly in ASIA.

The residential sector is a major source of BC emissions as well as other products of incomplete combustion like organic carbon (OC) and carbon monoxide (CO). Except for SSP1 and SSP5, BC emissions from this sector remain fairly constant until mid-century across all SSPs but then decline substantially in the second half of the century except in the SSP3 and SSP4 scenarios. The latter scenarios assume sustained use of traditional biomass throughout the century. This substantiates recent findings that emissions from the buildings sector are driven more by assumptions about energy access than explicit pollution controls (Rao et al., 2016).

Emissions from international shipping reflect assumptions on the level of implementation of proposed international regulations in the near-term as well as specific assumptions on the changes in fuel use in the baselines and climate mitigation scenarios over the longer-term (see SI for assumptions). The International Convention for the Prevention of Pollution from Ships or Marine Pollution Convention (MARPOL) Annex VI (IMO, 2006) sets limits on sulfur content of fuels and NO_X emissions from ship exhaust. While to some extent there are differences across SSPs in terms of levels of implementation of such protocols, we see that emissions in all the baselines show a downward trend for SO_2 emissions (50–80% decline compared to 2005 in 2030).

The land-use sector (including open biomass burning) is an important source of BC emissions (close to 30% of BC emissions in 2005). The assumptions made by IAMs for this sector vary quite substantially in their level of detail (see SI for details). The development of air pollutant emissions from this sector does not necessarily follow the assumptions driving the air pollution policy in the SSPs but rather, land use practices related to deforestation and savannah burning. In most scenarios emissions from land open burning change only marginally in the mid-term with the long-term tendency to decline, especially in the SSP1.

3.3.2. Climate mitigation scenarios

The emission responses to a carbon policy can generally be linked to changes in fuel consumption or changes in underlying technologies. See SI for primary and final energy details in the SSP scenarios. The intensity of the climate policy target is also an important factor; although more stringent mitigation targets as in the 26 scenario do not necessarily always lead to larger pollutant reductions compared the less stringent 45 case.

The aggregate response of SO_2 emissions to a climate policy is similar in all SSPs. This is due largely to coal combustion being a common source of both SO_2 and CO_2, and a similar relative response to a climate policy in the electricity generation sector. SO_2 emissions fall in all models as coal-fired electricity production either decreases or shifts to carbon capture and storage (CCS) technologies. So for example, SSP4 and SSP2 show increased shares of gas-fired CCS and nuclear power because of the high social acceptance for these options in those storylines. Reductions from a climate policy are larger in the SSP3 and SSP4 scenarios as compared to SSP1. This can partly be explained by the weaker assumptions on pollution control in the SSP3/4. The much stronger transportation BC emission controls in the SSP1/5 scenario and resulting low emission levels, coupled with substantial use of synthetic fuels, mean that, in absolute terms, there is less room for emissions to further decrease as liquid fuel consumption decreases

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under a climate policy. The larger baseline case emissions in SSP3 result in a potential for a larger relative reduction in the climate policy case. SO_2 emissions from international shipping drop off by the end of the century in the climate mitigation scenarios. This response is mainly due to the effect of high carbon prices in this sector and the move towards alternative fuels like liquefied natural gas (LNG) in this sector.

For NO_x emissions, we see that major reductions occur only mid-century. Before that, relative inertia in the energy system means that liquid fuels remain an important part of the fuel mix in this sector (close to or more than 90%). While pollutant controls in this sector are relatively numerous and stringent in many regions, continued oil use in this sector means that emissions do not decline rapidly even in the SSP1/5 scenarios. NO_x emission controls in the energy sector are usually less effective than SO_2 controls and as a result, we observe that NOx emissions response from this sector is less than that of SO_2 (see SI for summary of assumed controls).

