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Pathways to Achieve National Ambient Air Quality Standards (NAAQS) in India

Report | March 2019

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Industrial growth fuelled by clean energy can lower pollution, achieve economic growth, and create jobs.

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ABOUT CEEW

The Council on Energy, Environment and Water (CEEW) is one of South Asia's leading not-for-profit policy research institutions. The Council uses data, integrated analysis, and strategic outreach to explain – and change – the use, reuse, and misuse of resources. The Council addresses pressing global challenges through an integrated and internationally focused approach. It prides itself on the independence of its high-quality research, develops partnerships with public and private institutions, and engages with the wider public.

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- Energy and Climate Change;
- Food and Water;
- Poverty and Equity.

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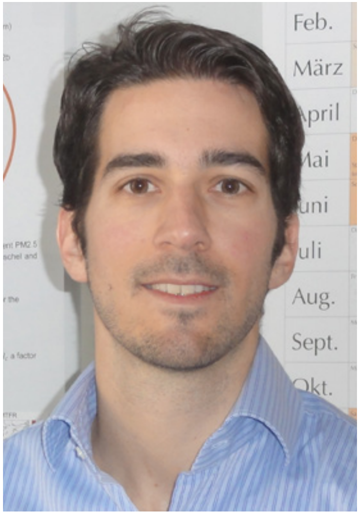

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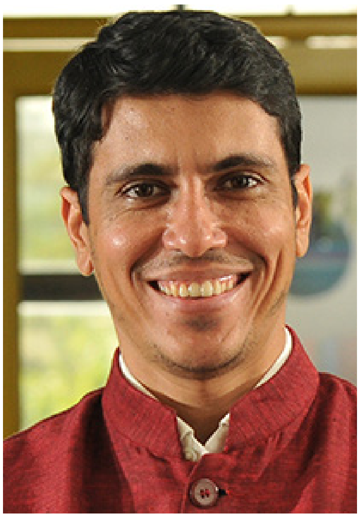

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ABBREVIATIONS

ACT	advanced control technology
APDRP	Accelerated Power Development and Reform Programme
BSES	Bharat Stage Emission Standards
CCS	carbon capture and storage
CEEW	Council on Energy, Environment and Water
CPCB	Central Pollution Control Board
CNG	compressed natural gas
CLE	current legislation
CSP	concentrating solar power
DDUGJY	Deen Dayal Upadhyaya Gram Jyoti Yojana
DALYs	disability-adjusted life years
DC	designated consumer
DISCOM	distribution company
EJ	exajoule
EMEP	European Monitoring and Evaluation Programme
ESP	electrostatic precipitator
FAME	Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles Scheme
FEEED	Framework for Energy Efficient Economic Development
FGD	flue gas desulphurisation
GAINS	Greenhouse Gas–Air Pollution Interaction and Synergies model
GCAM	Global Change Assessment Model
GDP	gross domestic product
GHG	greenhouse gas
HDSEI	Stage 1 control on heavy-duty vehicles with spark ignition engines
HDSEII	Stage 2 control on heavy-duty vehicles with spark ignition engines
HDSEIII	Stage 3 control on heavy-duty vehicles with spark ignition engines
HDEUVI	EURO-VI on heavy-duty diesel road vehicles
HED	high-efficiency deduster
IESS	India energy security scenarios
IIASA	International Institute for Applied Systems Analysis
IIMA	Indian Institute of Management Ahmedabad
INDC	intended nationally determined contribution
JGCRI	Joint Global Change Research Institute
LED	light-emitting diode
LFEUVI	EURO-VI on light duty spark ignition road vehicles (four-stroke engines)
LPG	liquefied petroleum gas
LSMD-I	low-sulphur diesel oil—stage 1 (0.2 % S)
LSMD-II	low-sulphur diesel oil—stage 2 (0.045 % S)
LSMD-III	low-sulphur diesel oil—stage 3 (0.001 % S)

NCEF	National Clean Energy Fund
NMEEE	National Mission for Enhanced Energy Efficiency
MTFR	maximum technically feasible reduction
MoEFCC	Ministry of Environment, Forest and Climate Change
MoP	Ministry of Power
NCR	National Capital Region
NCT	National Capital Territory
NDC	nationally determined contribution
NMEEE	National Mission for Enhanced Energy Efficiency
NMVOC	non-methane volatile organic compounds
NTPC	National Thermal Power Corporation
PAT	Perform Achieve and Trade scheme
PMUY	Pradhan Mantri Ujjwala Yojana
POP	persistant organic pollutant
PPM	primary particulate matter
RPO	renewable purchase obligation
SCR	selective catalytic reduction
SEC	specific energy consumption
SME	small and medium-sized enterprises
SNCR	selective non-catalytic reduction
SPV	solar photovoltaic
TSP	total suspended particles
VRE	variable renewable energy
VOC	volatile organic compound
VSBK	vertical shaft brick kiln
WHO	World Health Organization

Incentives for non-motorised transport can help reduce pollution in the coming years. It is also important to educate people to adopt practises that protect their health.

Image: iStock

Executive Summary

The rapid economic growth and steep population increase in India's urban areas, and the lack of policy measures to control pollution in these regions, are causing public health problems, significant environmental degradation, including of air, water, and land, and increased production of greenhouse gases. Together, these undermine the potential for sustainable socio-economic development of the country, and will particularly have severe implications for the poor.

High exposure to pollution

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

Globally, Indian cities rank poorly in terms of air pollution. Numerous monitoring sites across India report high concentrations of $PM_{2.5}$, which exceed the benchmark limit (of 40 µg/m³) suggested by the National Ambient Air Quality Standards (NAAQS).

It is estimated that in 2015, more than half the Indian population—about 670 million people—were exposed to ambient $PM_{2.5}$ concentrations that do not comply with India's NAAQS. Further, less than one per cent enjoyed air quality that met the global World Health Organization (WHO) benchmark limit of 10 µg/m³. About one-quarter of the population lived in areas where the WHO guideline was exceeded by more than nine times.

Exposure to air pollution poses a serious health burden in India. Available health impact assessments suggest that several hundred thousand cases of premature deaths annually are attributable to pollution.

It is estimated that in 2015, more than half the Indian population—about 670 million people—were exposed to ambient $PM_{2.5}$ concentrations that do not comply with India's NAAQS

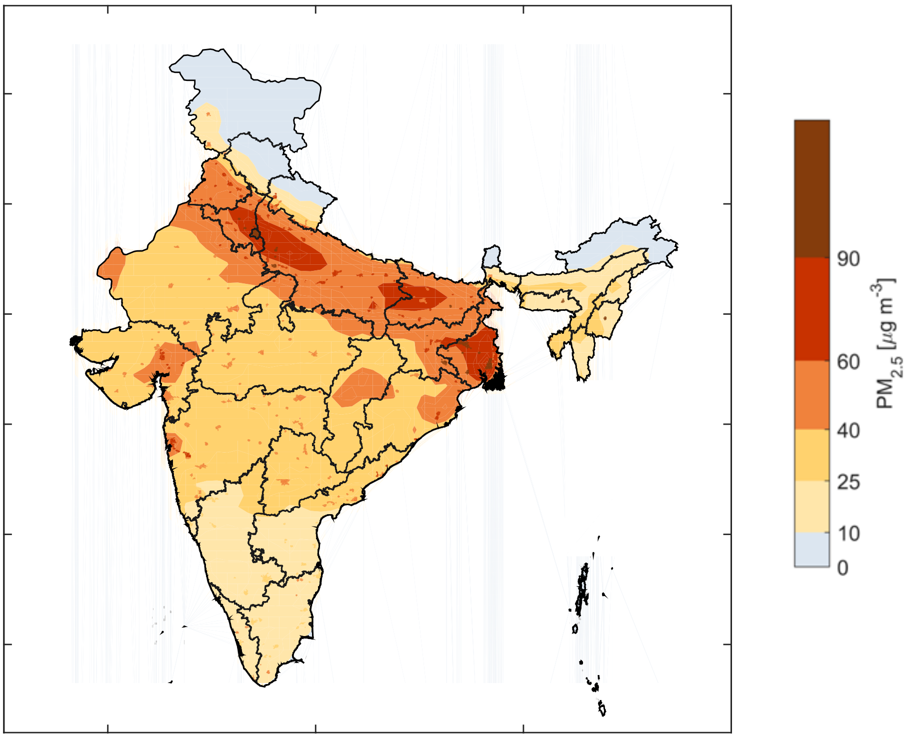

FIGURE E1: Ambient PM2.5 concentrations (annual mean concentrations) computed for 2015

Source: IIASA-CEEW analysis, 2019

Emission controls out-paced by economic growth

Current emission controls are effective, but their benefits are neutralised by rapid economic growth.

