Environment International 133 (2019) 105147

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Mitigation pathways towards national ambient air quality standards in India

Pallav Purohit[a,*], Markus Amann[a], Gregor Kiesewetter[a], Peter Rafaj[a], Vaibhav Chaturvedi[b], Hem H. Dholakia[b], Poonam Nagar Koti[b], Zbigniew Klimont[a], Jens Borken-Kleefeld[a], Adriana Gomez-Sanabria[a], Wolfgang Schöpp[a], Robert Sander[a]

[a] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[b] Council on Energy, Environment and Water (CEEW), New Delhi, India

ARTICLE INFO

Keywords:
Air quality
Fine particulate matter
Source-apportionment
Population exposure
Emission control costs
Co-benefits

ABSTRACT

Exposure to ambient particulate matter is a leading risk factor for environmental public health in India. While Indian authorities implemented several measures to reduce emissions from the power, industry and transportation sectors over the last years, such strategies appear to be insufficient to reduce the ambient fine particulate matter ($PM_{2.5}$) concentration below the Indian National Ambient Air Quality Standard (NAAQS) of 40 μg/m^3 across the country. This study explores pathways towards achieving the NAAQS in India in the context of the dynamics of social and economic development. In addition, to inform action at the subnational levels in India, we estimate the exposure to ambient air pollution in the current legislations and alternative policy scenarios based on simulations with the GAINS integrated assessment model. The analysis reveals that in many of the Indian States emission sources that are outside of their immediate jurisdictions make the dominating contributions to (population-weighted) ambient pollution levels of $PM_{2.5}$. Consequently, most of the States cannot achieve significant improvements in their air quality and population exposure on their own without emission reductions in the surrounding regions, and any cost-effective strategy requires regionally coordinated approaches. Advanced technical emission control measures could provide NAAQS-compliant air quality for 60% of the Indian population. However, if combined with national sustainable development strategies, an additional 25% population will be provided with clean air, which appears to be a significant co-benefit on air quality (totaling 85%).

1. Introduction

Air pollution is a major global health risk, with India estimated to have some of the worst levels globally (Balakrishnan et al., 2019). To improve air quality and enhance economic and social development, India has issued a National Ambient Air Quality Standard (NAAQS) for annual $PM_{2.5}$ concentrations of 40 μg/m^3 (CPCB, 2009). A wide range of regulations and policies have been implemented to control emissions from the important sources (viz. power plants, transport, etc.) in order to reach compliance with the Indian air quality standards and international guidelines. However, Indian cities rank high in global air pollution for $PM_{2.5}$ which is associated with severe health impacts. Numerous monitoring sites across India report high concentrations (CPCB, 2016), and continuous violations of NAAQS (Fig. S1). According to the World Health Organization (WHO) recent urban air quality database, 13 Indian cities have made it to the world's top 20 worst cities with respect to air pollution (WHO, 2018). It is estimated that only about 1% of the Indian population is exposed to less than the global WHO guideline level of 10 μg/m^3 annual mean $PM_{2.5}$ (IEA, 2016), and the majority of the population faces exposure of more than 35 μg/m^3, i.e., above the highest Target Level 1 defined by the WHO. While pollution is high in cities, health risks posed by air pollution affects urban and rural communities across all socio-economic tiers.

These high pollution levels cause significant health impacts (Balakrishnan et al., 2014; Cohen et al., 2017; Landrigan et al., 2017; David et al., 2019; Hong et al., 2019). While for India their exact quantification remains uncertain, the scientific literature estimates large numbers, ranging between 483,000 and 1,267,000 cases of premature deaths annually from outdoor pollution, and 748,000–1,254,000 cases from indoor pollution (Lim et al., 2012; Forouzanfar et al., 2015, 2016; Chowdhury and Dey, 2016; WHO, 2016; Balakrishnan et al., 2019). It is likely that these health impacts impose a significant burden on the economy; a recent estimate of the World Bank suggests for 2013 welfare losses equivalent to 7.7% of national Gross

* Corresponding author.
E-mail address: purohit@iiasa.ac.at (P. Purohit).

https://doi.org/10.1016/j.envint.2019.105147
Received 21 March 2019; Received in revised form 29 August 2019; Accepted 31 August 2019

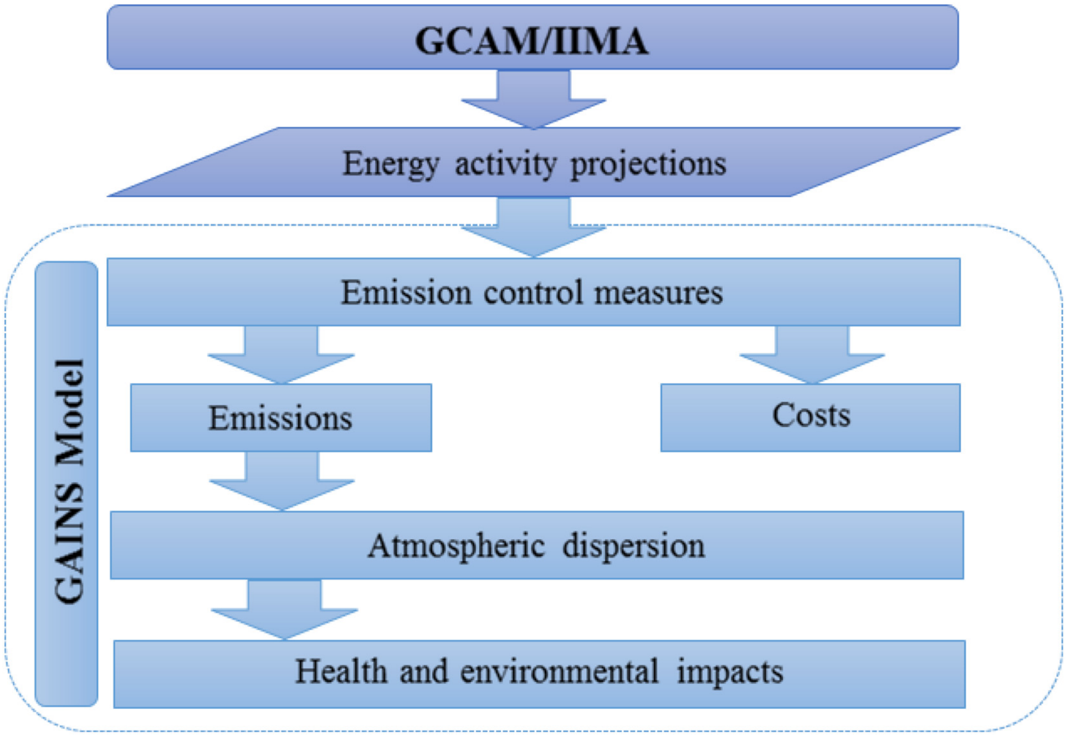

Fig. 1. The methodological approach: Soft linking GCAM-IIMA and GAINS.

Domestic Product (GDP) (World Bank, 2016). An estimate from the OECD suggests that ambient air pollution alone may cost India more than 0.5 trillion dollars per year (OECD, 2014).

Studies identify high ambient $PM_{2.5}$ concentrations in India originating largely from anthropogenic activities such as fossil fuel combustion in power generation, industrial processes, road transport, and solid fuel use in traditional residential cooking (CPCB, 2011; Guttikunda et al., 2014; Pant et al., 2015; Amann et al., 2017; Chowdhury et al., 2018; Gordon et al., 2018; Venkataraman et al., 2018). Without effective countermeasures, air quality can be expected to further deteriorate in the future as a consequence of growing levels of polluting economic activities. However, world-wide experience clearly demonstrates that clean air can be achieved without compromising social and economic development. To be most successful, this requires well-designed policies that prioritize cost-effective interventions for the sources that deliver the largest benefits, and that are well integrated with other development targets.

This study takes an outlook into the likely future evolution of air pollution emissions and ambient $PM_{2.5}$ concentrations and explores pathways towards achieving the NAAQS in India in the context of the dynamics of social and economic development. On top of the likely evolution under the current legislation, we discuss different intervention scenarios and their benefits and costs up to the year 2050, based on calculations with the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) integrated modeling tool (Amann et al., 2011).

The paper is structured as follows. Section 2 introduces the modeling tools used in this study. Key features of the current status of air quality in India, its drivers, resulting population exposure and basic characteristics of the dispersion of pollution in the atmosphere are discussed in Section 3. Section 3 considers future projections on economic development and explores the likely impacts on air quality from the current polices and regulations for energy and air quality. It also explores the scope for air quality improvements offered by advanced technical emission controls as well as from a more comprehensive set of sustainable development priority measures. Costs and benefits of these alternative policy interventions scenarios are discussed in Section 4, and conclusions are drawn in Section 5.

2. Methods and data

2.1. Approach

Exploring the effectiveness of alternative policy interventions on ambient air quality requires an integrated perspective that brings together a wide range of relevant aspects. These include demographic, social and economic development trends, urbanization, knowledge of the emission sources, technological and economic information of possible emission controls, the chemical and physical processes in the atmosphere, and health impacts caused by air pollution. To conduct such an assessment for India, this study employs a multi-disciplinary scientific framework consisting of two well-established scientific modeling tools: The Global Change Assessment Model (GCAM) model (see Section 2.2.1) investigates the socio-economic drivers of pollution, with special emphasis on the energy sector (including power, industry, transport, etc.). These are then fed into the GAINS model (see Section 2.2.2) to assess the effectiveness of policy interventions on population exposure and health impacts. Findings are derived from a comparison of scenarios of future air quality that quantify the impacts of alternative policy interventions. These scenarios explore, for 2030 and 2050, the likely future consequences of

- The emission control measures that were already implemented in 2015,
- The additional policies and measures that have been decided after 2015,
- The potential benefits from full application of advanced technological emission controls, and
- The co-benefits on air quality of sustainable development measures that are usually taken for other policy objectives.

2.2. Modeling tools

This study links two scientific modeling tools, i.e., the GCAM energy model developed at the Joint Global Change Research Institute (JGCRI), and the GAINS air pollution model, developed at the International Institute for Applied Systems Analysis (IIASA) (Fig. 1).

2.2.1. The GCAM model

For projections of future economic activities, the study employs energy use pathways generated with the GCAM model for India by the Council on Energy, Environment and Water (CEEW). Details of the GCAM model are provided in the supplementary information (SI) (section S.1). For India, GCAM has been customized by the Indian Institute of Management Ahmadabad (IIMA). The GCAM-IIMA model holds more detail on the building sector in India, distinguishing urban residential, rural residential and commercial building sectors. The energy demand in the transportation sector is modeled for passenger transport (road, rail and aviation), freight transport (road and rail), and international shipping with the demand for each service being driven by per-capita GDP. The industrial sector in GCAM-IIMA is modeled in an aggregate way, with industrial service demand responding to income growth and fuel prices. In GCAM-IIMA, increasing income induces higher demand of energy-services (e.g. cooling, mobility, cooking, appliances), and enhances the penetration of technologies and fuels for providing these services (e.g. electricity-based air-conditioners, oil-based cars, LPG based stoves). Alternative technologies compete on relative costs and efficiencies to provide energy for any given service in end-use sectors.

2.2.2. The GAINS model

The GAINS model developed by the International Institute for Applied Systems Analysis (IIASA) provides an authoritative framework for assessing strategies that reduce emissions of multiple air pollutants and greenhouse gases (GHGs) at least costs, and minimize their negative effects on human health, ecosystems and climate change (Amann et al., 2011; Sanderson et al., 2013; Klimont et al., 2017). GAINS describes the pathways of atmospheric pollution from anthropogenic driving forces to the most relevant health and environmental impacts. It brings together information on future economic, energy and agricultural development, emission control potentials and costs, atmospheric dispersion and environmental sensitivities towards air pollution as shown in the SI (section S.2). The GAINS model has been applied widely for policy analyses in Europe (Amann et al., 2011), South Asia (Purohit et al., 2010, 2013; Dholakia et al., 2013; Mir et al., 2016; Amann et al., 2017; Bhanarkar et al., 2018; Karambelas et al., 2018) and East Asia (Amann et al., 2008; Klimont et al., 2009; Zhao et al., 2013; Chen et al., 2015; Dong et al., 2015; Hong et al., 2019; Liu et al., 2019).