The BC emissions reduction in response to a carbon policy is smaller and we find that for CO_2 emission reductions of up to about 50%, mid-century in the 45 and 26 scenarios, BC emissions are generally only reduced by 10–20%. The scenarios show a substantial reduction in BC emissions from the transportation sector due to reductions in liquid fuel consumption and shift to electricity, hydrogen, electricity, and biomass-based liquids. There is relatively small response in the industrial sector BC emissions to climate policy, due to the limited scope for reductions in this sector, the continued use of liquid fuels, and a requirement for some level of carbonaceous fuels. These differences in response in the industrial sector are due, in part, to different representations of industrial fuel demand in these models. Traditional biomass consumption in the residential sector is only mildly impacted by a climate policy in all of the models, with most of the shifts already occurring in the baselines due to other policies and assumptions on energy access. For example, in the SSP1 scenario with relatively rapid rates of modernization in developing countries and a switch to cleaner or less polluting sources for cooking, climate policy does not bring additional reductions. Although not explored in detail here, we note that it is possible that climate policy may negatively impact emissions from this sector as a result of high carbon prices which may in some cases result in an increase in biomass use for cooking in developing countries in the short-term (see also Rao et al., 2016).

4. Ranges for regional air quality outcomes

In order to gain an initial understanding of the regional air quality outcomes across SSP scenarios, we estimate air quality under the SSP scenarios using TM5-FASST model (Van Dingenen et al., 2009), a reduced-form global air quality source-receptor model (AQ-SRM). This allows us to provide an approximate estimate of air quality outcomes, although as noted below, more detailed analysis, for example in CMIP6, is warranted. This approach of linking emission outcomes from IAMs to a reduced form air quality model and allows us to compute multi-model, multi-scenario air quality outcomes (Rao et al., 2016) (see SI for detailed description of the FASST model and its application to the SSP scenarios). We estimate annual average PM2.5 concentrations (fine particulate matter with diameter less than 2.5 μm) as well as six-month average ozone concentrations (Fig. 5). We further provide a comparison of the fraction of population exposed across the SSP scenarios to WHO levels defined as recommended maximum exposure level or air quality guideline (AQG) (10 $\mu g/m^3$) and two intermediate levels (35 $\mu g/m^3$ and 25 $\mu g/m^3$) (WHO, 2006). For this purpose, we use here as a basis, a median population trajectory (Riahi et al., 2012), which is comparable to the SSP2 and SSP4 population projections in 2050 (see SI for comparison of population across the SSP scenarios). Thus, our results as presented here do not reflect the diversity in regional population growth across the range of SSP narratives and only reflect the differences in assumptions on pollution control and underlying energy and land-use development. Future analysis using SSP-specific spatially explicit population estimates will be useful in enhancing our understanding of in terms of changes within a region due to major shifts in population distribution patterns.

We find that the range of PM2.5 and ozone levels for the different SSP scenarios is consistent with the RCP range (which was estimated using the same model and population basis), but displays a larger variability among the SSP variants. Differences are largest in particular in ASIA, in line with the wider diversity in growth patterns reflected in the pollutant emission trends. In all regions, the full range of model outcomes for the weak pollution control scenarios (SSP3/4) show significantly higher concentrations compared to those with strong pollution control (SSP1/5). We also find that, except for ASIA and the MAF, in all regions, more than 95% of the population is currently under the 25 $\mu g/m^3$ exposure level for all scenarios. By 2050, OECD countries strongly improve under all SSP scenarios, reducing concentrations further with 80 to 95% of the population exposed to levels below 10 $\mu g/m^3$. In the MAF region, mineral dust is responsible for most of the exposure above 25 $\mu g/m^3$, explaining why climate and air pollution policies have little impact on the exposed population. Currently in ASIA, average concentrations are around 25 $\mu g/m^3$, and almost 90% of the population is exposed to levels above 10 $\mu g/m^3$ and 45% to levels above 25 $\mu g/m^3$. However there is a wide variation across different parts of ASIA, with China having an average of 32 $\mu g/m^3$; India with an average of 30 $\mu g/m^3$; other regions have an average PM2.5 concentration below 10 $\mu g/m^3$ and at least 2/3 of the population exposed to 10 $\mu g/m^3$ or below. Because the ASIA mean PM2.5 concentration is near 35 $\mu g/m^3$, a positive or negative trend in PM2.5 by 2050 will be reflected in population exposure to this limit level. Indeed, the strong pollution control scenarios (SSP1 and SSP5) decrease the population fraction in the above 35 $\mu g/m^3$ exposure class to about 15%, whereas the low pollution control variants (SSP3 and SSP4) increase the fraction with 25 and 18% respectively.