The Indian government has already implemented emission controls for large stationary sources and road vehicles. While these measures help decouple air pollutant emissions and economic growth, their positive impact on ambient air quality is limited by the rapid expansion of economic activities. These measures will be insufficient for halting a further deterioration in air quality given the tenfold increase in GDP that is expected by 2050.

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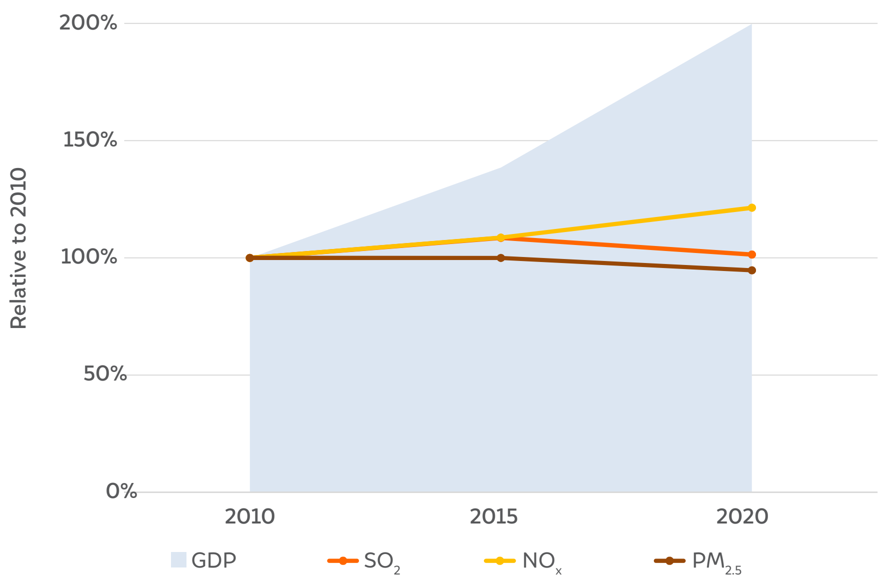


FIGURE E2: Trends in GDP and emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and primary particulate matter ($PM_{2.5}$) in India, 2010–2020

Source: IIASA-CEEW analysis, 2019

Compliance with 2018 legislations will be essential for stabilising pollution levels as the economy grows

The Indian government has enacted a wide range of pollution control policies and regulations since 2015, but their impact on air quality will critically depend on how effectively they are implemented and enforced. Full compliance with these new policies and regulations implies that by 2030 some areas could meet the NAAQS (Figure E3). As the population is expected to grow in future, this means nearly 210 million people get to breathe cleaner air. This will happen while allowing the economy to grow as well as lifting millions out of poverty. It will not, however, be sufficient to deliver significant air quality improvements across India.

These policy measures will not prevent a rebound in emission levels in the long run.. Even with full compliance with 2018 legislations, by 2050, 40 per cent more people (than today) will face pollution levels above the NAAQS. Implementation failure could increase the numbers significantly.

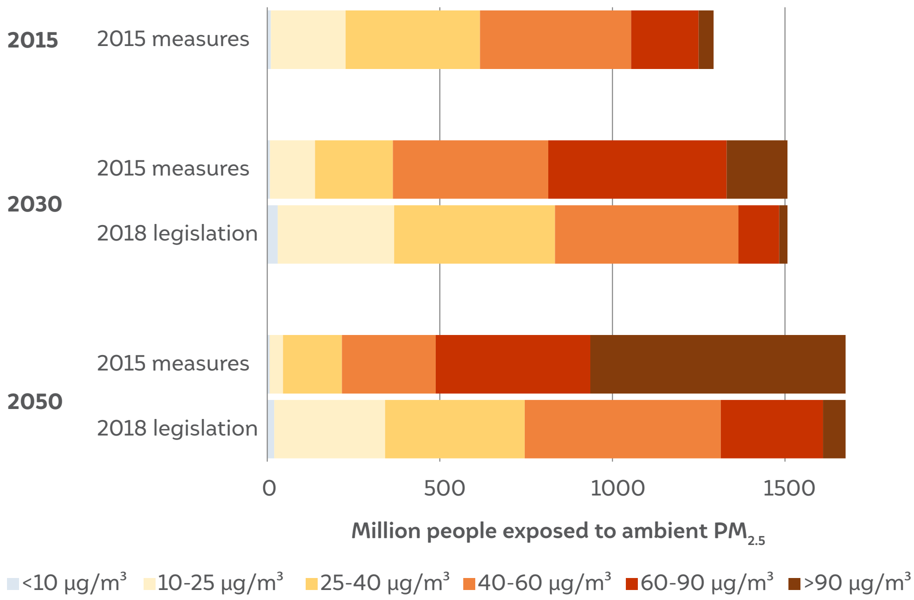


FIGURE E3: Distribution of population exposure to $PM_{2.5}$ in 2015, as well as projections for 2030 and 2050 as per 2015 measures and 2018 legislation scenarios

Source: IIASA-CEEW analysis, 2019

Solutions need cooperation

Effective solutions require regional cooperation between cities and states.

Effective solutions require regional cooperation between cities and states

Poor air quality is an inevitable consequence of the high population density, economic activity, and energy demands of the world's growing cities. However, air quality management is a problem that poses unique challenges due to the physical and chemical features of fine particulate matter.

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 hundred kilometres. Thus, a significant share of the particles found at any specific location would have originated from distant sources that are often outside the immediate jurisdiction and control of local authorities. This finding is best illustrated through a model analysis (Figure E4) that reveals the contribution of outside sources to ambient particulate matter concentrations. Figure 4 shows that in many Indian states, emission sources that are outside of their immediate jurisdiction contribute the largest share to (population-weighted) ambient pollution levels of $PM_{2.5}$. Mostly states cannot achieve significant improvements in their air quality and population exposure without emissions reductions in surrounding regions. Therefore, any cost-effective strategy to reduce pollution will require regionally coordinated approaches.

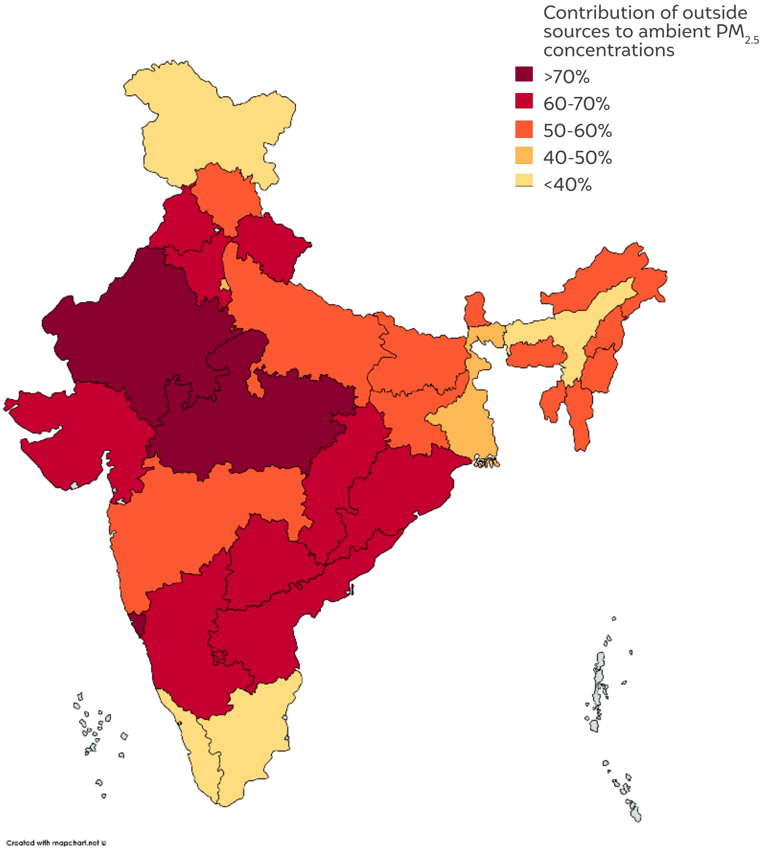


FIGURE E4: Contributions of emissions from other regions to population-weighted ambient $PM_{2.5}$ concentrations in each state/region

Source: IIASA-CEEW analysis, 2019

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

The $PM_{2.5}$ in ambient air originates 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 they originate from natural sources such as soil dust and sea salt. Another substantial fraction—secondary $PM_{2.5}$—is formed in the atmosphere through chemical reactions involving gaseous emissions. These precursor gases originate from energy combustion and industrial processes (SO_2, NO_x, and VOCs), and from agricultural activities (NH_3).