The Indian version of the GAINS model that is used for this study has a disaggregated representation of India in 23 sub-regions (Section S.2). The national energy projections supplied by GCAM-IIMA are allocated across Indian States using the proportional downscaling algorithm reported in Rafaj et al. (2013). For each of the states/regions considered in GAINS, the emission estimates for a particular emission control scenario consider (1) the detailed sectoral structure of the emission sources; (2) their technical features (e.g., fuel quality, plant types); and (3) the emission controls applied (GAINS includes a database of over 1000 technical measures). We have used New Policies Scenario (NPS) of the IEA's World Energy Outlook 2017 to analyze the impact of sources outside India. For each key source sector,[1] the spatial distribution patterns of PM and its precursor emissions are then estimated at a $0.5^0 \times 0.5^0$ longitude–latitude resolution (Klimont et al., 2017), based on relevant proxy variables. These estimates use the most recent data on population distribution, road networks, plant locations, open biomass burning, etc. that were originally developed within the Global Energy Assessment project (GEA, 2012).

For a given set of current or future emissions that emerges as a consequence of economic growth and the application of emission control measures, the GAINS model estimates the resulting ambient concentration fields. Due to their small size, $PM_{2.5}$ particles remain in the atmosphere for several days and are transported with the wind during this time, typically over several hundreds to 1000 km. To represent this long-range transport of pollution, GAINS considers the contributions from emissions within the particular State/region of interest as well as the inflow from the rest of India and neighboring countries. For this purpose, linear transfer coefficients are used that describe the impacts of emission changes at each source on ambient $PM_{2.5}$ concentrations throughout the model domain (Kiesewetter et al., 2015; Liu et al., 2019). Such coefficients have been derived from computations with the European Monitoring and Evaluation Programme (EMEP) chemistry transport model (Simpson et al., 2012) in which, for the meteorological conditions of 2015, emissions of one pollutant (primary $PM_{2.5}$, SO_2, NOx, NH_3, NMVOC) from one source region (each Indian State) were reduced by 15% at a time. The linearization of atmospheric calculations is a simplification which has been used in all regional implementations of GAINS so far, as it enables efficient scenario comparison as well as source attribution due to fast computation times. Uncertainties introduced by this step have been discussed by Amann et al. (2011); typically, biases are small enough to justify the use of the linearized approach.

For primary PM, the sensitivity simulations were done separately for low-level sources (residential and road transport) and all other sources, so that the different spatial distributions and dispersion characteristics of ground-level versus high-stack sources are properly reflected. Considering that (1) high stack sources disperse pollution across large areas, and (2) the formation of secondary aerosols occurs on longer spatial and temporal scales, a $0.5^0 \times 0.5^0$ spatial resolution is considered sufficient for the dispersion of primary PM emissions from high stack sources and the formation and transport of secondary aerosols. However, the dispersion patterns of primary $PM_{2.5}$ emissions from low-level sources of primary PM show strong local gradients. These are reflected for Delhi NCT through the application of the GAINS-City Delhi model (Amann et al., 2017; Bhanarkar et al., 2018), which has been developed with a 2 km × 2 km resolution. For other cities with more than 100,000 inhabitants, finer spatial detail is added based on fine-scale population distribution data (www.worldpop.org (Gaughan et al., 2013)) with 100 m × 100 m resolution (Rafaj et al., 2018). The fine-resolved population data are used in conjunction with urban polygon shapes from the Global Rural-Urban Mapping Project (CIESIN, 2011) to distribute emissions of residential sources, and to downscale calculated ambient concentrations to urban and rural parts of each grid cell (Liu et al., 2019).

Results are presented in form of (1) maps showing the fields of ambient concentration of $PM_{2.5}$, (2) population-weighted mean concentration of $PM_{2.5}$ for each Indian State/region, and (3) source apportionment. Population-weighted mean concentrations are computed by overlaying the calculated fields of ambient $PM_{2.5}$ concentrations with gridded population data, i.e., with a 100 m × 100 m resolution for cities with more than 100,000 inhabitants, and with a $0.5^0 \times 0.5^0$ resolution for the other areas. For future years, calculations consider urbanization trends following the projections of population growth for urban and rural areas (based on the UN World Urbanization Prospects 2011 (UNDESA, 2012)). Source apportionment charts are generated by the same methodology, however not summing up over all individual contributions of emissions from different source regions, sectors, and pollutants, after multiplying them with the respective atmospheric transfer coefficients.

[1] Source sectors and sources have been used interchangeably in this study.

Table 1
Scenario description.

Scenario	Activity projections	Air pollution control policies
1. 2018 air pollution legislation	GCAM-IIMA baseline projections	Current legislation implemented until June 2018
2. 2015 policies and measures		Current legislation implemented until 2015
3. Advanced emission control technology		Advanced emission control technologies
4. Sustainable development measures	GCAM-IIMA 2 °C *decarbonization scenario*	Advanced emission control technologies

2.2.3. Emission scenarios

In this study we have analyzed the a) evolution of air quality under current legislations, and b) scope for further air quality improvements (see Table 1 below). We have analyzed two scenarios: the "2015 policies and measures" scenario and the '2018 air pollution legislation' or baseline scenario under the evolution of air quality under current legislations. The "2015 policies and measures" scenario exclude all emission regulations that have been enacted after 2015 whereas the '2018 air pollution legislation' scenario includes all emission regulations/standards that were in force in mid-2018. Under the scope for further air quality improvements we have analyzed two additional scenarios: a) advanced emission control technology (ACT) scenario assuming more stringent standards in India (with a 10 years delay compared to other industrialized countries) and b) sustainable development measures scenario (SDS) exploring response strategies to the 2 °C temperature increase limit by 2100 (Chaturvedi et al., 2018) along with ACT measures and additional emission controls for non-industrial sources (e.g. clean cookstoves, road paving). Further details on emission scenarios are provided in sections 3.3 and 3.4.

2.2.4. Data sources

The assumptions on macro-economic development taken in this study follow the medium economic growth rate projections of NITI Aayog,[2] with an annual GDP growth rate of 6.7% from 2012 to 2047. Urbanization is assumed to increase to about 50% in 2050, and it is assumed that income inequalities between urban and rural populations will decline in the future. As a consequence of the current program to provide clean cooking fuel to households, in the baseline it is assumed that biomass will be entirely replaced by alternative cooking fuels by 2040 in rural area and by 2030 in urban area (Table S8). Assumptions and data sources of the GCAM-IIMA model are described in detail in the SI (section S.3).

Nation-wide GCAM-IIMA projections of future economic activities provided by CEEW have been downscaled to the State level in the GAINS model, and supplemented with additional data on the structure of transport sources (cars, trucks, motorcycles and mopeds) and the split of liquid fuels used in the residential sector for cooking and lighting, etc. Activity data that cause non-exhaust emissions from mobile sources, as well as industrial process emissions (production of energy-intensive products, agricultural activities, storage and handling of materials, waste treatment, etc.) were derived from the GAINS database.

The GAINS model provides routines and default emission information for a wide range of sources, emerging from the experience that has been accumulated with GAINS model applications around the world over the last 30 years. While these encompass a wide range conditions under very different technological and development stages, they are not necessarily applicable to all emission sources that are important in India. Significant efforts have been undertaken to compile input data for GAINS from Indian statistics and more work is required to confirm and improve the current database.

[2] India Energy Security Scenarios (IESS) of the National Institution for Transforming India (NITI Aayog), Govt of India, New Delhi (See: http://iess2047.gov.in).

3. Results

Using the soft-coupled GCAM-IIMA and GAINS models described above, we analyze India's air quality in the current situation (Section 3.1), the macroeconomic trends driving future evolution (Section 3.2), the likely future evolution of air quality if current legislation is effectively enforced (Section 3.3), and the scope for intervention measures (Section 3.4). We show maps of ambient annual mean $PM_{2.5}$ concentrations, population exposure distribution, and source contributions to ambient $PM_{2.5}$.

3.1. Understanding of the current situation

3.1.1. Emissions of $PM_{2.5}$ and its precursor substances

Using the regional activity statistics, it is estimated that in 2015 (taken as base year) about 9.8 megatons (Mt) of SO_2, 7.2 Mt. of NO_x, 5.8 Mt. of primary $PM_{2.5}$ and 7.9 Mt. of NH_3 were emitted in India.[3] The largest populous State of India – Uttar Pradesh – contributes the largest share of $PM_{2.5}$ emissions (14%) primarily due to the large number of households using solid fuels for cooking whereas Maharashtra, the second largest populous State, contributes the largest shares of SO_2 (12%) emissions in the national total (Fig. 2) due to the highest installed capacity of thermal power plants. In 2015, 6 States namely Maharashtra, Tamil Nadu, Gujarat, Uttar Pradesh, Andhra Pradesh and Rajasthan contributed half of the total NOx emissions of the country. Maharashtra contributes the largest share of NO_x emissions (10%) followed by Tamil Nadu (9.5%) due to the high vehicle density and limited controls in power plants. Uttar Pradesh – the top producer of food grain in India – contributes the largest share of NH_3 emissions predominantly from the agriculture and waste sector.

For SO_2, almost 82% of total emissions originated from power generation and industrial energy combustion. 45% of NO_x emissions are estimated from mobile sources, while industrial sources contributed 16% and the power sector 30%. The largest sources of $PM_{2.5}$ were the residential sector (52%) with its incomplete combustion of solid fuels, and the industrial sector (18%). NH_3 emissions were predominantly released from agricultural activities - livestock farming, fertilizer application, manure management, etc. (Fig. S2).

Most noteworthy, the relative contributions to total emissions differ significantly across the Indian States. For instance, solid fuel (biomass) combustion for residential cooking is most important in the major states of the Indo-Gangetic Plain, while it has a very small contribution in Delhi NCT and Goa due to the enhanced access to clean fuels in these States. In contrast, transportation makes the largest contributions to NO_x emissions in Delhi NCT, and SO_2 emissions from the power plant sector dominate in Haryana and Maharashtra (Fig. S2).

3.1.2. Ambient concentrations of $PM_{2.5}$

According to the estimates with the GAINS model, largest $PM_{2.5}$ concentrations (Fig. 7) occur in the Indo-Gangetic Plain due to the high density of polluting sources and reduced ventilation caused by the obstruction from the Himalayas. Elsewhere in the nation high concentrations coincide with densely populated areas or large cities. A

[3] See: GAINS scenario < NAAQS_GCAM_REF_CLE_V2 > available at: http://gains.iiasa.ac.at/gains/INN/index.login

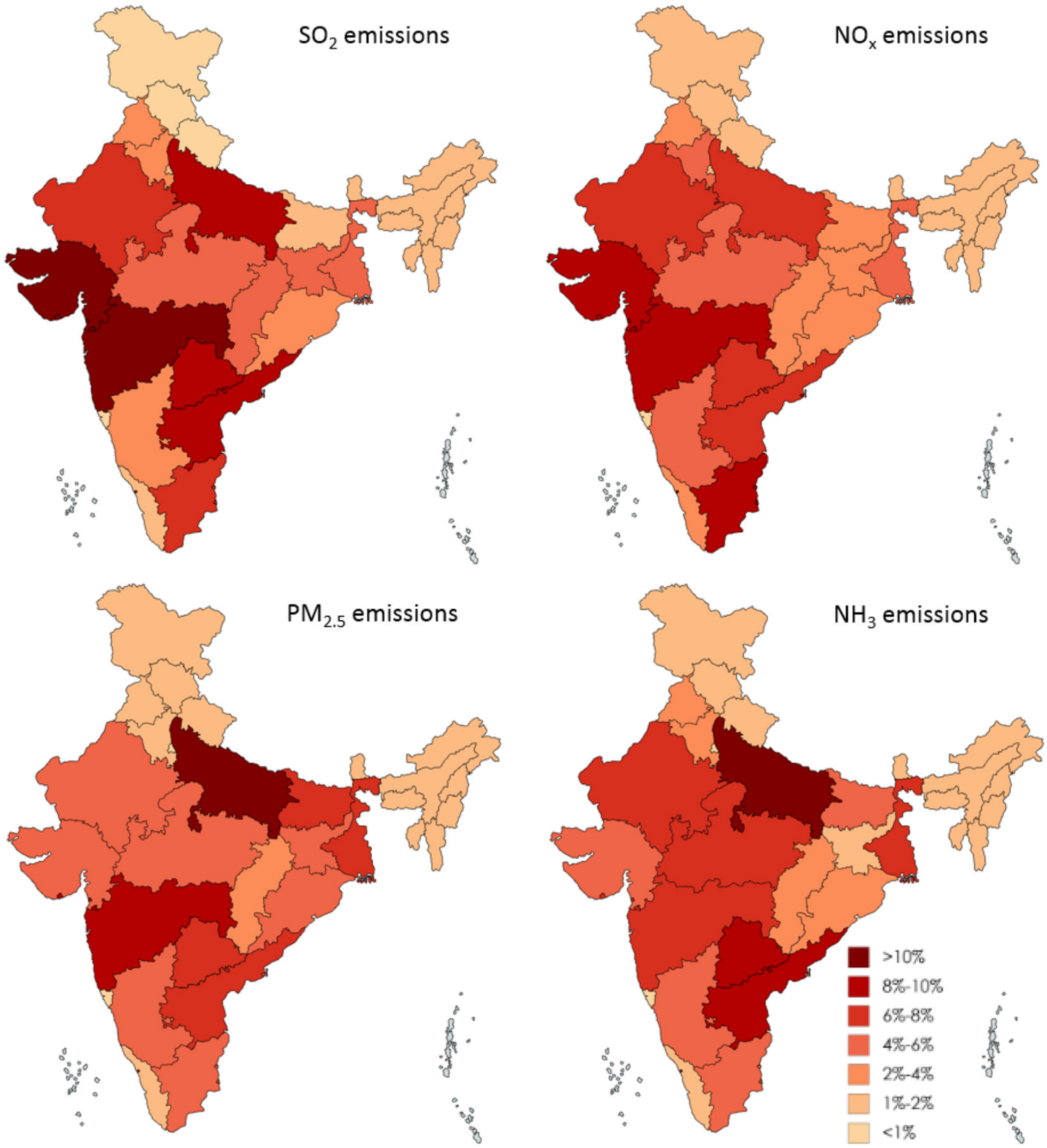

Fig. 2. State-wise contribution (in %) to the $PM_{2.5}$ precursor emissions in India, estimated in this study for 2015, by region.