By 2050, climate policy leads to substantial co-benefits on pollution levels in ASIA, where PM2.5 levels decrease by 5–11 $\mu g/m^3$ relative to the baseline scenario. For the other regions, the maximal benefit is around 2 $\mu g/m^3$. The highest climate policy co-benefits are observed in scenarios SSP3/SSP4 direct air pollution policies were assumed to be less effective, in particular for ASIA (see also SI).

Ozone precursors are, in general, more difficult to control and ozone levels have a larger impact from remote sources as well as increasing methane concentrations. We find that in the SSP scenarios, regional ozone levels do show clear regional differences by 2050. ASIA as a whole is not able to stabilize ozone at present levels even under strong air pollution policies (SSP1 and SSP5), although also in this case large differences in trends are found between individual countries. India's ozone concentrations are estimated to increase (or stabilize) from 63 ppbv in 2005 to 2050 values of 63, 70, or 80 ppbv for the low, medium and high pollution control variant, respectively, while ozone in China decreases from 56ppbv in 2005 to 48, 50, or 53 ppbv respectively in 2050.

5. Discussion

The SSP scenarios were developed to include narratives on future air pollution control that are consistent with current trends

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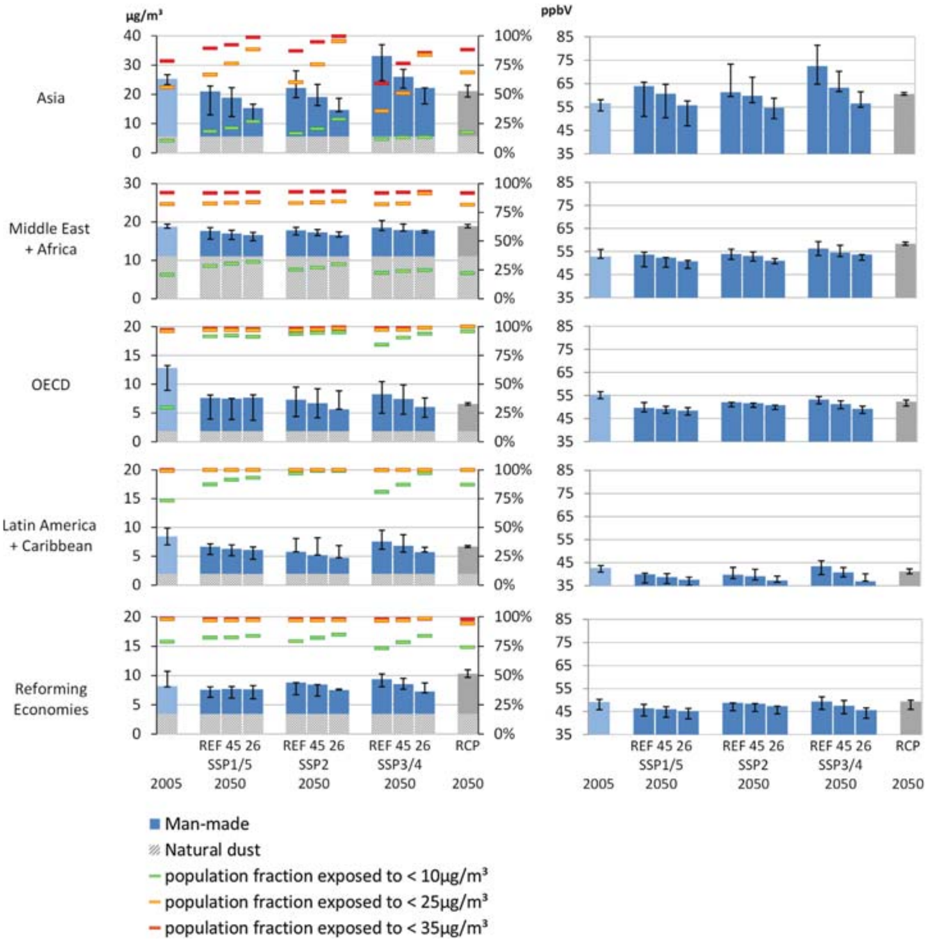