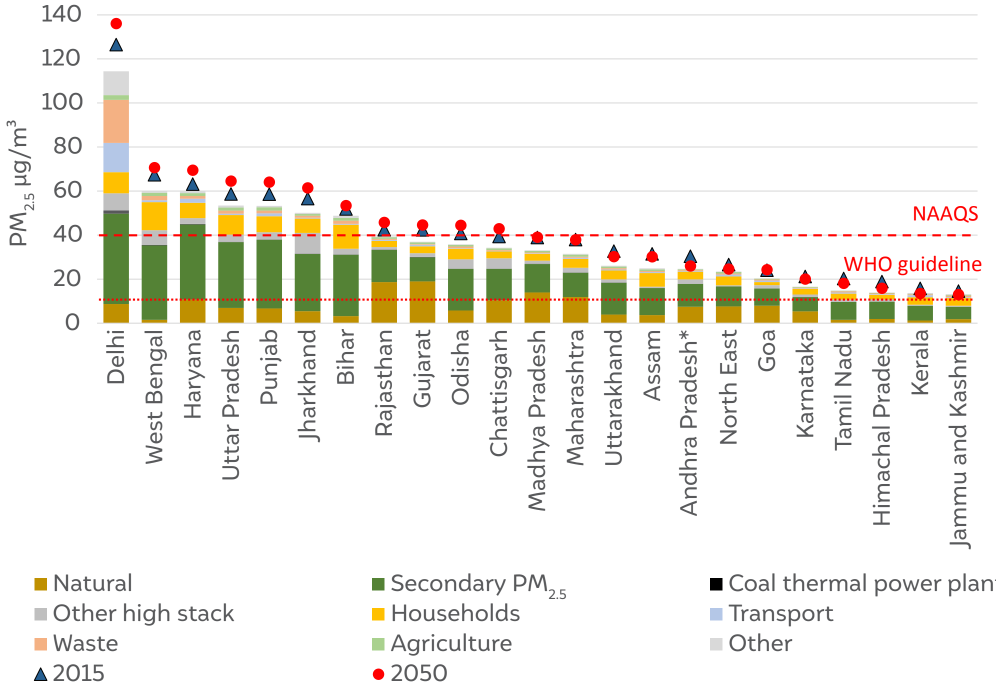
In contrast to many other countries, in India, the various precursor emissions do not only originate from sources that are associated with industrial development and more affluent lifestyles, which have shown rapid growth in recent years. Rather, a significant share of emissions still originates from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

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

A significant share of emissions still originates from sources associated with poverty and underdevelopment, such as solid fuel use in households and waste management practices

FIGURE E5:
Sectoral origin of population-weighted ambient $PM_{2.5}$ exposure in Indian states in 2015

Source: IIASA-CEEW analysis, 2019



Secondary particles formed in the atmosphere from agricultural NH_3 emissions through chemical reactions with SO_2 and/or NO_x emissions
** Including Telangana*

Policies and measures are available that could bring air quality more into compliance with NAAQS.

Several technical and non-technical interventions are already being applied in different parts of the world to improve air quality. While they are being employed in India in a limited way, wider application could theoretically deliver significant air quality benefits.

Advanced technical emission controls can deliver air quality improvements in India, but they will not be sufficient to achieve NAAQS everywhere.

Beyond what is included in the 2018 emission control legislation, there is scope to realise additional emission reductions and further improvements in air quality in India through a more comprehensive application of advanced technical emission controls, in line with models widely adopted in many other countries across the world. Without premature scrapping of existing capital stock, such a strategy could provide NAAQS-compliant air quality to 60 per cent of the Indian population if accompanied by ongoing efforts to provide universal access to clean household fuels.

Policies and measures are available that could bring air quality more into compliance with NAAQS

A package of development measures that support other policy priorities can deliver significant co-benefits for air quality

Measures that prioritise development can also facilitate air quality improvements in India, even if they are not primarily targeted at air pollution. These measures often fall under the jurisdiction of departments where air quality managers are not represented, and which do not have policy frameworks that prioritise air quality, such as economic and social development, energy or agricultural policies, or urban management.

If combined with advanced technical emission controls, such development measures could provide NAAQS-compliant air quality to about 85 per cent of the Indian population, and could reduce mean population exposure to $PM_{2.5}$ to about one-third of 2015 levels (Figure E6).

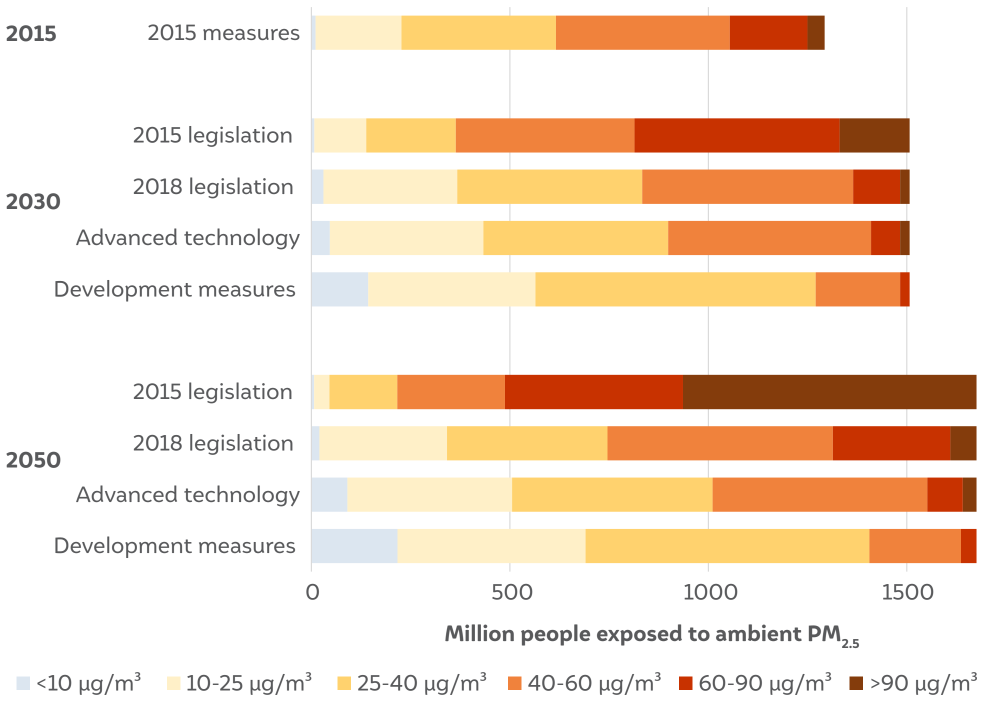


FIGURE E6: Distribution of population exposure in 2015, and projected emission control scenarios in 2030 and 2050

Source: IIASA-CEEW analysis, 2019

Development measures can deliver a wide range of benefits. The development measures identified in this report promote and encourage reduction of most polluting activities and encourages their substitution with cleaner alternatives, without diminishing human welfare. These measures include, for example, energy efficiency improvements, enhanced public transport, increased use of cleaner cookstoves, and the replacement of coal with natural gas and renewables (solar/wind) in the power and industry sectors. The portfolio also includes improved waste management and agricultural production practices. In addition to their air quality and health benefits, these measures will also contribute to multiple Sustainable Development Goals.

The most obvious benefit will be the reduction in greenhouse gas emissions—an essential dimension of SDG 13 ('Take urgent action to combat climate change and its impacts')—resulting in a decline of CO_2 emissions by about 60 per cent in comparison to the baseline case (Figure 7). Even without dedicated measures focused on methane, CH_4 emissions would be 40 per cent lower, and black carbon emissions would decline by 80 per cent as compared to 2015 levels.

Furthermore, the NO_x and VOC emission reduction measures taken in the interest of lowering ambient $PM_{2.5}$ concentrations will also produce less ground-level ozone, and thereby will deliver additional benefits to human health and vegetation and, in particular, will reduce damage to agricultural crops. However, the quantification of these effects was outside of the scope of this study.

Pursuing development goals as well as the judicious use of advanced emissions controls can help deliver cleaner air to nearly eighty per cent of India's population over the next decade.