north–south gradient is observed for the pollutants (Fig. 7), which is certainly influenced by the emission distribution (maximum in northern India, in the Indo-Gangetic Plain) as well as the direction of advection in air (prevailing westerly, with northerly component). Moreover, there is a clear North-South gradient in $PM_{2.5}$ concentrations: concentrations reach 126 μg/m^3 in Delhi NCT, and range between 40 and 70 μg/m^3 in all Northern, Western, Eastern and Northeastern States of IGP. About 661 million people living there are exposed to ambient concentrations (far) above the NAAQS. Concentrations fall to levels between 20 and 30 μg/m^3 in the Southern States, totaling a resident population of about 250 million people. Cleanest air is found in the Himalayan States (viz. Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Sikkim and Arunachal Pradesh) with computed annual $PM_{2.5}$ concentrations as low as 15 μg/m^3 due to low level of economic activities and population density (Fig. S3). This means that further action is required to comply with NAAQS in all northern States,[4] while southern States need to ensure that their future economic development will not compromise air quality. A comparison of modeled $PM_{2.5}$ concentrations to observations is shown in the SI (Section S.2.1). Although there is considerable scatter, overall the model seems to reproduce observed concentrations reasonably well.

3.1.3. Population exposure to $PM_{2.5}$

While absolute levels of $PM_{2.5}$ concentrations are relevant for compliance with the NAAQS, health impacts of pollution – and health benefits from policy interventions – are linked to population exposure, i.e., how many people are exposed to different levels of $PM_{2.5}$. Total population-weighted average exposure is estimated at 44 μg/m^3, which is somewhat lower than other recent estimates (Chowdhury et al., 2019; GBD MAPS Working Group, 2018); the main difference in particular to the latter study seems to be a lower contribution of natural dust in the GAINS model (as obtained from the EMEP CTM), which is a very uncertain component in atmospheric modeling.[5] For 2015, the model

[4] In our definition, all the states in Indo-Gangetic Plains and three hilly states in north (Jammu and Kashmir, Himachal Pradesh and Uttarakhand) are northern states.

[5] Natural component includes inside state, neighboring states, long-range within India and outside India – all lumped together.

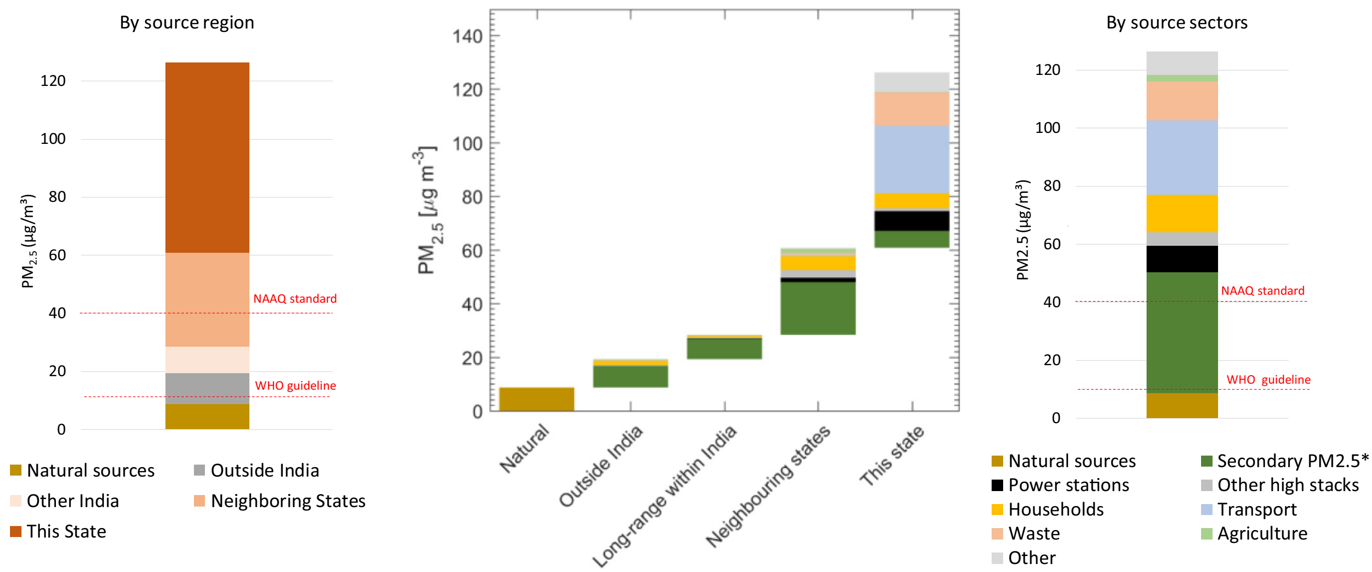

Fig. 3. Sources of $PM_{2.5}$ concentrations (population-weighted annual mean) in Delhi NCT in 2015. The x-axis distinguishes the spatial origin of $PM_{2.5}$, i.e., from left to right: i) total from natural sources (soil dust, sea salt, wildfires) without distinction of geographical origin, ii) anthropogenic emissions from other countries, iii) anthropogenic emissions from non-neighboring Indian States, iv) anthropogenic sources in the neighboring States (Uttar Pradesh and Haryana), and v) anthropogenic emission sources within the Delhi NCT.

analysis suggests that about 616 million people in India have enjoyed air quality that conforms to the national air quality standard, while almost 677 million people were exposed to higher concentrations (Fig. S4) and only < 1% enjoyed air quality conforming with the global WHO guideline value of 10 µg/m^3. Highest population exposure occurred in the States in the Indo-Gangetic Plain. A full exposure distribution is shown in Fig. 10 (in comparison to future scenarios analyzed in this study).

3.1.4. Source apportionment

Source apportionment figures that quantify the contributions from the different emission sources and regions to ambient $PM_{2.5}$ in a given region are helpful to inform analyses of (cost-effective) response measures that could improve population exposure and bring down ambient concentrations to national and international air quality standards. Using the methodology described in Section 2.2.2, the GAINS tool can produce source apportionments for any location or State within the model domain, distinguishing contributions originating from different economic sectors as well as geographical origin in each emission source region considered in the model (i.e., Indian States).

For instance, for the National Capital Territory (NCT) of Delhi (Fig. 3) it is estimated that approximately half of the population exposure to $PM_{2.5}$ is caused by emissions within the NCT territory. Another 50% of $PM_{2.5}$ in ambient air in Delhi NCT is transported into the city from outside, out of which about half comes from the surrounding States Haryana and Uttar Pradesh, and rest from even more remote anthropogenic sources and natural sources. Furthermore, the sectoral source apportionment indicates that about 20% of $PM_{2.5}$ in ambient air originates from primary $PM_{2.5}$ emissions from mobile sources (exhaust and non-exhaust emissions), and about 10% from household fuels and waste management, respectively. About one third consists of secondary $PM_{2.5}$, formed from SO_2 and/or NO_x emissions through chemical reactions with NH_3 from agricultural sources.

As to be expected, the relative importance of emission sources for ambient $PM_{2.5}$ concentrations varies widely over India, due to differences in orographic and meteorological conditions, population densities and the structure of emission sources. In general, smaller States and especially cities experience larger inflow of pollution from the surroundings than larger territorial units (Fig. S5). For instance, despite of the large size of Punjab with about 28 million inhabitants, only ~40% of population-weighted mean ambient $PM_{2.5}$ originates from emission sources within the domain of the Punjab State of India (Fig. 4a). Another 60% of $PM_{2.5}$ in ambient air in Punjab is transported from outside, out of which about half comes from the regions outside India and another half from other States in India and natural sources. Even in Uttar Pradesh, with currently about 200 million inhabitants, only about 50% of population-weighted $PM_{2.5}$ originates from local emission sources. Detailed source apportionment estimates for all States are provided in the SI (section S.4).

The share of secondary $PM_{2.5}$ varies from 27% in the North-eastern States to 55% in the Odisha State, due to high emissions of SO_2, NO_x and NH_3 (Fig. 4b). Even in Delhi NCT, one third of $PM_{2.5}$ consists of secondary aerosols as shown in Fig. 3. These secondary inorganic and organic particles are formed in the atmosphere through reactions of primary gaseous pollutants (nitrogen oxides NO_x, ammonia NH_3, sulfur dioxide SO_2 and non-methane volatile organic compounds NMVOCs). In contrast to widespread belief, road traffic is not the dominating source.

3.2. Macroeconomic trends driving future air quality

To explore the effectiveness of alternative policy interventions on air quality in the context of the rapid social and economic development in India, this study develops a range of future emissions scenarios and assesses their impacts on ambient $PM_{2.5}$ concentrations, population exposure and emission control costs. All projections are based on a common set of assumptions on macro-economic development, and illustrate the impacts of different energy and air quality policy interventions.

The baseline projection of population and economic development follows the recent plans of the Indian government as characterized in the India Energy Security Scenarios (IESS) 2047 tool developed by NITI Aayog (GoI, 2015). It assumes an annual population growth in India of 1.2% per year until 2030 and of 0.46% per year thereafter, resulting by 2050 in a 31% larger population than in 2015 (Fig. S6a). At the same time, economic wealth (expressed as GDP/capita) will improve by 5% per year, which results in an almost 10 times higher total economic output (GDP) in 2050 (Table S1).

Corresponding projections of energy use have been developed with the GCAM-IIMA model (Section 2.2.1). Notably, these reflect the