Fig. 5. Left panel: region-population weighted mean PM2.5 in $\mu g/m^3$ (left axis) from marker scenario (blue color bars) and average from the 3 RCP scenarios (grey bar), contribution of natural PM2.5 (hatched area) for the year 2005 (leftmost bar) and 2050. Green, orange and red colored markers indicate the fraction of the population exposed to <10, <25 and $<35\ \mu g/m^3$ respectively (right axis). Right panel: mean ozone concentration (maximal 6-monthly mean of daily maximum ozone). For the grouped scenarios SSP1/5 and SSP3/4 the concentration represents the mean of the respective marker scenarios. Error bars show the concentration range (min/max) of regional averages from all models in the (set of) SSP scenarios shown, including non-marker. For the RCP bars, the error bar indicates the min/max range within the set of 3 RCP2.6, RCP4.5 and RCP8.5 scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in air quality policies; experience in control technology application; and regional differences in affluence and degree of control.

This new generation of global scenarios results in a much wider range of air pollution emission trajectories than the RCPs. The baseline realizations of SSP3 scenario have global emissions at or above the highest level in the RCPs, while the SSP1 scenario is generally near the lower end or below the RCPs. Pollutant emissions in climate mitigation cases are lower still, with some SSP trajectories below the RCP emission levels. The SSP scenarios, thus, provide a wide range of future emissions, for use in global and regional studies of climate and sustainability.

The SSP1 and SSP5 scenarios, which include assumptions on globally successful implementation of strong pollution controls, bring the most significant reductions in air pollutant emissions; by mid-century emissions decline globally by 30–50% in the baseline scenarios and up to 70% in the climate mitigation scenarios. The SSP2, middle of the road scenario, generally achieves reductions by 2100 similar to SSP5. In the SSP3 scenario,where current pollution control plans are not fully achieved, global pollutant emissions do not substantially decline and even slightly increase in the mid-term. In spite of improving emission intensity in all regions, the improvements in the developing world are too small to offset growth in fossil fuel use and other emission drivers. Even by the end of the century when emission intensities in the highest polluting regions decline to the current OECD levels, global emissions remain high in SSP3, barely below the current levels. Except for the strongest climate policy cases considered, the air pollution control policies in SSP3 still result in relatively higher air pollutant emissions, although there are significant reductions in SO_2 and NO_X. The emission trajectories for the SSP4 marker

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scenario are similar, although lower than, those in SSP3. By the end of the century, however, SO_2, NO_x, and BC emission levels are comparable to those of SSP2.

Climate mitigation scenarios result in lower pollutant emissions than the corresponding baselines with the magnitudes of reductions depending on the baseline scenario emission levels. In the relatively more sustainable narratives,s, e.g., SSP1 and SSP5, climate policy does not bring large further reductions in air pollution; but in cases of more heterogeneous futures with uneven development and lower baseline pollutant control levels, e.g., SSP3 and SSP4, successful implementation of climate policies result in larger declines in air pollutant emissions. The co-benefits from climate policies accrue heterogeneously across pollutants and sectors with SO_2 and NO_x emissions showing the most reductions, primarily from electricity generation, industry and transportation sectors. BC emissions are primarily reduced from the residential sector, although in some cases, increasing biomass use as a result of high fossil fuel prices could imply an increase in emissions from this sector.