If combined with advanced technical emission controls, such development measures could provide NAAQS-compliant air quality to about 85 per cent of the Indian population

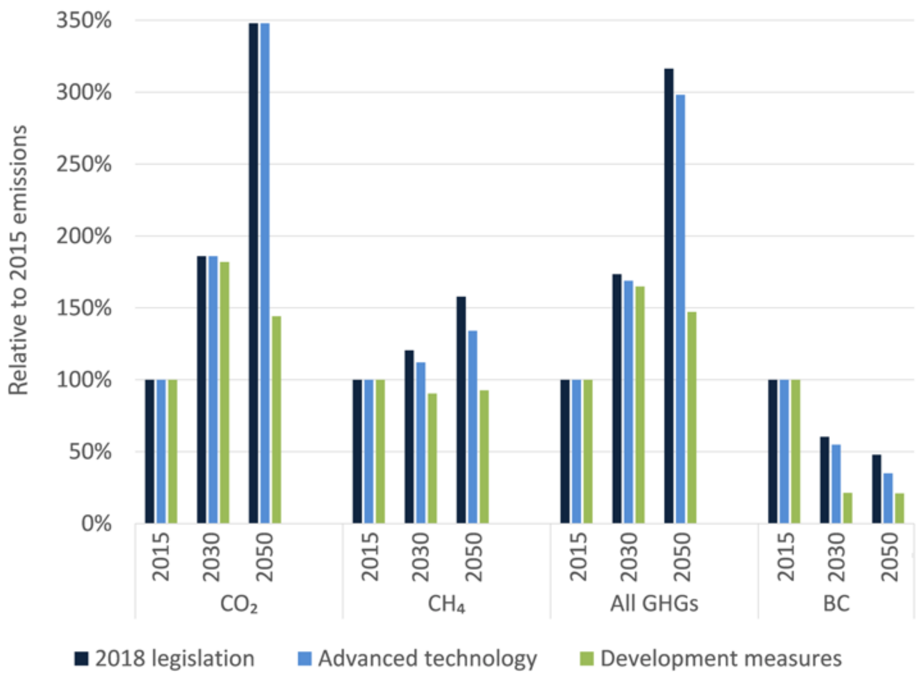


FIGURE E7:
Greenhouse gas and black carbon emissions in India in 2015, and projected emission control scenarios for 2030 and 2050

Source: IIASA-CEEW analysis, 2019

Urbanisation and population growth will fuel housing demand. Managing construction waste is important for pollution control.

Image: iStock

1. Introduction

India is making rapid progress in terms of economic growth and poverty reduction. However, this rapid urbanisation and the concurrent limited control of pollution are, at the same time, causing public health problems and significant environmental degradation, including of air, water, and land, and increased emission of greenhouse gases. These undermine the potential for sustainable socio-economic development and will have severe implications for the poor.

Today, more than 90 per cent of the world's population lives in areas where the air quality fails to meet the World Health Organization's global limit for $PM_{2.5}$ (WHO, 2016a). It is estimated that long-term exposure to excessive ambient and household air pollution contributes to about 6–7 million premature deaths from stroke, heart attack, lung cancer, and chronic lung diseases worldwide (HEI, 2018; WHO, 2016a). Nearly 90 per cent of these premature deaths occur in low- and middle-income countries, with close to two out of three in Asia and the Pacific.

Indian cities rank poorly in terms of air pollution, with several recording levels of $PM_{2.5}$ that are associated with serious health impacts. Numerous monitoring sites across India report

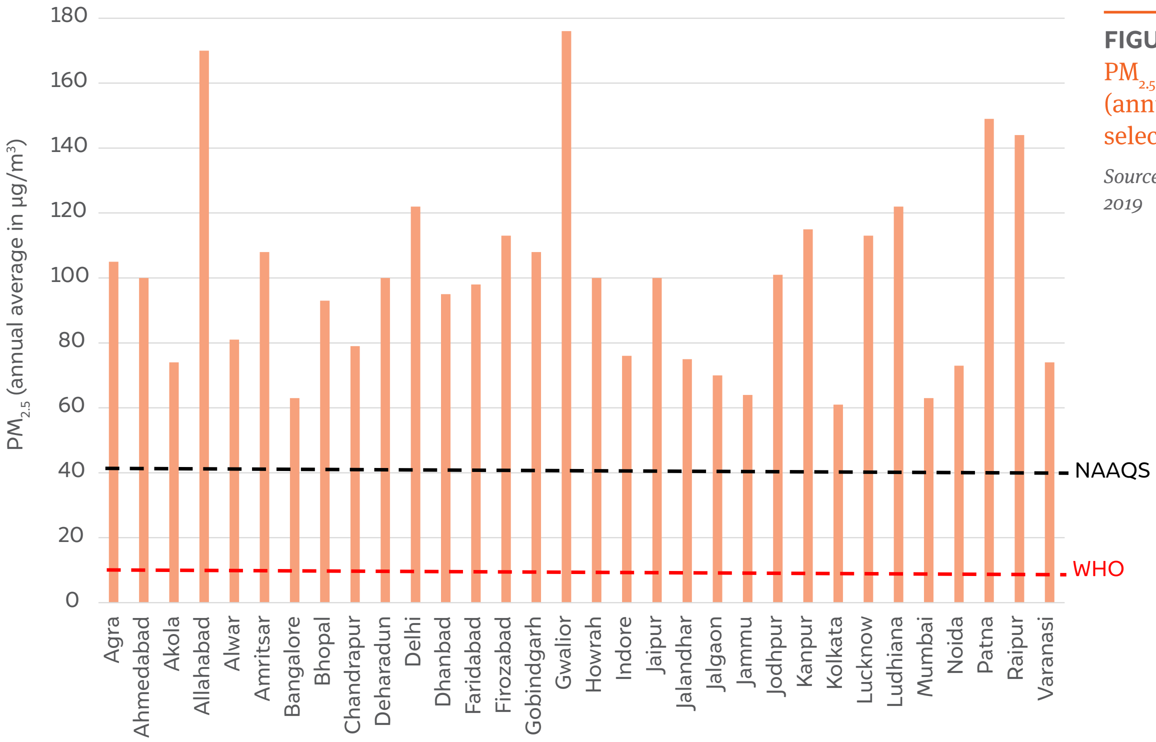
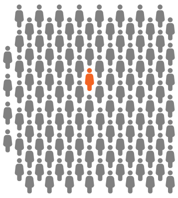


FIGURE 1:
$PM_{2.5}$ Concentrations (annual average) in select indian cities

Source: IIASA-CEEW analysis, 2019

high concentrations of $PM_{2.5}$ (CPCB, 2016), and NAAQS are being continuously violated (Figure 1). According to the WHO's recent Urban Air Quality Database, 10 Indian cities are ranked among world's top 20 worst cities with respect to air pollution (WHO, 2016c). It is estimated that only about one per cent of the Indian population is exposed to air that meets the WHO recommended $PM_{2.5}$ level (IEA, 2016), and the majority faces exposure of more than 35 µg/m³, which is above Target Level 1, the highest risk level defined by WHO. While pollution is high in cities, health risks posed by air pollution affect urban and rural communities across all socio-economic tiers.



Only about one per cent of the Indian population is exposed to air that meets the WHO recommended $PM_{2.5}$ level

These high pollution levels cause significant health impacts (Balakrishnan et al., 2014). While precise data is unavailable for India, the scientific literature estimates that between 483,000 and 1,267,000 cases of premature deaths occur annually from outdoor pollution, and 748,000 to 1,254,000 cases from indoor household pollution (Forouzanfar et al., 2016, 2015; Lim et al., 2012; WHO, 2016a). These health impacts are likely to impose a significant burden on the economy: a recent World Bank study estimates that welfare losses for 2013 were equivalent to 7.7 per cent of the national GDP (World Bank, 2016).

Studies have shown that the high ambient $PM_{2.5}$ concentrations in India originate largely from anthropogenic activities such as fossil fuel combustion in power generation, industrial processes, and motor vehicles, and solid fuel use in traditional residential cooking (Amann et al., 2017; CPCB, 2011; Pant et al., 2015; Chowdhury et al., 2018; Venkataraman et al., 2018). Without effective countermeasures, air quality is expected to further deteriorate as a result of polluting economic activities.

However, worldwide experience clearly demonstrates that clean air can be achieved without compromising social and economic development. This requires well-designed policies that prioritise cost-effective interventions for the sources that deliver the largest benefits, and that are well integrated with other development targets.