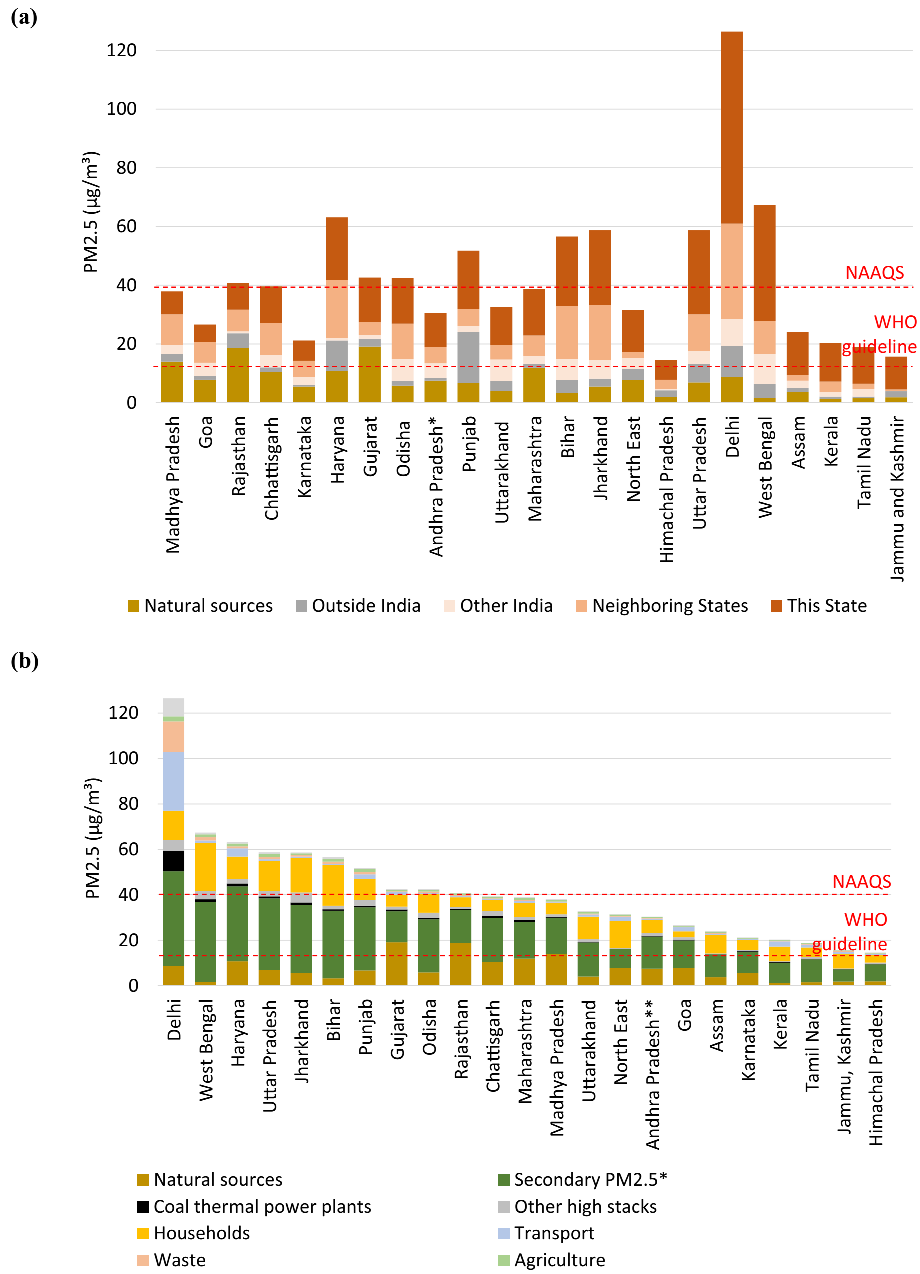

Fig. 4. a) Spatial origin of ambient $PM_{2.5}$ exposure in the Indian States, 2015 (ranked by decreasing shares of pollution inflow); b) Sectoral origin of population-weighted ambient $PM_{2.5}$ exposure in the Indian States in 2015. (*) Secondary inorganic and organic aerosols (**) Including Telangana.

current climate and energy policies and regulations (see: Section S.5), as well as relevant policy intentions of the Indian Government, in particular the targets for renewables and coal and the push to provide universal, reliable electricity access. These interventions in the energy sector offer significant opportunities for reducing both GHGs and other health-damaging pollution (West et al., 2013; Markandya et al., 2018; Vandyck et al., 2018). Thereby, total primary energy consumption increases by a factor of 3.2 between 2015 and 2050, with a general shift towards cleaner fuels. Biomass use is projected to decline by two thirds, primarily due to the promotion of clean cooking with liquefied petroleum gas (LPG), including free connections to poor rural households. In contrast, the highest increases are anticipated for other renewables (wind, solar, hydropower) and for nuclear energy (by a factor of 14 and 9, respectively), and oil and gas consumption will increase 4.3 and 6.6 times (Fig. S6b).

3.3. Evolution of air quality under current legislation

3.3.1. The 2015 policies and measures

In 2015, India has already implemented a range of emission control measures, mainly controls of primary particulate matter (dust) at large stationary sources (power plants) and measures to reduce exhaust emissions from road vehicles (Table S2). As a benchmark for further analyses, a '2015 measures' scenario explores the positive effects on future air quality of the measures that have already been implemented on the ground and combines them with economic growth projections and their accompanying structural changes. This scenario thus excludes all emission regulations that have been enacted after 2015. Since 2010, the existing measures have effectively decoupled the trends of air pollutant emissions from economic growth (Fig. 5). However, their impacts on ambient air quality are not directly visible since they are offset by the rapid expansion of economic activities. This will prevail in the

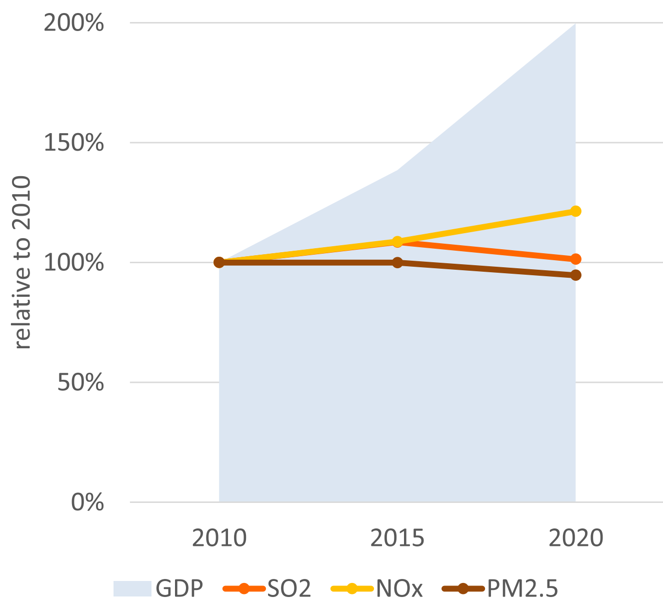

Fig. 5. Trends of GDP and emissions of SO_2, NO_x and primary $PM_{2.5}$ in India, 2010–2020.

future, and the already implemented measures will not be sufficient to halt a further deterioration in air quality in view of the 10-fold increase in GDP that is expected up to 2050 (Table S1).

3.3.2. The '2018 air pollution legislation' scenario

To provide a reference for assessing the effectiveness of additional policy interventions, the '2018 legislation' emission scenario illustrates the impacts of a timely implementation and effective enforcement of all emission control measures, regulations and standards that were in force by mid-2018, in particular those that have been decided after 2015 (Table S3). Further details are provided in the SI (sections S.5–S.6).

3.3.2.1. Emission controls. In particular, this scenario assumes full success of the latest policies to provide access to clean fuels for poor households (see Section S.5). For stationary sources, it assumes effective implementation of the current PM, SO_2 and NO_X emission standards (MoEFCC, 2015) for power plants and industrial combustion sources (see Section S.6). For mobile sources (road and off-road), the 2018 legislation scenario considers the Indian Bharat Stage (BS) emission standards for historic years,[6] and assumes introduction of the BS-VI stage to new all on-road vehicle categories after 2020 (MoRTH, 2016) and for as well as BS-IV for non-road machinery from 2020 followed by BS-V from 2024 (ICCT, 2018).

3.3.2.2. Emissions. Timely and effective implementation of the 2018 air pollution control legislation will have significant impact on future emissions in India and enable ambitious economic growth lifting millions of people out of poverty without major further increases in PM precursor emissions. Particularly until 2030, full implementation of current regulations should allow reduction of emission levels, while beyond 2030 continued economic growth will offset some of the positive impacts of current legislation (Fig. 6).

Effective implementation of the recent regulations for the power sector (MoEFCC, 2015) will cut total national SO_2 emissions by half in 2030, although without further controls the continued growth in energy use will offset much of these achievements thereafter. However, emissions from industrial activities remain high, and little progress is foreseen for this sector. For NO_x, current legislation, if effectively implemented, will achieve significant cuts in the power sector and for mobile sources in the coming 20 years, but emissions are expected to rebound afterwards. However, no trend reversal can be anticipated for industrial sources, and by 2050 total NO_x emissions in India could be 30% higher than in 2015.

For $PM_{2.5}$ emissions, current policies and plans should deliver large reductions in the emissions from the residential sector, mainly due to the enhanced access to clean fuels (LPG, electricity, solar) under the *Pradhan Mantri Ujjwala Yojana* (PMUY[7]) scheme (Kar et al., 2019). Also, for the power sector, $PM_{2.5}$ will decrease as a consequence of flue gas desulphurization (FGD) and Electrostatic precipitator (ESP) controls. No major net changes are expected for emissions from mobile sources, as the decline of exhaust emissions from the Bharat-VI standards will be offset by the anticipated increase in the vehicle fleet, and in particular by the higher non-exhaust emissions (road dust, tire and brake wear). Most notably, the absence of stringent regulations will let $PM_{2.5}$ emissions from the industrial sector increase by a factor of three following the increase in industrial production.

3.3.2.3. Air quality. We estimate that by 2030, the reductions in $PM_{2.5}$ and SO_2 emissions that are expected from the full implementation of the 2018 legislation will show positive impacts on ambient $PM_{2.5}$ levels throughout India (Fig. 7a). On average, concentrations will decline by about 14% compared to 2015 (Table S4), and the highest (population-weighted) concentrations – computed for Delhi NCT - will decline from 126 in 2015 to 114 $\mu g/m^3$. However, after 2030 concentrations could rebound again, and exceed the 2015 levels substantially by 2050.

While the 2018 legislation will enable significant economic growth without major changes in current air pollution levels, effective implementation of the new regulations and policies introduced after 2015 will be critical. Without these measures, ambient $PM_{2.5}$ concentrations levels would increase by 40% in 2030 and double by 2050, reaching unprecedented levels of more than 250 $\mu g/m^3$ (Fig. S7a).

As mentioned in the methodology description (Section 2), in our approach meteorological fields are fixed to the year 2015 to demonstrate the effects of emission changes under otherwise constant conditions. It is well possible that meteorological patterns change under a changed future climate and lead to a modification of population exposure independent of emission changes (Chowdhury et al., 2018).

3.3.2.4. Population exposure to $PM_{2.5}$. By 2030, stringent implementation of 2018 legislation will bring approximately 55% of the population (833 million people) within the exposure level under the NAAQS limit ($\leq 40\ \mu g/m^3$), compared to 516 million people in 2015 (Table S5). However, by 2050 the number of people within NAAQS limit will decrease to 44% (745 million people). Approximately, 930 million people will be exposed to concentrations above the NAAQS standard if no further action is taken (see Fig. 10 below).

3.3.2.5. Source contributions to ambient $PM_{2.5}$. Economic development combined with the source-sector specific emission controls of the 2018 legislation will lead to differentiated trends in the sectoral emissions across India, and consequently also alter the (relative and absolute) contributions made by different emission sources to ambient $PM_{2.5}$ concentrations. As mentioned above, full implementation of the 2018 legislation should deliver an overall decline of ambient $PM_{2.5}$ levels of

[6] Indian emission standards for four-wheel vehicles started in 2000 onwards by implementing India 2000 (equivalent to Euro-I).

[7] Pradhan Mantri Ujjwala Yojana (PMUY) is a scheme of the Ministry of Petroleum & Natural Gas (MoPNG), Government of India for providing liquefied petroleum gas (LPG) connections to women from Below Poverty Line (BPL) households. As of June 2017, over 10 million people switched away from solid fuels, and it is envisaged to provide free LPG connections to a total of 80 million poor households by 2020 with more than 73 million already installed by June 2019.

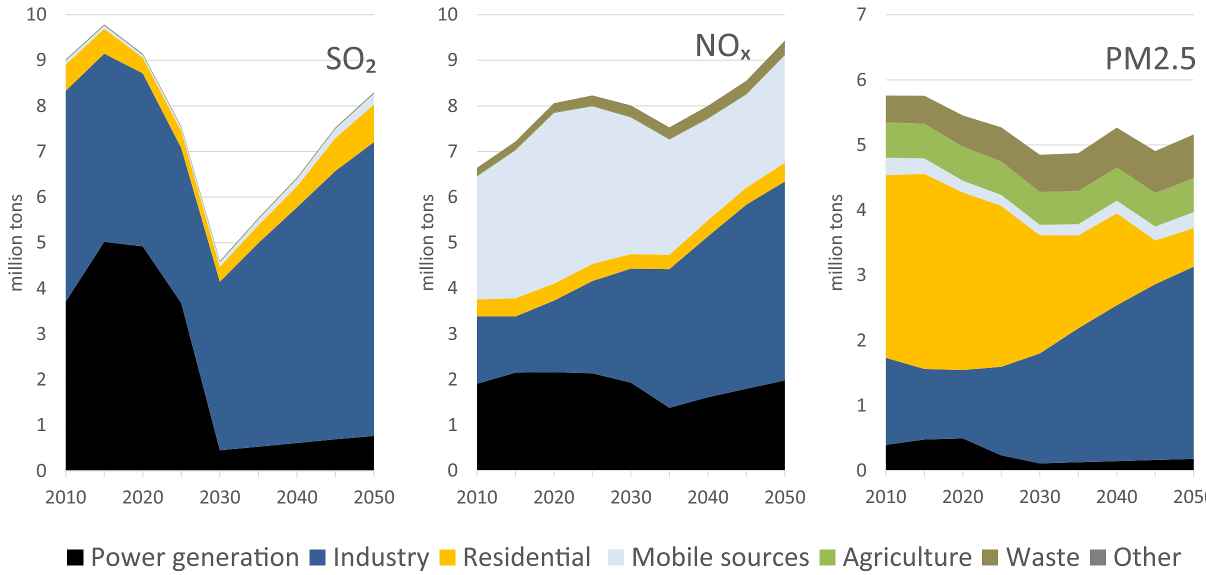

Fig. 6. Air pollutant emissions by sector in the 2018 legislation scenario.

