LETTERS
PUBLISHED ONLINE: 18 MAY 2014 | DOI: 10.1038/NCLIMATE2178
nature climate change

Air-pollution emission ranges consistent with the representative concentration pathways

Joeri Rogelj[1,2*], Shilpa Rao[2], David L. McCollum[2], Shonali Pachauri[2], Zbigniew Klimont[2], Volker Krey[2] and Keywan Riahi[2,3]

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

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Universitätstrasse 16, CH-8092 Zürich, Switzerland, [2]International Institute for Applied Systems Analysis (IIASA) Schlossplatz 1, A-2361 Laxenburg, Austria, [3]Graz University of Technology Inffeldgasse, A-8010 Graz, Austria.
* e-mail: joeri.rogelj@env.ethz.ch

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

NATURE CLIMATE CHANGE DOI: 10.1038/NCLIMATE2178

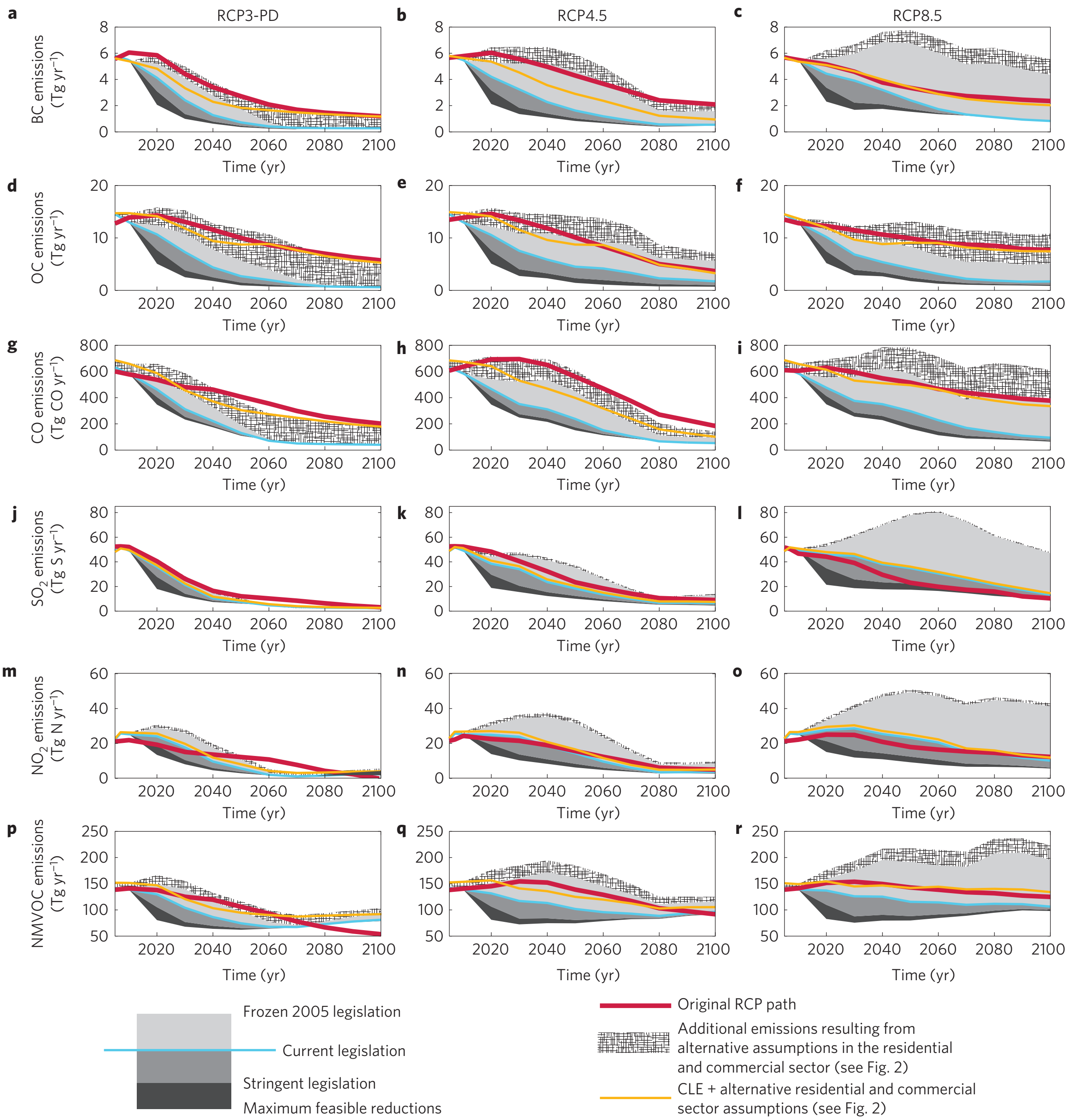

Figure 1 | Ranges of anthropogenic air-pollutant emissions consistent with the representative concentration pathways (RCPs). a–r, Results for RCP3-PD, RCP4.5 and RCP8.5 are shown in the left, middle and right column, respectively, and for BC (**a**–**c**), OC (**d**–**f**), CO (**g**–**i**), SO_2 (**j**–**l**), 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