Image: iStock

Waste burning in landfills is a big source of secondary $PM_{2.5}$.

A faster adoption of new standards will dramatically reduce pollution from thermal power plants.

To improve air quality and enhance economic and social development, the Indian government has issued a National Ambient Air Quality Standard (NAAQS) of annual $PM_{2.5}$ concentrations of 40 µg/m³. A wide range of regulations and policies should control emissions from the important sources in order to achieve compliance with Indian air quality standards and international guidelines (CPCB, 2010).

1.1 A focus on fine particulate matter ($PM_{2.5}$)

In comparative risk assessments conducted to estimate the global burden of disease, exposure to fine particulate matter ($PM_{2.5}$) was identified as the largest health risk of air pollution (Lim et al., 2012). Due to their small size of less than 2.5 micrometres (µm), $PM_{2.5}$ particles penetrate deep into cells and respiratory systems where they can cause a wide range of negative health impacts. Epidemiological studies consistently show robust associations between exposure to $PM_{2.5}$ and mortality risk from ischemic heart disease, stroke, chronic obstructive pulmonary disease, acute lower respiratory infections, and lung cancer (Burnett et al., 2014; Pope et al., 2011).

The $PM_{2.5}$ found in ambient air is emitted by a variety of sources. Fine particles are directly emitted during the combustion of fossil fuels and biomass; they are caused by industrial processes; and they originate from natural sources such as soil dust and sea salt. A significant share of $PM_{2.5}$ is also formed in the atmosphere through chemical reactions involving gaseous precursor emissions.

While the sources and chemical processes that generate fine particles ($PM_{2.5}$) in the atmosphere are manifold and complex, the main mechanisms and features are well understood. For instance, in India, chemical measurements of $PM_{2.5}$ clearly demonstrate the shares of primary and secondary particles, during episodes and over the full year (Chakraborty et al., 2016). Primary particles include carbonaceous particles (black carbon and organic carbon) from biomass burning, non-carbonaceous particles from industrial processes (e.g., cement and steel production), fly ash, soil and road dust, and sea salt. About one-third of ambient $PM_{2.5}$ consists of secondary aerosols[1] (Philip et al., 2014; Pant et al., 2015; Sharma and Dikshit, 2016), generated through chemical reactions between gaseous precursor emissions, i.e., NH_3 (from agricultural sources), SO_2 and NO_x (mainly from fuel combustion), and non-methane volatile organic compounds (NMVOCs).

The high population densities, economic activities, and energy demands in the world's growing cities means that poor air quality is often regarded as an urban problem. However, the physical and chemical features of $PM_{2.5}$ add an important spatial challenge to the task of air quality management. 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 hundred kilometres. As a consequence, a significant proportion of particles found at any specific location would have originated from distant sources that are often outside the immediate jurisdiction and control of local authorities. Research shows that even in megacities such as Delhi, more than half of the ambient $PM_{2.5}$ found in urban areas originates from pollution sources that are outside the immediate jurisdiction of the municipal administration (Amann et al., 2017).

1.2 Population exposure to $PM_{2.5}$ – a shared metric for air quality impacts

Provision of good living conditions, including sufficiently clean air, is an overarching policy objective that is also tied to many of the Sustainable Development Goals. However, as there is great scientific uncertainty regarding how to quantify the health impacts of exposure to polluted air, the measures that have been proposed are regarded as somewhat controversial.

Provision of good living conditions, including sufficiently clean air, is an overarching policy objective that is also tied to many of the Sustainable Development Goals

Thus, for the purposes of this report, i.e., to promote a common understanding of measures that could improve air quality in India, the analysis refrains from employing such health impact quantifications, but applies a more physical-based metric to measure progress towards clean air. Along the same lines, this report uses different statistics related to population exposure as a shared metric. This considers the location of people as well as the different levels of $PM_{2.5}$ to which they are exposed.

The report presents the population-weighted mean exposure (for a given region), which is computed from fine-scale population and $PM_{2.5}$ concentration data. A second metric, the exposure distribution, quantifies how many people (or which share of the population) are exposed to different levels of $PM_{2.5}$.

The likely health benefits from changes in population exposure (due to different assumptions on emission control interventions) can then be quantified with different health impact assessment methodologies that have been developed for such purposes, with due consideration of the uncertainties associated with methodological knowledge gaps, data

1 SO_2, NO_x and NH_3 drive the formation of inorganic secondary $PM_{2.5}$ (secondary inorganic aerosols, SIA) in the form of ammonium sulphate and nitrate, through chemical reactions in air. The transformation of volatile and semi-volatile organic species is also responsible for the formation of secondary organic aerosol (SOA), which makes a smaller contribution to ambient $PM_{2.5}$ relative to SIA.

imperfections, assumptions about future economic development, and changes in the health status of the population.

1.3 Structure of this report

This report explores pathways towards achieving NAAQS in India, given social and economic development dynamics. Section 2 introduces the modelling tools used in this study. Section 3 discusses key features of air quality status in India, its drivers, the resulting population exposure, and the basic characteristics of pollution dispersion in the atmosphere. Section 4 considers future projections of economic development, and explores the likely impact of current polices and regulations on energy and air quality. It also explores the scope for air quality improvements using advanced technical emission controls as well as using a more comprehensive set of development priority measures. The costs and benefits of these alternative policy intervention scenarios are discussed in Section 5, and conclusions are drawn in Section 6.

Road dust is among the largest contributors to PM_{10} levels.

Image: iStock

2. Methods and Data

Measuring 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 knowledge of demographic, social, and economic development trends; urbanisation; emission sources; technological and economic information on possible emission controls; chemical and physical processes in the atmosphere; and the health impacts caused by air pollution.

To conduct such an assessment for India, this study employs a multidisciplinary scientific framework consisting of two well-established scientific modelling tools. The Global Change Assessment Model, or GCAM (see Section 2.1.2), investigates the socio-economic drivers of pollution, with a special emphasis on the energy sector. This data is then fed into the Greenhouse Gas–Air Pollution Interaction and Synergies (GAINS) model (see Section 2.1.1), to assess the effectiveness of policy interventions in reducing population exposure and health impacts. Findings are derived by comparing 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 implemented on the ground in 2015
- The additional policies and measures that have been decided after 2015
- The potential benefits from the full application of advanced technological emission controls
- The co-benefits for air quality resulting development measures that are usually in support of other policy objectives

2.1 Modelling tools

This report links two scientific modelling tools (Figure 2):: 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).

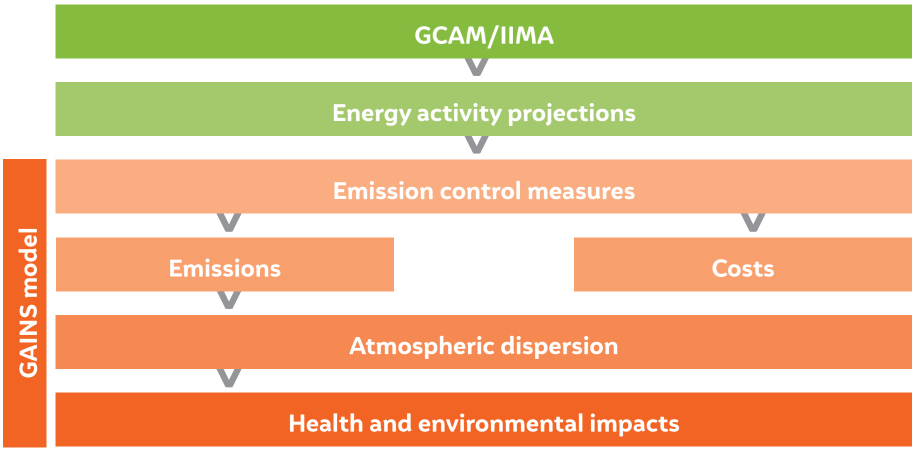


FIGURE 2:
The Methodological Approach: Soft linking GCAM-IIMA and GAINS

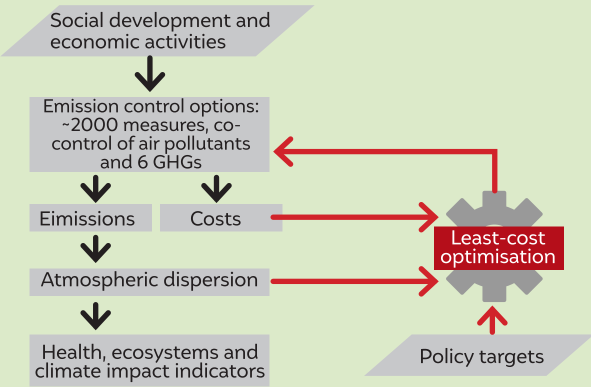
Source: IIASA-CEEW analysis, 2019

2.1.1 The GAINS model

The GAINS model developed by IIASA provides an authoritative framework for assessing the least costly strategies for reducing emissions of multiple air pollutants and greenhouse gases, and minimising their negative effects on human health, ecosystems, and climate change (Klimont et al., 2009; Amann et al., 2011; Purohit et al., 2010; Sanderson et al., 2013; Klimont et al., 2017; Rafaj et al., 2018). GAINS describes the pathways of atmospheric pollution from anthropogenic driving forces to health and environmental impacts. It brings together information on future economic, energy, and agricultural development, the scope for emissions control and associated costs, atmospheric dispersion, and environmental sensitivities towards air pollution, as shown in Table 1.