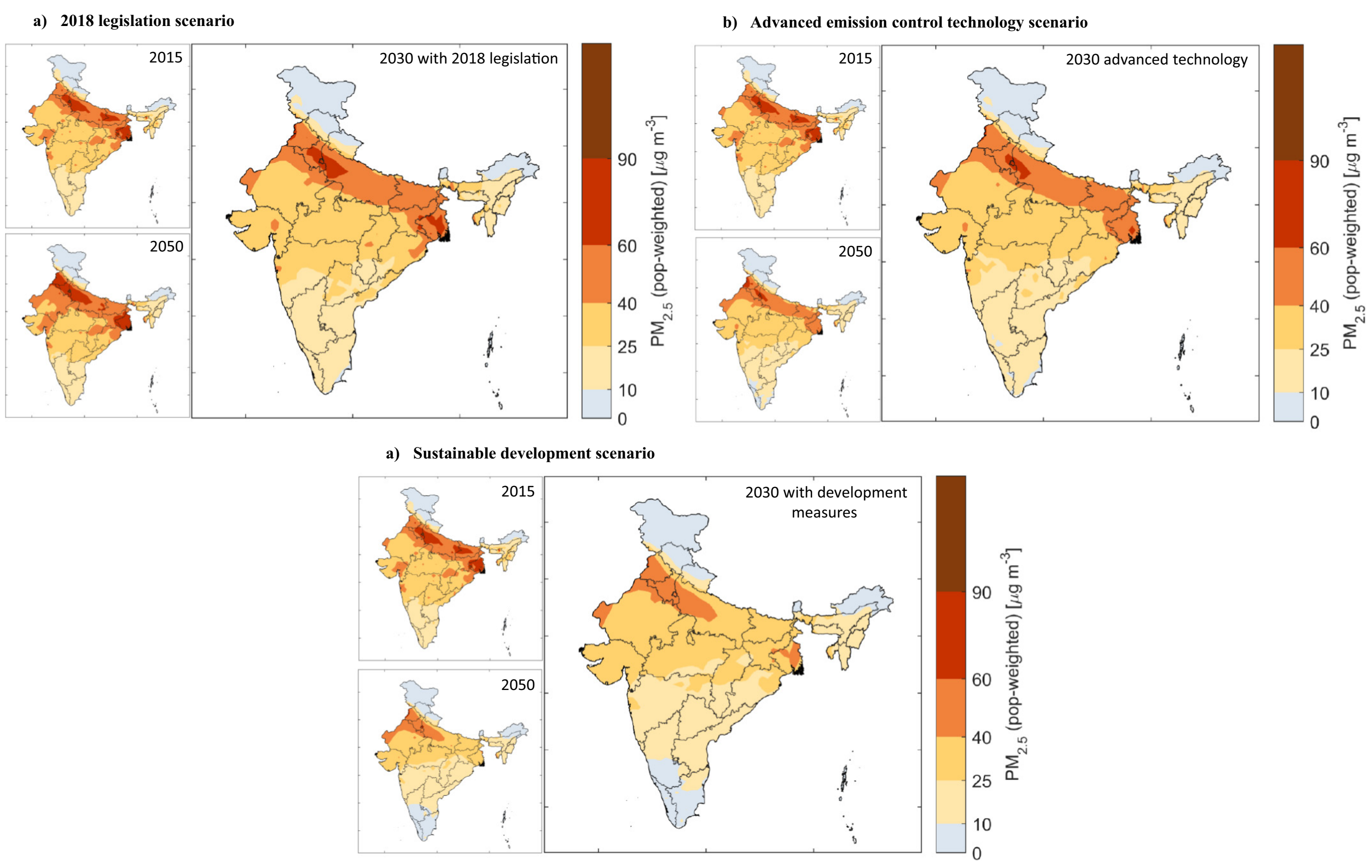

Fig. 7. Ambient concentrations of $PM_{2.5}$, in a) 2015 and for the 2018 legislation scenario in 2030 and 2050; b) 2015 and for the advanced technology scenario in 2030 and 2050; and c) 2015 and for the sustainable development scenario in 2030 and 2050.

about 14% by 2030. However, this improvement is a composite result of diverging trends in different sectors: Current regulations are expected to decrease the contribution of primary PM emitted in the power sector by up to 90%, and those of the transport and residential sectors by typically 40%. In contrast, lacking emission controls will increase the contributions from industrial sources by typically 50% (Fig. 8a). Secondary particles will still contribute a significant share of $PM_{2.5}$ over large regions in India (up to 60% in Punjab), while natural sources will remain dominating in Rajasthan and Gujarat. This source attribution provides relevant input for the prioritization of additional policy interventions to move closer to national and international air quality standards.

Furthermore, inter-State transport of pollution in the atmosphere will continue to play an important role, so that effective air quality management in India will continue to require coordination and co-operation between States. Especially in the Indo-Gangetic Plain where

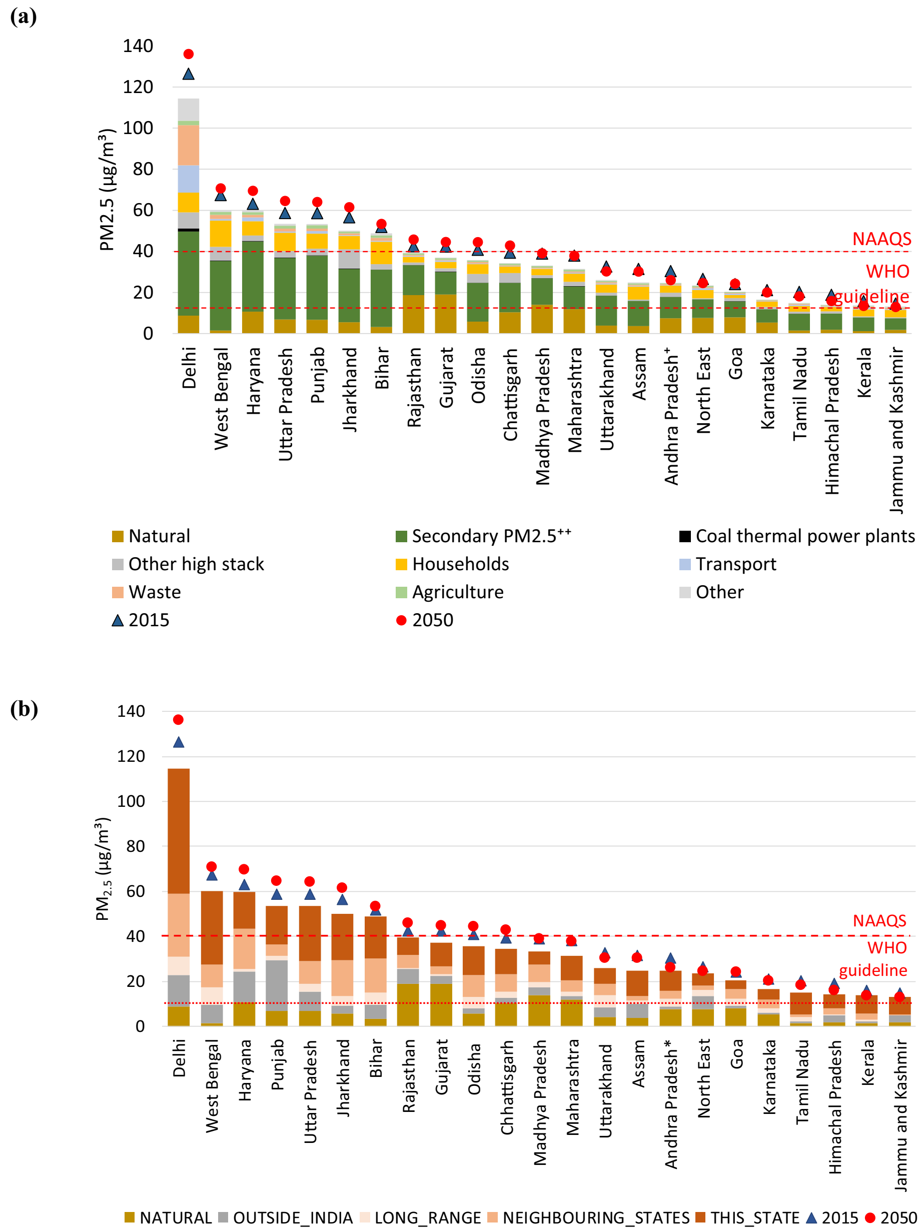

Fig. 8. a) Sectoral contributions to ambient annual mean $PM_{2.5}$ concentrations for the 2018 legislation case in 2030 (population-weighted), with indications of the total concentrations in 2015 and 2050; b) Source contributions to (population-weighted) annual mean concentrations of $PM_{2.5}$ for the 2018 legislation case in 2030.

many States face significant exceedances of the NAAQS, the transport of PM and precursor gases from neighboring States will remain a major contributor to urban $PM_{2.5}$ levels (Fig. 8b). Transboundary transport is dominated by secondary pollution (Fig. 8b), while primary PM plays a role mostly for local pollution sources. Hence, reductions in both primary PM and precursor emissions of secondary aerosols will be needed to bring down $PM_{2.5}$ to safe levels.

3.4. *The scope for further air quality improvements*

3.4.1. *Advanced technical measures*

The recently adopted emission control policies impose emission standards for priority sources (large boilers and industrial installations, road transport) that require installation of technical (end-of-pipe) emission controls measures. However, they do not always include the full range of emission sources, especially smaller installations and existing plants, and not all relevant pollutants. Also, they do not exhaust the full potential that is offered by advanced technology.

An illustrative 'advanced technology' scenario explores the potential benefits that are offered by latest emission control technology that is already widely adopted in many industrialized countries (e.g., in the EU and Japan). Compared to the '2018 legislation' case, this scenario assumes stricter emission limit values for large point sources for SO_2, NO_x and PM/TSP (Table S6). For mobile sources, tighter controls would be introduced for non-road mobile machinery, while for road vehicles the standards follow the BS-VI introduction schedule as assumed in the 2018 legislation scenario. To reduce ammonia emissions, improved manure management practicies in livestock production and efficient application of urea based mineral fertilzers is assumed following experience in Europe.

This advanced emission control technology (ACT) scenario assumes penetration of cleaner technologies only in the course of capacity expansions or of regular replacement of outdated equipment, without premature scrapping of existing capital stock. Furthermore, it is assumed that the more stringent standards would be applied in India with a 10 years delay compared to other industrialized countries, so that,

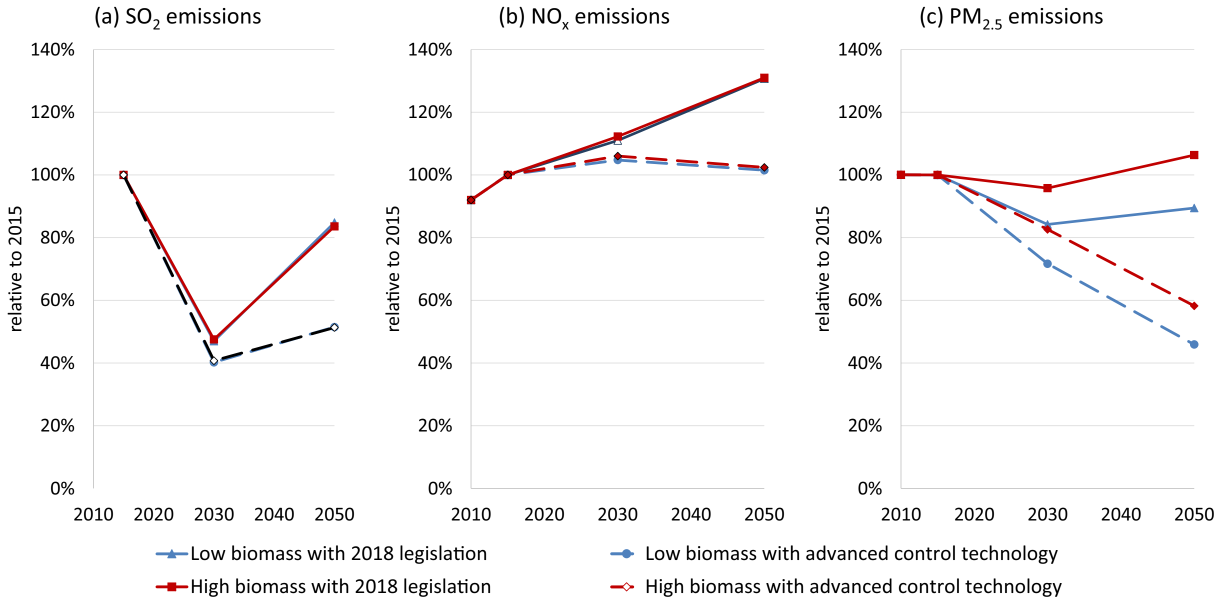

Fig. 9. Air pollutant emissions for the 2018 legislation and the ACT scenarios, for the baseline case assuming successful introduction of clean household fuels, and a less optimistic variant.

e.g., the current EU legislation (Amann et al., 2014) would be fully introduced in India by 2025. However, this scenario restricts the scope of ACT only to emission control equipment but does not consider further structural changes in the economy that are offered by wider and accelerated introduction of other advanced technologies (e.g., energy efficiency improvements, advanced production processes).