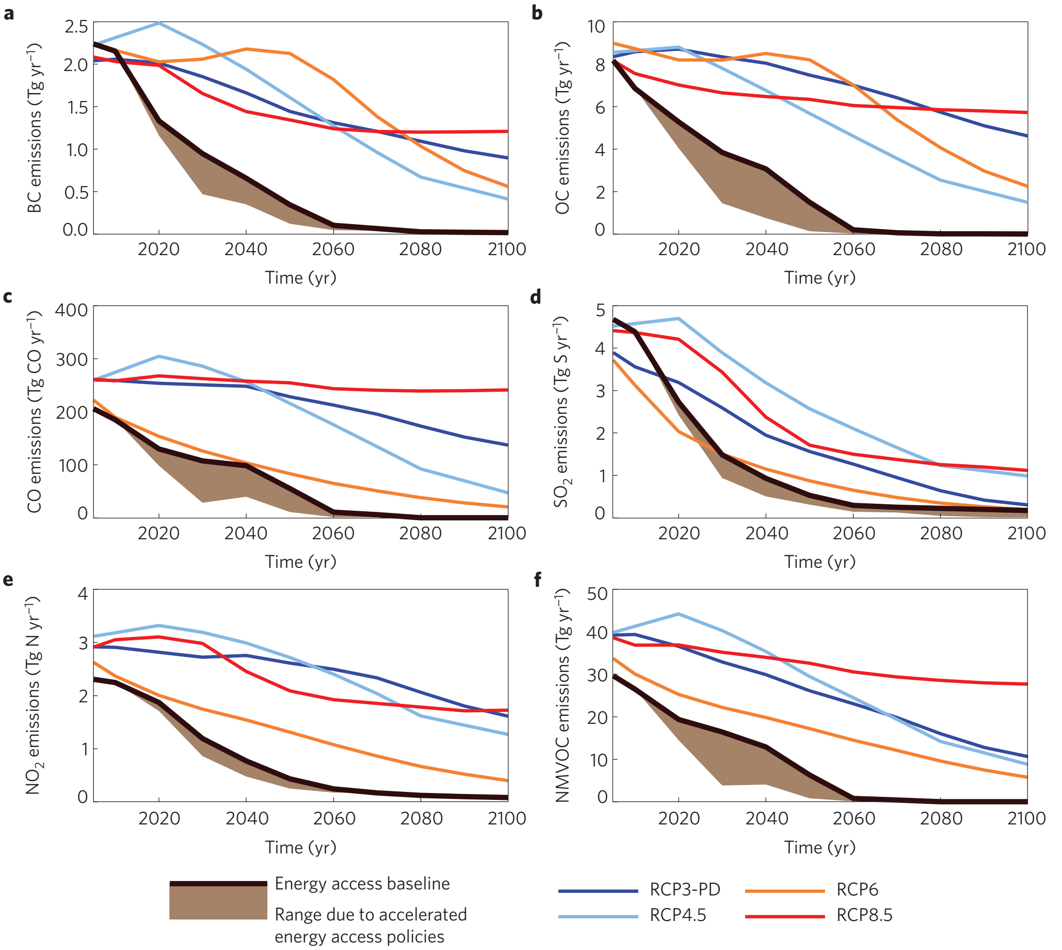

Figure 2 | Influence of energy access policies on air pollutants from the residential and commercial sector. a–f, Results are provided for BC (**a**), OC (**b**), CO (**c**), SO_2 (**d**), NO_2 (**e**) and NMVOC (**f**). Original representative concentration pathway (RCP) emissions are given in blue, 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.