TABLE 1:
The GAINS model

Source: CEEW compilation



The GAINS (Greenhouse Gas–Air Pollution Interactions and Synergies) model explores cost-effective multi-pollutant emission control strategies to meet environmental objectives related to air quality impacts (on human health and ecosystems) and greenhouse gases. GAINS, developed by the International Institute for Applied Systems Analysis (IIASA), brings together data on economic development and the structure, control potential, and costs of emission sources, the formation and dispersion of pollutants in the atmosphere, and an assessment of the environmental impacts of pollution (http://gains.iiasa.ac.at).

GAINS addresses air pollution impacts on human health from fine particulate matter and ground-level ozone; vegetation damage caused by ground-level ozone; the acidification of terrestrial and aquatic ecosystems and excess nitrogen deposition to soils; as well as the mitigation of greenhouse gas emissions. GAINS describes the interrelations between these multiple effects and the pollutants (SO_2, NO_x, PM, NMVOC, NH_3, CO_2, CH_4, N_2O, F-gases) that contribute to these effects at the European scale.

For each of the source regions considered in the model, GAINS explores the cost-effectiveness of more than 1,000 measures to control emissions to the atmosphere. It computes the atmospheric dispersion of pollutants and analyses the costs and environmental impacts of pollution control strategies. Using its optimisation mode, GAINS can identify the least-cost balance of emission control measures across pollutants, economic sectors, and countries that meet user-specified air quality and climate targets.

GAINS describes the pathways of atmospheric pollution from anthropogenic driving forces to health and environmental impacts

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; Liu et al., 2013).

The Indian version of the GAINS model that is used for this study employs a spatially disaggregated representation of India comprising 23 subregions.[2] The national energy projections supplied by GCAM are allocated across Indian states using the proportional downscaling algorithm reported by Rafaj et al. (2013). Total energy consumption is distributed across states based on their shares as derived from subnational energy and industrial statistics. These statistics were compiled initially for the first version of the GAINS-India model (Purohit et al., 2010), and were later updated for the GAINS-City model for Delhi and its neighbouring states (Amann et al., 2017; Bhanarkar et al., 2018) as well as for the World Energy Outlook 2015 study focusing on India (Cofala et al., 2015). The downscaling procedure also allocates energy consumption to subsectors and fuel types that are not explicitly provided by the energy model. These include various transport categories (road/off-road; cars/trucks/buses; land-based/ships), industrial demand activities (cement/metals/chemicals/others; furnaces/boilers), and fuel conversion (refineries/coking/others).

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, which is computed by downscaling the activity projection as described above; (2) their technical features (e.g., fuel quality, plant types); and (3) the emission controls applied (GAINS includes a database of over 1,000 technical measures). For each key source sector, 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 resulting from 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 from several hundred to 1,000 kilometres.

To account for this long-range transportation of pollution, GAINS considers the contribution of emissions from within the particular state/region of interest, as well as the inflow from the rest of India and neighbouring countries (Kiesewetter et al., 2015; Liu et al., 2019). For this purpose, linear transfer coefficients are used to describe the emission changes at each source on ambient $PM_{2.5}$ concentrations throughout the model domain. Such coefficients have been computed using 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, SO_2, NO_x, NH_3, NMVOC) from one source region (each Indian state) were reduced by 15 per cent at a time. For primary $PM_{2.5}$, 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

2 Andhra Pradesh (including Telangana); Assam; West Bengal; Bihar; Chhattisgarh; Delhi NCT; North East (excluding Assam); Goa; Gujarat; Haryana; Himachal Pradesh; Jharkhand; Karnataka; Kerala; Maharashtra; Madhya Pradesh; Orissa; Punjab; Rajasthan; Tamil Nadu; Uttaranchal: Uttar Pradesh; and Jammu and Kashmir.

formation of secondary aerosols occurs on longer spatial and temporal scales, a 0.5º × 0.5º spatial resolution is considered sufficient to track 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 has been added based on fine-scale population distribution data drawn from www.worldpop.org (Gaughan et al., 2013) with a 100 m × 100 m resolution (Rafaj et al., 2018).

Results are presented in the form of maps showing ambient concentration of $PM_{2.5}$, and population-weighted mean concentrations of $PM_{2.5}$ for each Indian state/region. The latter 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 0.5º × 0.5º resolution for other areas. For future years, calculations consider urbanisation trends following the projections of population growth for urban and rural areas, based on the UN World Urbanization Prospects, the 2011 Revision (UNDESA, 2012).

2.1.2 The GCAM model

For projections of future economic activities, the study employs energy-use pathways generated with the GCAM model for India (Figure 3).

For projections of future economic activities, the study employs energy-use pathways generated with the GCAM model for India

GCAM is a global integrated assessment model for energy, economy, land use, and climate (McJeon et al., 2014). It provides a detailed representation of the energy sector both on the supply and demand side. GCAM models energy demand for three end-use sectors: buildings, industry, and transport. Model descriptions for the residential and commercial building sector can be found in Eom et al. (2012) and Chaturvedi et al. (2014), and for the transportation sector in Kyle and Kim (2011) and Mishra et al. (2013). The GCAM industrial module distinguishes various industrial sectors such as steel, paper, cement, etc. (Zhou et al., 2013). On the supply side, electricity production is modelled in detail, and takes into consideration nine fuels competing for electricity production, with more than one technology within each category of fuel.

For India, GCAM has been customised by the Indian Institute of Management Ahmadabad (IIMA). The IIMA-GCAM model provides more detail on the building sector in India, and distinguishes urban residential, rural residential, and commercial building sectors. Energy demand in the transportation sector is modelled for passenger transport (road, rail, and aviation), freight transport (road and rail), and international shipping, with the demand for each service computed based on per capita GDP. The industrial sector in GCAM-IIMA is modelled in an aggregate way, with industrial service demand responding to income growth and fuel prices. Demand for electricity generation and other forms of energy is determined for the end-use sectors where increases in income are likely to enhance the penetration of electricity-based technologies (e.g., air conditioning) and other-fuel based technologies (e.g., oil-based cars). Alternative technologies compete on relative costs and efficiencies to provide energy for any given service in end-use sectors. For example, electric cars compete with oil-based cars to provide passenger transportation services, and light-emitting diode (LED) bulbs compete with fluorescent and incandescent lightbulbs to provide lighting services in the buildings sector (Chaturvedi et al., 2018).