Two sensitivity cases are considered that explore the role providing access to clean household fuels:

- ACT combined with the rapid penetration of clean household fuels that is assumed in the 2018 legislation scenario.
- ACT with slower introduction of clean cooking fuels (i.e. LPG, Electricity).

Full and effective implementation of ACT measures could avoid the rebound of SO_2 emissions after 2030 and stabilize NO_x emissions at the current levels. For primary $PM_{2.5}$, they could lower emissions by 15% in 2030 (compared to the 2018 legislation), and by about 40% in 2050 (Fig. 9). However, for $PM_{2.5}$ the success of providing clean household fuels will be another determining factor. Combined, India could reduce its primary $PM_{2.5}$ emissions by 60% in 2050, compared to 2015.

The emission reductions offered by ACT would have considerable benefits on ambient air quality (Fig. 7b) and bring large parts of India in compliance with the NAAQS. However, purely technologically based policy interventions will not be sufficient to achieve the NAAQs throughout the Indo-Gangetic Plain (Table S7).

3.4.2. Sustainable development measures

As indicated above, even ACT solutions, despite their potentially high costs (Amann et al., 2017), will not be sufficient to approach the NAAQS standards in important regions in India (e.g. IGP), as they do not effectively address some emission sources that are of particular importance in India. Furthermore, concentrations will remain substantially above the global WHO guideline value, which has been established as an aspirational target to protect human health. As shown in the sectoral source apportionment analysis (e.g., Fig. 8a), after implementation of the 2018 legislation non-industrial sources (e.g., road dust, household fuel use, agricultural activities, and waste mangement) will still make large contributions to population exposure. However, these are not effectively addressed in the ACT scenario.

While India is pursuing ambitious sustainable development policies which eventually might eliminate such sources that are related to poverty, their strong benefits for air quality deliver an additional incentive to accelerate such policies. An illustrative 'sustainable development scenario (SDS)' explores the potential air quality gains from such policy interventions that are aimed at a wider development context (Table S8). To this end, the scenario adopts for the energy sector the projection of energy use, energy systems transformation and economic activities that has been developed by CEEW in the context of exploring response strategies to the 2 °C temperature increase limit by 2100 (Chaturvedi et al., 2018). In addition, it assumes full application of advanced emission control technologies as in the ACT scenario. Most importantly, this scenario considers additional emission controls for non-industrial sources, such as clean cookstoves, efficient enforcement of bans of burning of agricultural/municipal waste and road paving, that are important for Indian conditions.

The far-reaching transformative changes in the energy system of the SDS measures together with ACT controls and the SDS measures will lead to substantially lower emissions of $PM_{2.5}$ precursors. Tables S9–S12 in the SI presents SO_2, NO_x, $PM_{2.5}$ and NH_3 emissions by States/regions in 2015, 2030 and 2050 under 2018 legislation, ACT and SDS measures scenario. Compared to the 2015, SO_2 emissions decrease by 50%. Similarly, NO_x emissions decline by about 50% in 2050, and $PM_{2.5}$ by 80%. These emission changes will have profound impacts on air quality and bring large parts in India in compliance with the NAAQS for $PM_{2.5}$ (Fig. 7c).

3.4.3. Impacts on population exposure to $PM_{2.5}$

In 2030, population exposure to $PM_{2.5}$ will be strongly determined by the degree of compliance with the recent policies and emission control regulations. In particular, effective implementation of the post-2015 legislation will reduce population exposure to $PM_{2.5}$ in India by up to 50% in 2050 compared to a hypothetical case without these regulations (Fig. S7b). Further improvements are offered by ACT measures (about 10 $\mu g/m^3$ in 2050) and SDS measures (about 7 $\mu g/m^3$ in 2050).

These improvements in ambient air quality will be mirrored by the population exposure (Fig. 10). In 2015, more than 50% of the Indian population (677 million people) experienced air quality that did not conform the NAAQS. The SDS measures combined with technical

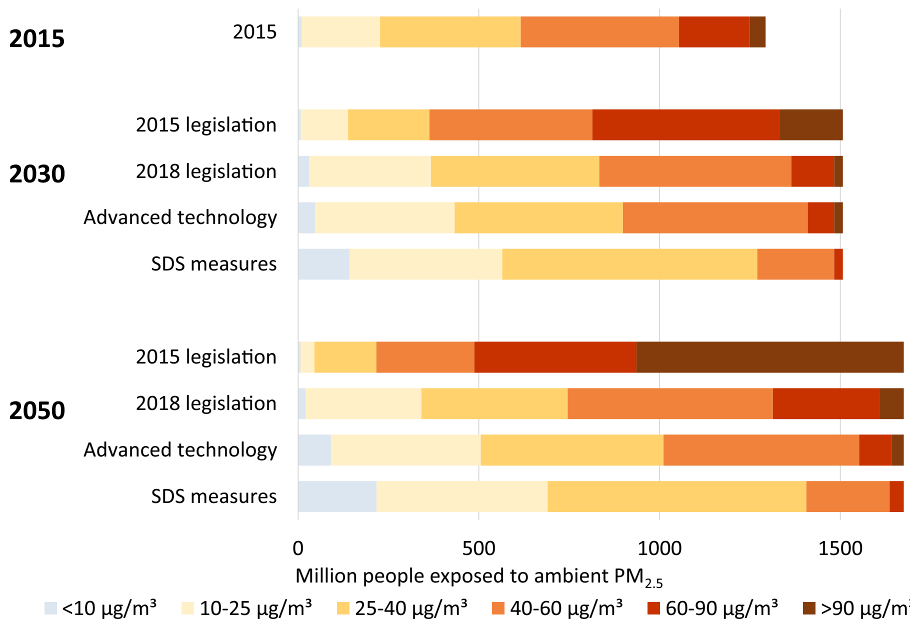

Fig. 10. Distribution of population exposure for 2015 and the emission control scenarios in 2030 and 2050.

emission controls could reduce this number by two thirds, i.e., to 236 million people (approximately 15% of the total population) in 2030 and to 270 million people in 2050. It should be noted that part of the remaining $PM_{2.5}$ exposure originates from natural sources like soil dust, or from sources outside India, which are not under India's control (Fig. 8b).

4. Costs and benefits

4.1. Emission control costs

The GAINS model estimates life-cycle costs for emission reductions from a social planner's perspective focusing on the diversion of societal resources. This approach excludes transfer payments such as taxes, subsidies and profits, and balances up-front investments with subsequent cost savings, for example from lower energy consumption. Moreover, the GAINS model estimates the scope for further environmental improvements that is offered by commercially available emission control technologies (excluding the potential from structural changes), their costs, and the composition of cost-effective portfolios of measures that achieve higher environmental protection at least cost.

With such a perspective, it is estimated that in 2015 India spent about 0.7% of its GDP (12 billion € per year) on emission controls (World Bank, 2016), with significant benefits for air quality and human well-being. More than 80% of total costs are associated with mobile sources, i.e., for the nation-wide BS-III standards and BS-IV standards in Delhi and other 13 cities. Control measures for large stationary sources in the power sector accounted for about 7% of total costs (Fig. 11) followed by 5% in non-road machinery and 4% in industrial processes and combustion sector.

The dominating share of emission control costs for mobile sources prevail in the future across all emission control scenarios. While the additional emission controls considered in this analysis affect mainly stationary sources, their share in total costs accounts for not more than 35% in 2030 and < 30% in 2050. For the power sector, FGD accounts for 12% of total costs in 2030 and 7% in 2050. In the transport sector, the share of the cost of ACT measures in heavy duty trucks in total cost will increase from 25% in 2030 to 27% in 2050, whereas the share for ACT measures in cars will increase from 18% in 2030 to 29% in 2050. Costs for FGD in industry increases by 64% between 2030 and 2050 in the 2018 legislation scenario, however, the share in total costs decreased by half (from 4% in 2030 to 2% in 2050).

Notably, since the scenario with SDS measures considers a host of policies to decrease the consumption of fossil fuels, also associated emission control costs will be lower than in the ACT case. Overall, air pollution emission control costs will increase from 0.7% of the GDP in 2015 to 1.4–1.7% of the GDP in 2030. In 2050, with an almost 10-fold increase in GDP, air pollution controls will consume 1.1–1.5% of the GDP, or 1.5% of the increase in economic wealth (GDP) between 2015 and 2050.

4.2. Implications for SDGs

Compared to the ACT scenario that does not modify the levels of economic activities, the SDS measures addresses pollution sources in a more holistic way. It promotes reduction and substitution of most polluting activities by cleaner alternatives without diminishing human welfare through, e.g., energy efficiency improvements, enhanced public transport, use of cleaner cook stoves, and the replacement of coal with natural gas and renewables (solar/wind) in power and industry. In the sustainable development scenario, India's CO_2 emissions would be about 60% lower in 2050 than in the 2018 legislation case. In the SDS measures, CH_4 emissions would be 40% lower in 2050 compared to the baseline case, and black carbon emissions would decline by 80% compared to 2015 (Fig. 12).

Furthermore, there are additional benefits to other sustainable development goals (SDGs[8]) (Longhurst et al., 2018). A non-exhaustive list of benefits includes, inter alia, accelerated infrastructure development (power grid expansion, loss reduction, enhanced gas distribution networks, waste management practices), time savings from avoided biofuel collection, additional jobs for the manufacturing of clean technologies (e.g., efficient and electric stoves, renewable energy), more

[8] SDGs are a collection of 17 global goals set by the United Nations General Assembly in 2015 for the year 2030. SDGs include: 1) No Poverty, 2) Zero Hunger, 3) Good Health and Well-being, 4) Quality Education, 5) Gender Equality, 6) Clean Water and Sanitation, 7) Affordable and Clean Energy, 8) Decent Work and Economic Growth, 9) Industry, Innovation, and Infrastructure, 10) Reducing Inequality, 11) Sustainable Cities and Communities, 12) Responsible Consumption and Production, 13) Climate Action, 14) Life Below Water, 15) Life on Land, 16) Peace, Justice, and Strong Institutions, 17) Partnerships for the Goals (UN, 2015).

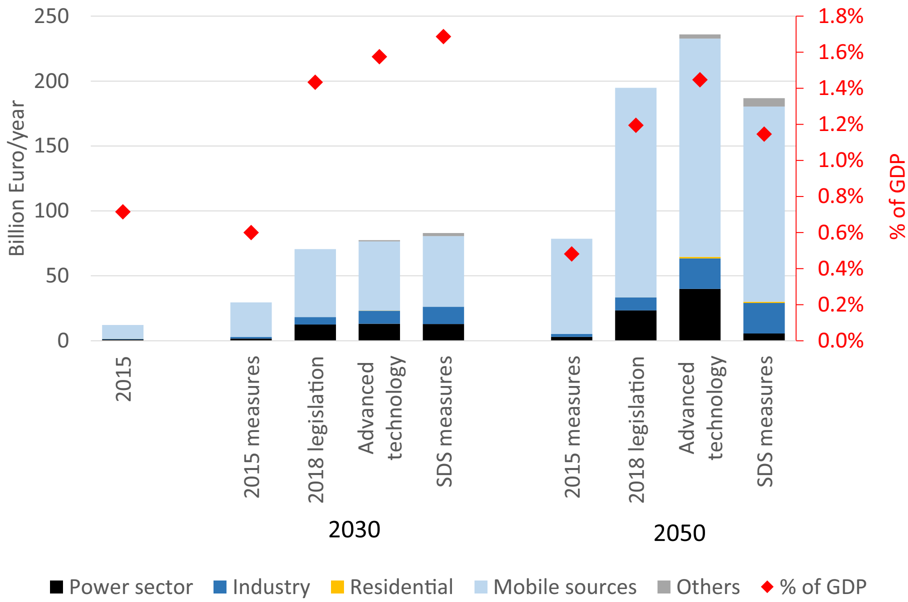

Fig. 11. Air pollutant emission control costs for the various scenarios.

efficient land use due to less ash and soot disposal, lower emissions of other toxic substances (Hg, POPs) with subsequent health benefits, improved traffic management, improved protection of historical monuments and buildings, and enhanced economic gains from tourism.