The SSP baseline scenarios, except SSP1 and SSP5, result in either deterioration or only marginal improvement of air quality in much of the low- to middle-income world by 2050. SSP1/5 brings larger improvements but still leaves a relatively large number of people exposed to levels of pollution above WHO recommended levels, especially in Asia. Lower emission levels are achieved in a strategy combining climate mitigation policy with energy access, however some densely populated regions such as South Asia, face pollution challenges in most scenarios. More detailed regional analysis is warranted to explore possible pathways for improved air quality in these regions.

Achieving sustainable low pollution futures will require intensified action on pollution control and will need to be supported by adequate and coordinated institutional capacity. A key to developing a robust response to the challenge of air pollution robust implementation of integrated air quality management systems incorporating strengthening of institutional mechanisms, assessment of air quality (monitoring, emission inventories, source apportionment, air pollution exposure and damage), evaluation of control strategies, and the development of integrated strategies.

We identify a number of applications and future directions for the SSP scenarios:

Firstly, the current set of scenarios represents one set of internally consistent realizations of the SSP storylines. i,Alternative realizations of the pollution narratives with different IAMs could provide a richer basis for analysis in the future. Another important aspect is more sophisticated quantitative approaches to representing the narratives in IAMs, including for example, more direct use of emissions to concentration relationships and impacts, which would allow for endogenous estimation of pollutant concentration levels. We note that similar emission factors do not necessarily translate into similar concentrations across regions, and that there could be a need to adjust control policies to match the local circumstances in each region. This is particularly true as regions get wealthier and have more resources that could be allocated towards controlling pollution levels. Thus while the quantitative approach adopted here is relatively simplistic, as integration methodologies advance, greater consistency can be achieved in future work.

Within the current scenarios, we do not account for large changes in the direction or degree of pollution control. For example as sulfur dioxide emissions decrease, nitrogen species and secondary organic aerosols can become important determinants of particulate concentrations, which might change the focus of pollutant control efforts. Inclusion of such iterative effects could substantially alter the levels of such pollutants. We also note that we exclude in the current set, scenarios of absolute failure in planned pollution control, although historical evidence indicates that this could occur in times of economic or political instability. Inclusion of such scenarios in the future could be useful to isolate the impacts of pollution control policies. Further, the current set of SSP scenarios does not include a direct representation of pollutant control costs. although a few studies have also now begun to incorporate pollutant emission control costs into integrated assessment models (Wang et al., 2016). Ultimately, more advanced representations of pollution control costs, and technological changes over time would allow much greater consistency in long-term pollutant emission scenarios and improve their real-world applicability.

Secondly, while the SSP scenarios could be used as boundary conditions for regional studies on air pollution; downscaling and spatial interpretations of the scenarios will be vital to develop climate model projections as well as for detailed health and ecosystem analysis. This paper explores some initial projections on air quality but a detailed air quality assessment would require the use of a full chemical transport model which would significantly enhance the quality of assumptions in the current set of scenarios. This work is planned in subsequent phases of the scenario development. One next step for the SSP scenarios will be downscaling for use in global modeling studies, such as the Coupled Model Intercomparison Project phase 6 (CMIP6), which will include projections made by coupled chemistry-climate models. Current plans are to first downscale from native IAM resolution to the country level and then to a spatial grid, similar to previous efforts with global scenarios including the IPCC SRES and RCP scenarios (van Vuuren et al., 2007; Riahi et al., 2011). Data on air pollutant emissions will be made available in different source categories and in a geographically explicit manner. This could be particularly useful in terms of additional regional analyses, including a closer look at health and ecosystem implications.

To conclude, the SSP scenarios represent a new generation of scenarios that explicitly allow for inclusion of sustainability objectives including air pollution and assess their interactions with climate policy. In this paper, we have broadly examined some key trends and results. Future efforts can be expected to significantly enhance this endeavor.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.05.012.

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