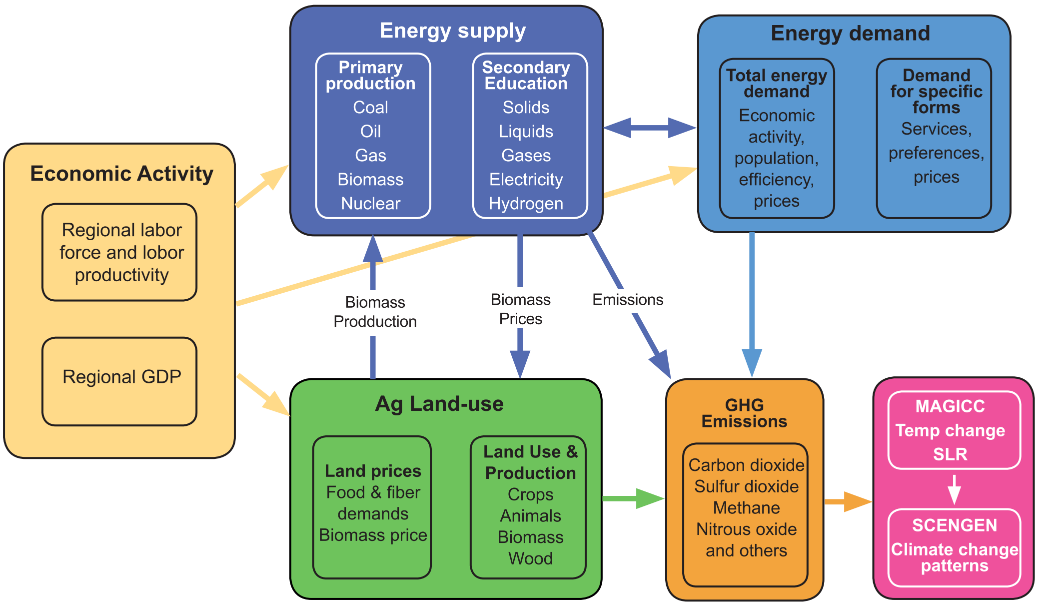


FIGURE 3: Schematic representation of Global Change Assessment Model

Source: Joint Global Change Research Institute/Pacific Northwest National Laboratory, USA

2.1.3 Data sources

The assumptions regarding macroeconomic development made in this study follow the medium economic growth rate projections of NITI Aayog, with an annual growth rate of 6.7 per cent from 2012 to 2047. Urbanisation is assumed to increase to about 50 per cent by 2050, and it is assumed that income inequalities between urban and rural populations will decline in the future. As a baseline, it is assumed that as a consequence of the current programme to provide clean cooking fuel to households, biomass will be entirely replaced by alternative cooking fuels by 2040. The assumptions and data sources underlying the GCAM model are described in detail in Annex 1.

Nationwide GCAM 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, lighting, etc. Data on activities 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 experiences that have been accumulated through GAINS model applications around the world over the last 30 years. While these encompass a wide range of 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 made to compile input data for GAINS from Indian statistics, although not all data could be extracted from these sources with sufficient robustness, and more work is required to confirm and improve the current databases.

Assumptions regarding macroeconomic development made in this study follow the medium economic growth rate projections of NITI Aayog

Mobility choices impact $PM_{2.5}$ levels. Emissions from diesel vehicles are proven to be carcinogenic.

Image: iStock

3. Understanding of the Current Situation

To explore the scope and effectiveness of potential future policy interventions, the analysis starts with an inventory of current emission sources, based on detailed spatial statistics.

Activity data on pollution-generating activities at the national level provided by the GCAM model have been downscaled to the state level using the proportional downscaling algorithm of the GAINS model. Emission factors have been adjusted to reflect (to the extent local information is available) the India-specific technical features of sources, and an inventory of already implemented and decided emission control measures has been compiled. Subsequently, the atmospheric dispersion calculation of GAINS (see Section 2.1.1) is used to compute the transport and chemical conversion of emissions in the atmosphere, with the aim of estimating the resulting fields of $PM_{2.5}$ across the model domain, and calculating the resulting population exposure.

3.1 Emissions of $PM_{2.5}$ precursor substances

According to regional activity statistics, it is estimated that in 2015 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 (Table 2). India's largest state, Uttar Pradesh, contributes the largest share of emissions of $PM_{2.5}$ (14 per cent) and NH_3 (14 per cent) to the national total, whereas the second large state, Maharashtra, contributes the largest share of emissions of SO_2 (12 per cent) and NO_x (10 per cent) (Figure 4).

GAINS regions	SO_2	NO_x	Primary $PM_{2.5}$	NH_3
Andhra Pradesh	853.3	555.9	431.6	714.0
Assam	57.9	89.0	130.2	187.4
Bihar	176.5	191.1	396.0	501.1
Chhattisgarh	497.7	277.7	212.7	201.3
Delhi	79.9	173.4	25.1	19.8
Goa	36.7	35.7	9.8	5.0
Gujarat	1,038.3	629.5	332.8	403.1
Haryana	381.1	355.9	130.6	334.4
Himachal Pradesh	23.3	59.8	30.2	56.6
Jammu and Kashmir	27.9	52.0	40.6	98.6
Jharkhand	601.2	306.2	277.6	171.8
Karnataka	438.8	358.7	279.9	383.5
Kerala	170.4	281.3	134.9	61.5

TABLE 2: Precursor emissions of $PM_{2.5}$ estimated for 2015 (kilotons)

Source: IIASA-CEEW analysis, 2019

Madhya Pradesh	548.4	388.4	368.8	555.9
Maharashtra	1,222.2	709.1	509.0	623.5
North East (excl. Assam)	55.7	93.5	64.7	84.6
Odisha	406.0	255.1	280.6	286.8
Punjab	309.3	227.4	124.2	342.9
Rajasthan	715.3	478.4	357.0	535.1
Tamil Nadu	708.7	685.8	312.1	400.6
Uttar Pradesh	896.7	582.2	820.8	1327.7
Uttaranchal	29.3	37.9	37.8	76.4
West Bengal	511.6	392.9	445.2	556.3
Total	9,786.2	7216.9	5752.2	7927.9

Note: Andhra Pradesh includes Telangana

The largest sources of fine particles ($PM_{2.5}$) in the atmosphere were from the residential sector (52 per cent)

Almost 82 per cent of the total SO_2 emissions originated from power generation and industrial energy combustion activities; an estimated 45 per cent of NO_x emissions come from mobile sources; industrial sources contributed 16 per cent; and the power sector contributed 30 per cent. The largest sources of fine particles ($PM_{2.5}$) in the atmosphere were the residential sector (52 per cent), with its incomplete combustion of solid fuels, and the industrial sector (18 per cent). NH_3 emissions were predominantly released from agricultural activities such as livestock farming, fertiliser application, and manure management (Figure 4). Approximately one-third of the total SO_2 emissions came from three states, namely Maharashtra, Gujarat, and Uttar Pradesh. Six states (Maharashtra, Tamil Nadu, Gujarat, Uttar Pradesh, Andhra Pradesh, and Rajasthan) contributed about half of the total NO_x emissions, whereas one-third of the total primary $PM_{2.5}$ emissions originated in the states of Uttar Pradesh, Maharashtra, and West Bengal, primarily due to the large share of the population in those states using solid fuels for cooking.

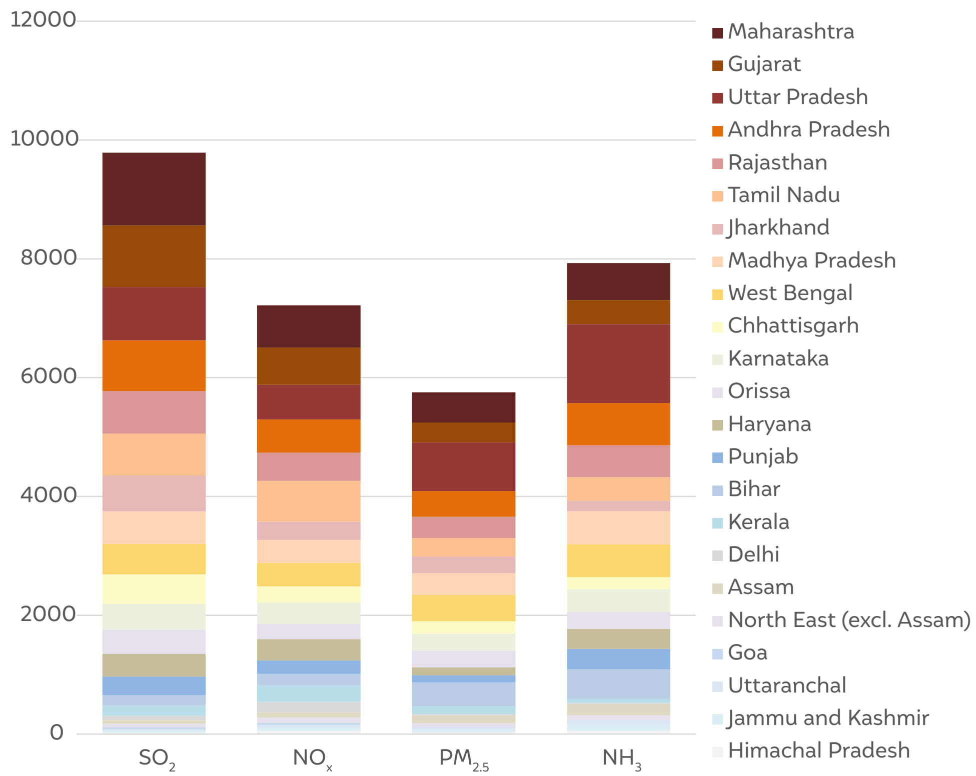


FIGURE 4: Emissions of $PM_{2.5}$ precursors in India by region, estimated for 2015