5. Conclusions

The fast economic and population growth in India's urban areas and the limited control of pollution are causing public health problems and significant environmental degradation, including air, water, land and GHGs, which undermines the potential for sustainable socioeconomic development of the country, particularly with impacts on the poor. This study explores pathways towards achieving the NAAQS in India in the context of the dynamics of social and economic development. To conduct such an assessment for India, this study employs a multi-disciplinary scientific framework consisting of two well-established scientific modeling tools: a) the GCAM-IIMA model that investigates the socio-economic drivers of pollution, with special emphasis on the energy sector and b) the GAINS model to assess the effectiveness of policy interventions on population exposure and health impacts. The following inferences can be drawn based on a detailed source-apportionment at the subnational level presented in this study:

- A large share of the Indian population is exposed to pollution levels that do not conform to global and national air quality standards.

It is estimated that in 2015 more than half of the Indian population, i.e., about 670 million people, was exposed to ambient $PM_{2.5}$ concentrations that do not comply with India's NAAQS, and only < 1% enjoyed air quality conforming with the global WHO guideline value of 10 μg/m^3. About one quarter of the population lived in areas where the WHO guideline was exceeded by more than nine times. The high exposure of the Indian population to air pollution imposes serious burdens on the health of citizens. Although, due to the lack of India-specific

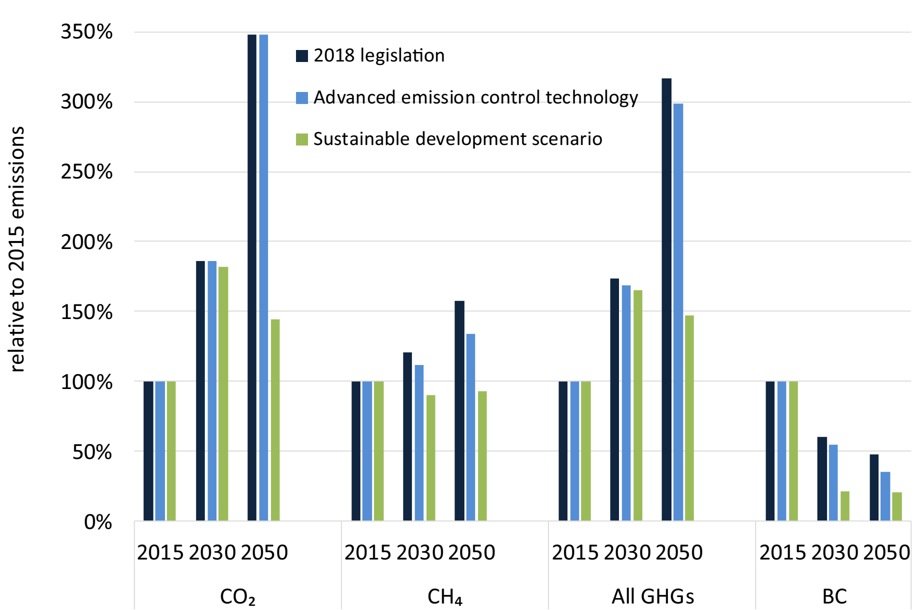

Fig. 12. GHG and black carbon emissions in India for the emission control scenarios.

studies, quantifications of health impacts are uncertain, available health impact assessments suggest several hundred thousand cases of premature deaths annually.

- Current emission controls are effective, but their impacts are compensated by rapid economic growth.

The Indian government has already implemented emission controls, especially for large stationary sources and road vehicles. While these existing measures are effectively decoupling the trends of air pollutant emissions from economic growth, their impacts on ambient air quality are not directly visible since they are compensated by the rapid expansion of economic activities. In particular, the already implemented measures will not be sufficient to halt a further deterioration in air quality in view of the 10-fold increase in GDP that is expected up to 2050.

- Compliance with 2018 legislation will be essential for stabilizing pollution levels despite economic growth.

After 2015, the Indian government has issued a wide range of pollution control policies and regulations. Their actual benefits on air quality will critically depend on the effectiveness of implementation and enforcement. By 2030, full compliance could avoid a 70% increase in the number of people living in areas where the NAAQS are exceeded. Thereby, these new policies and regulations could allow the economy to grow and lift millions out of poverty without further worsening of air quality. At the same time, they will not be sufficient to deliver significant air quality improvements, and even with full implementation average population exposure to $PM_{2.5}$ will not decline by more than 14% in 2030. Also, these policies and measures will not be sufficient to avoid a rebound in emissions in the long run after they will have reached their full impact around 2030. Even with full 2018 legislation, by 2050, 40% more people will face pollution levels above the NAAQS compared to today, and implementation failure could increase the numbers significantly.

- Effective solutions require regional cooperation between cities and States.

High population density, economic activities and energy demand in the world's growing cities implies that poor air quality would be one of the urban problems. However, the physical and chemical features of fine particulate matter add an important spatial challenge to the air quality management task. Due to their small size and thermodynamic properties, $PM_{2.5}$ particles remain in the atmosphere for several days, during which they are typically transported over several hundreds of kilometers. Thus, as a consequence, a significant share of particles found at any specific location originates from distant sources, which are often outside the immediate jurisdiction and control of the local authorities. At the same time, an important share of the impacts of emissions occur in other States and regions.

The model analysis for India reveals that in many of the Indian States emission sources that are outside of their immediate jurisdictions make the dominating contributions to (population-weighted) ambient pollution levels of $PM_{2.5}$. As a consequence, most of the States cannot achieve significant improvements in their air quality and population exposure on its own without emission reductions in the surrounding regions, and any cost-effective strategy requires regionally coordinated approaches.

- Effective solutions must address all sources that contribute to $PM_{2.5}$ formation.

$PM_{2.5}$ in ambient air emerges from a variety of sources. Fine particles are directly emitted during the combustion of fuels and biogenic material, they are caused by industrial processes, and are emitted from natural sources (soil dust, sea salt). Another substantial fraction, i.e., secondary $PM_{2.5}$, is formed in the atmosphere through chemical reactions involving gaseous emissions. These precursor gases originate from energy combustion (SO_2, NO_x, VOCs), from agricultural activities (NH_3) and from industrial processes (e.g., VOCs, SO_2, NO_x).

In contrast to many other countries in the world, in India the various precursor emissions do not only originate from sources that are associated with industrial development and more affluent lifestyles, which show rapid growth in the last years. In addition, a significant share of emissions still originates from sources associated with poverty and underdevelopment, such as solid fuel use in households and poor waste management practices.

Any effective reduction of $PM_{2.5}$ levels in ambient air and the resulting health burden needs to balance emission controls across all these source sectors and sources. A focus on single source alone will not deliver effective improvements and is likely to waste economic resources to the detriment of further economic and social development.

- Policies and measures are available that could bring air quality more in compliance with the NAAQS.

There exists a wide portfolio of practical intervention options of technical and non-technical nature that are already applied in different parts of the world to improve air quality. While they are partly already employed in India, wider application could - theoretically - offer significant air quality benefits. Beyond what is included in the 2018 emission control legislation, there is scope for additional emission reductions and further improvements in air quality in India from a more comprehensive application of ACT measures, in line with examples widely adopted in many other countries in the world. Without premature scrapping of existing capital stock, such a strategy could provide NAAQS-compliant air quality to 60% of the Indian population, if accompanied by the ongoing efforts to provide universal access to clean household fuels. Therefore, ACT measures can deliver air quality improvements in India, but will not be sufficient to achieve the 100% NAAQS-compliant.

SDS priority measures offer further means for air quality improvements in India, even if they are not primarily targeted on air pollution. Often, they fall under the jurisdiction of different authorities and are discussed in different policy frameworks where air quality managers are often not represented. These include, inter alia, measures that are intimately related to economic and social development, energy or agricultural policies, or urban management.

If combined with ACT, such SDS measures could provide NAAQS-compliant air quality to about 85% of the Indian population and reduce mean population exposure to $PM_{2.5}$ by about one third compared to 2015. Therefore, a package of SDS measures that are usually taken for other policy priorities can deliver significant co-benefits on air quality.

- The sustainable development measures can deliver a wide range of benefits.

The portfolio of the SDS measures identified in this study promotes reduction and substitution of most polluting activities by cleaner alternatives without diminishing human welfare through, e.g., energy efficiency improvements, enhanced public transport, increased use of cleaner cookstoves and the replacement of coal with natural gas and renewables (solar/wind) in power and industry sector. Also, it includes improved waste management and agricultural production practices. Thereby, in addition to their air quality and health benefits, these measures contribute to multiple SDGs. Most obvious are the interactions with GHG emissions, an essential dimension of SDG 13 (climate action) resulting in decline of CO_2 emissions by about 60% in comparison to the baseline case. Even without dedicated measures focused on methane, CH_4 emissions would be 40% lower whereas black carbon emissions would decline by 80% compared to 2015 in the SDS. Furthermore, the NO_x and VOC emission reductions taken in the interest of lowering ambient $PM_{2.5}$ concentrations will also produce less ground-level ozone, and thereby deliver additional benefits to human health and vegetation, in particular reducing damage to agricultural crops. However, the quantification of these effects was outside of the scope of this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the ClimateWorks Foundation (grant number 17-1082). The authors would like to thank the six anonymous reviewers for their helpful and constructive comments that greatly contributed to improving the final version of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.105147.

References

Amann, M., Kejun, J., Hao, J., Wang, S., Wei, W., Xing, J., Zhang, Ch., Bertok, I., Borken, J., Cofala, J., Heyes, Ch., Hoglund, L., Klimont, Z., Purohit, P., Rafaj, P., Schöpp, W., Toth, G., Wagner, F., Winiwarter, W., 2008. GAINS-Asia: Scenarios for Cost-Effective Control of Air Pollution and Greenhouse Gases in China. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., Winiwarter, W., 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model Softw. 26, 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012.

Amann, M., Borken-Kleefeld, J., Cofala, J., Hettelingh, J.-P., Heyes, C., Hoglund-Isaksson, L., Holland, M., Kiesewetter, G., Klimont, Z., Rafaj, P., Posch, M., Sander, R., Schoepp, W., Wagner, F., Winiwarter, W., 2014. The Final Policy Scenarios of the EU Clean Air Policy Package. TSAP Report #11 (No. TSAP Report #11). International Institute for Applied Systems Analysis, Laxenburg, Austria.

Amann, M., Purohit, P., Bhanarkar, A.D., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Kiesewetter, G., Klimont, Z., Liu, J., Majumdar, D., Nguyen, B., Rafaj, P., Rao, P.S., Sander, R., Schöpp, W., Srivastava, A., Vardhan, B.H., 2017. Managing future air quality in megacities: a case study for Delhi. Atmos. Environ. 161, 99–111. https://doi.org/10.1016/j.atmosenv.2017.04.041.

Balakrishnan, K., Cohen, A., Smith, K.R., 2014. Addressing the burden of disease attributable to air pollution in India: the need to integrate across household and ambient air pollution exposures. Environ. Health Perspect. 122, A6–A7. https://doi.org/10.1289/ehp.1307822.

Balakrishnan, K., Dey, S., Gupta, T., Dhaliwal, R.S., Brauer, M., Cohen, A.J., et al., 2019. The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: the Global Burden of Disease Study 2017. The Lancet Planetary Health 3, e26–e39. https://doi.org/10.1016/S2542-5196(18)30261-4.

Bhanarkar, A.D., Purohit, P., Rafaj, P., Amann, M., Bertok, I., Cofala, J., Rao, P.S., Vardhan, B.H., Kiesewetter, G., Sander, R., Schöpp, W., Majumdar, D., Srivastava, A., Deshmukh, S., Kawarti, A., Kumar, R., 2018. Managing future air quality in megacities: co-benefit assessment for Delhi. Atmos. Environ. 186, 158–177. https://doi.org/10.1016/j.atmosenv.2018.05.026.

Chaturvedi, V., Koti, P.N., Chordia, A.R., 2018. Sustainable Development, Uncertainties, and India's Climate Policy Pathways towards Nationally Determined Contribution and Mid-Century Strategy. Council on Energy, Environment and Water (CEEW), New Delhi.