Received 3 January 2014; accepted 3 March 2014; published online 18 May 2014

References

1. Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An overview of CMIP5 and the experiment design. *Bull. Amer. Meteorol. Soc.* **93,** 485–498 (2011).
2. Moss, R. H. *et al.* The next generation of scenarios for climate change research and assessment. *Nature* **463,** 747–756 (2010).
3. Van Vuuren, D. *et al.* The representative concentration pathways: An overview. *Climatic Change* **109,** 5–31 (2011).
4. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* **118,** 5380–5552 (2013).
5. IPCC *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
6. Huber, M. & Knutti, R. Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geosci* **5,** 31–36 (2012).
7. Shindell, D. *et al.* Simultaneously mitigating near-term climate change and improving human health and food security. *Science* **335,** 183–189 (2012).
8. Amann, M., Klimont, Z. & Wagner, F. Regional and global emissions of air pollutants: Recent trends and future scenarios. *Annu. Rev. Environ. Resour.* **38,** 31–55 (2013).
9. Chuwah, C. *et al.* Implications of alternative assumptions regarding future air pollution control in scenarios similar to the representative concentration pathways. *Atmos. Environ.* **79,** 787–801 (2013).
10. McCollum, D. L., Krey, V. & Riahi, K. An integrated approach to energy sustainability. *Nature Clim. Change* **1,** 428–429 (2011).
11. Van Vuuren, D. P. *et al.* Exploring the ancillary benefits of the Kyoto Protocol for air pollution in Europe. *Energ. Policy* **34,** 444–460 (2006).
12. Bollen, J., Hers, S. & van der Zwaan, B. An integrated assessment of climate change, air pollution, and energy security policy. *Energ. Policy* **38,** 4021–4030 (2010).
13. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *J. Geophys. Res.* **118,** 5380–5552 (2013).
14. Riahi, K. *et al.* RCP 85—A scenario of comparatively high greenhouse gas emissions. *Climatic Change* **109,** 33–57 (2011).
15. McCollum, D. *et al.* Climate policies can help resolve energy security and air pollution challenges. *Climatic Change* **119,** 479–494 (2013).
16. Riahi, K. *et al. Global Energy Assessment-Toward a Sustainable Future* Ch. 17, 1203–1306 (Cambridge Univ. Press International Institute for Applied Systems Analysis, 2012).
17. Rao, S. *et al.* Better air for better health: Forging synergies in policies for energy access, climate change and air pollution. *Glob. Environ. Change* **23,** 1122–1130 (2013).
18. Rogelj, J., McCollum, D. L. & Riahi, K. The UN's 'Sustainable Energy for All' initiative is compatible with a warming limit of 2 °C. *Nature Clim. Change* **3,** 545–551 (2013).
19. Pachauri, S. *et al.* Pathways to achieve universal household access to modern energy by 2030. *Environ. Res. Lett.* **8,** 024015 (2013).
20. Van Vuuren, D. *et al.* RCP26: Exploring the possibility to keep global mean temperature increase below 2 °C. *Climatic Change* **109,** 95–116 (2011).
21. Thomson, A. *et al.* RCP45: A pathway for stabilization of radiative forcing by 2100. *Climatic Change* **109,** 77–94 (2011).
22. Van Ruijven, B. *et al.* Modeling energy and development: An evaluation of models and concepts. *World Dev.* **36,** 2801–2821 (2008).
23. Pozzer, A. *et al.* Effects of business-as-usual anthropogenic emissions on air quality. *Atmos. Chem. Phys.* **12,** 6915–6937 (2012).
24. Nakicenovic, N. & Swart, R. *IPCC Special Report on Emissions Scenarios* (Cambridge Univ. Press, 2000).
25. Riahi, K., Gruebler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Soc.* **74,** 887–935 (2007) (Special Issue: Greenhouse Gases—Integrated Assessment).
26. Masui, T. *et al.* An emission pathway for stabilization at 6 W m^{-2} radiative forcing. *Climatic Change* **109,** 59–76 (2011).
27. Granier, C. *et al.* Evolution of anthropogenic and biomass burning emissions of air pollutants at global and regional scales during the 1980–2010 period. *Climatic Change* **109,** 163–190 (2011).
28. Van Ruijven, B. *et al.* Enhancing the relevance of shared socioeconomic pathways for climate change impacts, adaptation and vulnerability research. *Climatic Change* **122,** 481–494 (2014).
29. O'Neill, B. *et al.* A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change* **122,** 387–400 (2013).
30. Rao, S. & Riahi, K. The role of non-CO_2 greenhouse gases in climate change mitigation: Long-term scenarios for the 21st century. *Energy J.* **27,** 177–200 (2006).
31. Amann, M. *et al.* Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environ. Modell. Softw.* **26,** 1489–1501 (2011).
32. Rogelj, J., McCollum, D. L., Reisinger, A., Meinshausen, M. & Riahi, K. Probabilistic cost estimates for climate change mitigation. *Nature* **493,** 79–83 (2013).
33. Pachauri, S. *et al. Global Energy Assessment—Toward a Sustainable Future* Ch. 19, 1401–1458 (Cambridge Univ. Press, International Institute for Applied Systems Analysis, 2012).

Acknowledgements

J.R. was supported by the Swiss National Science Foundation (project 200021-135067).

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.