Chen, F., Yamashita, K., Kurokawa, J., Klimont, Z., 2015. Cost–benefit analysis of reducing premature mortality caused by exposure to ozone and PM2.5 in East Asia in 2020. Water Air Soil Pollut. 226, 1–17. https://doi.org/10.1007/s11270-015-2316-7.

Chowdhury, S., Dey, S., 2016. Cause-specific premature death from ambient PM2.5 exposure in India: estimate adjusted for baseline mortality. Environ. Int. 91, 283–290. https://doi.org/10.1016/j.envint.2016.03.004.

Chowdhury, S., Dey, S., Smith, K.R., 2018. Ambient PM 2.5 exposure and expected premature mortality to 2100 in India under climate change scenarios. Nat. Commun. 9, 318. https://doi.org/10.1038/s41467-017-02755-y.

Chowdhury, S., Dey, S., Guttikunda, S., Pillarisetti, A., Smith, K.R., Girolamo, L.D., 2019. Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources. PNAS 116, 10711–10716. https://doi.org/10.1073/pnas.1900888116.

CIESIN, 2011. Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Urban Extents Grid.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., et al., 2017. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. Lancet 389, 1907–1918. https://doi.org/10.1016/S0140-6736(17)30505-6.

CPCB, 2009. National Ambient Air Quality Standards. Central Pollution Control Board (CPCB), Ministry of Environment, Forests and Climate Change (MoEF&CC), Government of India, New Delhi, India.

CPCB, 2011. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities: National Summary Report. Central Pollution Control Board (CPCB), Ministry of Environment, Forest and Climate Change (MoEF&CC), New Delhi, India.

CPCB, 2016. NAQI Status of Indian Cities in 2015–16. Central Pollution Control Board (CPCB), Ministry of Environment, Forest and Climate Change, Government of India, New Delhi.

David, L.M., Ravishankara, A.R., Kodros, J.K., Pierce, J.R., Venkataraman, C., Sadavarte, P., 2019. Premature mortality due to PM2.5 over India: effect of atmospheric transport and anthropogenic emissions. GeoHealth 3, 2–10. https://doi.org/10.1029/2018GH000169.

Dholakia, H.H., Purohit, P., Rao, S., Garg, A., 2013. Impact of current policies on future air quality and health outcomes in Delhi, India. Atmos. Environ. 75, 241–248. https://doi.org/10.1016/j.atmosenv.2013.04.052.

Dong, H., Dai, H., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., Fujii, M., Masui, T., 2015. Pursuing air pollutant co-benefits of CO_2 mitigation in China: a provincial leveled analysis. Appl. Energy 144, 165–174. https://doi.org/10.1016/j.apenergy.2015.02.020.

Forouzanfar, M.H., Alexander, L., Anderson, H.R., Bachman, V.F., Biryukov, S., Brauer, M., et al., 2015. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990–2013: a systematic analysis for the global burden of disease study 2013. Lancet 386, 2287–2323. https://doi.org/10.1016/S0140-6736(15)00128-2.

Forouzanfar, M.H., Afshin, A., Alexander, L.T., Anderson, H.R., Bhutta, Z.A., Biryukov, S., et al., 2016. Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. Lancet 388, 1659–1724. https://doi.org/10.1016/S0140-6736(16)31679-8.

Gaughan, A.E., Stevens, F.R., Linard, C., Jia, P., Tatem, A.J., 2013. High resolution population distribution maps for Southeast Asia in 2010 and 2015. PLoS One 8, e55882. https://doi.org/10.1371/journal.pone.0055882.

GBD MAPS Working Group, 2018. Burden of Disease Attributable to Major Air Pollution Sources in India (No. Special Report 21). Health Effects Institute, Boston, MA.

GEA, 2012. Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

GoI, 2015. India Energy Security Scenarios (IESS) 2047. National Institution for Transforming India (NITI Aayog), Government of India, New Delhi.

Gordon, T., Balakrishnan, K., Dey, S., Rajagopalan, S., Thornburge, J., Thurston, G., Agrawal, A., Collman, G., Guleria, R., Limaye, S., Salvi, S., Kilaru, V., Nadadur, S., 2018. Air pollution health research priorities for India: perspectives of the Indo-U.S. communities of researchers. Environ. Int. 119, 100–108. https://doi.org/10.1016/j.envint.2018.06.013.

Guttikunda, S.K., Goel, R., Pant, P., 2014. Nature of air pollution, emission sources, and management in the Indian cities. Atmos. Environ. 95, 501–510. https://doi.org/10.1016/j.atmosenv.2014.07.006.

Hong, Y.-C., Hicks, K., Malley, C., Kuylenstierna, J., Emberson, L., Balakrishnan, K., et al., 2019. Air Pollution in Asia and the Pacific: Science-Based Solutions [WWW Document]. http://ccacoalition.org/en/resources/air-pollution-asia-and-pacific-science-based-solutions, Accessed date: 6 November 2018.

ICCT, 2018. India Bharat Stage IV and V Non-road Emission Standards. International Council on Clean Transportation (ICCT), Washington D.C.

IEA, 2016. World Energy Outlook Special Report: Energy and Air Pollution. International Energy Agency (IEA), Paris, France.

Kar, A., Singh, D., Pachauri, S., Bailis, R., Zerriffi, H., 2019. Ujjwala at 6 crores: impact on cooking energy transition and climate change. In: The Ujjwala Saga - Unending Happiness and Health. Ministry of Petroleum and Natural Gas, Government of India, New Delhi, pp. 16–21.

Karambelas, A., Holloway, T., Kinney, P.L., Fiore, A.M., DeFries, R., Kiesewetter, Gregor, Heyes, C., 2018. Urban versus rural health impacts attributable to PM 2.5 and O 3 in northern India. Environ. Res. Lett. 13, 064010. https://doi.org/10.1088/1748-9326/aac24d.

Kiesewetter, G., Borken-Kleefeld, J., Schoepp, W., Heyes, C., Thunis, P., Bessagnet, B., Terrenoire, E., Amann, M., 2015. Modelling street level PM10 concentrations across Europe: source apportionment and possible futures. Atmos. Chem. Phys. 15, 1539–1553. https://doi.org/10.5194/acp-15-1539-2015.

Klimont, Z., Cofala, J., Xing, J., Wei, W., Zhang, C., Wang, S., Kejun, J., Bhandari, P., Mathur, R., Purohit, P., Rafaj, P., Chambers, A., Amann, M., Hao, J., 2009. Projections of SO_2, NO_x, and carbonaceous aerosols emissions in Asia. Tellus 61B, 602–617. https://doi.org/10.1111/j.1600-0889.2009.00428.x.

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., Schöpp, W., 2017. Global anthropogenic emissions of particulate matter including black carbon. Atmos. Chem. Phys. 17, 8681–8723. https://doi.org/10.5194/acp-17-8681-2017.

Landrigan, P.J., Fuller, R., Acosta, N.J.R., Adeyi, O., Arnold, R., Basu, N., et al., 2017. The

Lancet Commission on Pollution and Health. The Lancet 0. https://doi.org/10.1016/S0140-6736(17)32345-0.
Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380, 2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8.
Liu, J., Kiesewetter, G., Klimont, Z., Cofala, J., Heyes, C., Schoepp, W., et al., 2019. Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. Environ. Int. https://doi.org/10.1016/j.envint.2018.09.059. in press.
Longhurst, J., Barnes, J., Chatterton, T., De Vito, L., Everard, M., Hayes, E., Prestwood, E., Williams, B., 2018. Analysing air pollution and its management through the lens of the unsustainable development goals: a review and assessment. WIT Trans. Ecol. Environ. 230, 3–14.
Markandya, A., Sampedro, J., Smith, S.J., Dingenen, R.V., Pizarro-Irizar, C., Arto, I., González-Eguino, M., 2018. Health co-benefits from air pollution and mitigation costs of the Paris Agreement: a modelling study. The Lancet Planetary Health 2, e126–e133. https://doi.org/10.1016/S2542-5196(18)30029-9.
Mir, K.A., Purohit, P., Goldstein, G.A., Balasubramanian, R., 2016. Analysis of baseline and alternative air quality scenarios for Pakistan: an integrated approach. Environ. Sci. Pollut. Res. 23, 21780–21793. https://doi.org/10.1007/s11356-016-7358-x.
MoEFCC, 2015. Environment (Protection) Amendment Rules, 2015. Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, New Delhi.
MoRTH, 2016. The Gazette of India: Extraordinary - G.S.R. 187(E). Ministry of Road Transport and Highways (MoRTH), Government of India, New Delhi.
OECD, 2014. The Cost of Air Pollution: Health Impacts of Road Transport. OECD Publishing.
Pant, P., Shukla, A., Kohl, S.D., Chow, J.C., Watson, J.G., Harrison, R.M., 2015. Characterization of ambient PM2.5 at a pollution hotspot in New Delhi, India and inference of sources. Atmos. Environ. 109, 178–189. https://doi.org/10.1016/j.atmosenv.2015.02.074.
Purohit, P., Amann, M., Mathur, R., Gupta, I., Marwah, S., Verma, V., et al., 2010. GAINS-Asia. Scenarios for Cost-Effective Control of Air Pollution and Greenhouse Gases in India. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
Purohit, P., Munir, T., Rafaj, P., 2013. Scenario analysis of strategies to control air pollution in Pakistan. J. Integr. Environ. Sci. 10, 77–91. https://doi.org/10.1080/1943815X.2013.782877.
Rafaj, P., Schöpp, W., Russ, P., Heyes, C., Amann, M., 2013. Co-benefits of post-2012 global climate mitigation policies. Mitig Adapt Strateg Glob Change 18, 801–824. https://doi.org/10.1007/s11027-012-9390-6.
Rafaj, P., Kiesewetter, G., Gül, T., Schöpp, W., Cofala, J., Klimont, Z., Purohit, P., Heyes, C., Amann, M., Borken-Kleefeld, J., Cozzi, L., 2018. Outlook for clean air in the context of sustainable development goals. Glob. Environ. Chang. 53, 1–11. https://doi.org/10.1016/j.gloenvcha.2018.08.008.
Sanderson, W., Striessnig, E., Schöpp, W., Amann, M., 2013. Effects on well-being of investing in cleaner air in India. Environ. Sci. Technol. 47, 13222–13229. https://doi.org/10.1021/es402867r.
Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L.D., Fagerli, H., et al., 2012. The EMEP MSC-W chemical transport model – technical description. Atmos. Chem. Phys. 12, 7825–7865. https://doi.org/10.5194/acp-12-7825-2012, 2012.
UN, 2015. Transforming our World: The 2030 Agenda for Sustainable Development (A/RES/70/1): Resolution Adopted by the General Assembly on 25 September 2015. U.N. General Assembly.
UNDESA, 2012. World Urbanization Prospects: The 2011 Revision. United Nations, Department of Economic and Social Affairs, New York, USA.
Vandyck, T., Keramidas, K., Kitous, A., Spadaro, J.V., Dingenen, R.V., Holland, M., Saveyn, B., 2018. Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges. Nat. Commun. 9, 4939. https://doi.org/10.1038/s41467-018-06885-9.
Venkataraman, C., Brauer, M., Tibrewal, K., Sadavarte, P., Ma, Q., Cohen, A., et al., 2018. Source influence on emission pathways and ambient $PM_{2.5}$ pollution over India (2015–2050). Atmos. Chem. Phys. 18, 8017–8039. https://doi.org/10.5194/acp-18-8017-2018.
West, J.J., Smith, S.J., Silva, R.A., Naik, V., Zhang, Y., Adelman, Z., Fry, M.M., Anenberg, S., Horowitz, L.W., Lamarque, J.-F., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nat. Clim. Chang. 3, 885–889. https://doi.org/10.1038/nclimate2009.
WHO, 2016. Ambient Air Pollution: A Global Assessment of Exposure and Burden of Disease. World Health Organization (WHO), Geneva, Switzerland.
WHO, 2018. WHO Global Ambient Air Quality Database (Update 2018). World Health Organization (WHO), Geneva, Switzerland.
World Bank, 2016. The Cost of Air Pollution: Strengthening the Economic Case for Action. The World Bank Group, Washington, D.C.
Zhao, B., Wang, S.X., Liu, H., Xu, J.Y., Fu, K., Klimont, Z., Hao, J.M., He, K.B., Cofala, J., Amann, M., 2013. NOx emissions in China: historical trends and future perspectives. Atmos. Chem. Phys. 13, 9869–9897. https://doi.org/10.5194/acp-13-9869-2013.