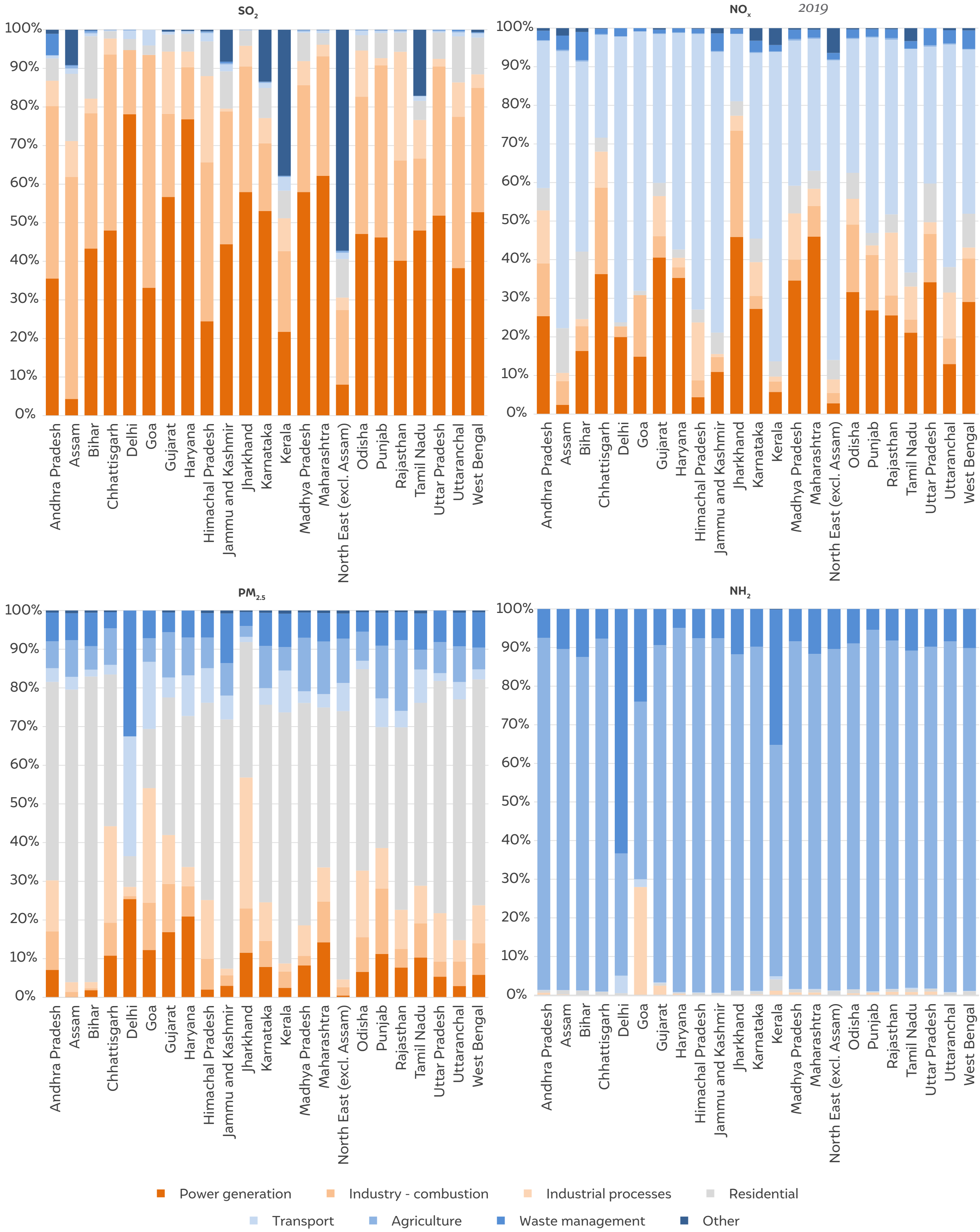
Source: IIASA-CEEW analysis, 2019

Note: Andhra Pradesh includes Telangana

Most noteworthy, the relative contributions to total emissions differ significantly across the Indian states. For instance, solid fuel (biomass) combustion for residential cooking is the most important contributor in the major states of the Indo-Gangetic Plain, while in Delhi NCT and Goa, it contributes only a small amount due to the enhanced access to clean fuels in these states. By contrast, NO_x emissions from transportation make the largest contribution to total emissions in Delhi NCT, and SO_2 emissions from the power plant sector dominate in Haryana and Maharashtra (Figure 5).

FIGURE 5: Relative contributions of different sectors to the precursor emissions of $PM_{2.5}$ in the Indian states, GAINS estimates for 2015

Source: IIASA-CEEW analysis, 2019



3.2 Ambient concentrations of $PM_{2.5}$

According to estimates from the GAINS model, the largest $PM_{2.5}$ concentrations occur in the Indo-Gangetic Plain (IGP) due to the high density of polluting sources and reduced ventilation caused by the obstructing presence of the Himalayas (Figure 6). Elsewhere in the nation, high concentrations coincide with densely populated areas or large cities. There is a clear north–south gradient in $PM_{2.5}$ concentrations: concentrations reach 126 µg/m³ in Delhi NCT, and range between 40 and 70 µg/m³ in the northern, western, eastern and north-eastern states of the IGP. About 661 million people living in that region are exposed to ambient concentrations far above the NAAQS. Concentrations fall to levels of between 20 and 30 µg/m³ in the southern states, where the total population is about 250 million. The cleanest air is found in the Himalayan states, with annual $PM_{2.5}$ concentrations as low as 15 µg/m³. This means that efforts to comply with NAAQS are clearly required in all the northern states, while the southern states need to ensure that their future economic development will not compromise air quality.

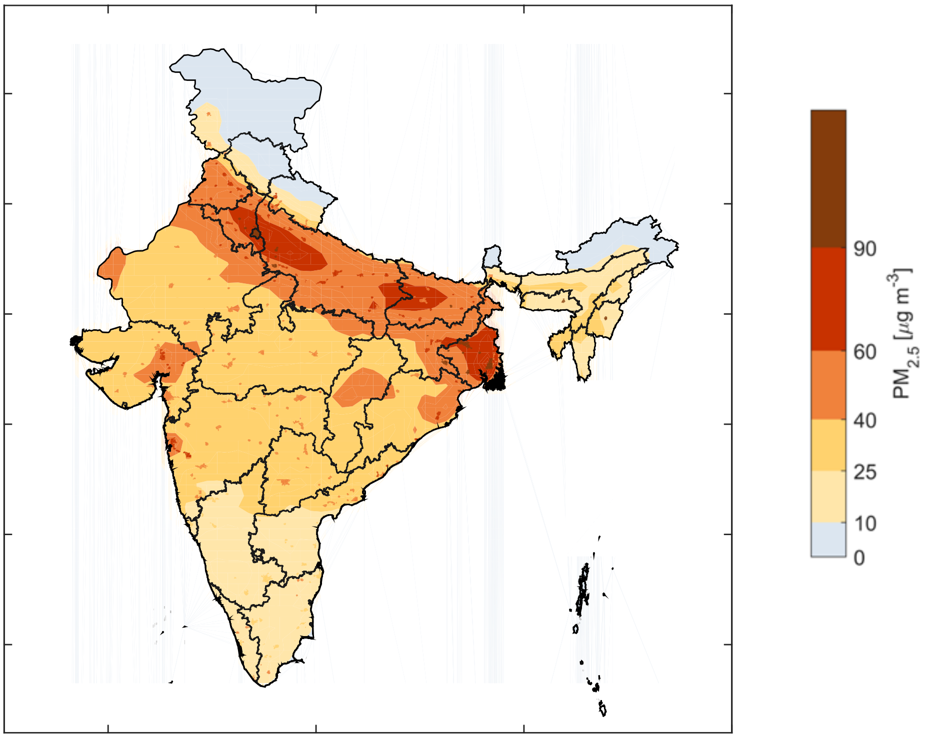


FIGURE 6: Ambient levels of $PM_{2.5}$ modelled for 2015 (annual mean concentrations, µg/m³)

Source: IIASA-CEEW analysis, 2019

3.3 Population exposure to $PM_{2.5}$

While absolute levels of $PM_{2.5}$ concentrations are relevant for compliance with the NAAQS, the health impacts of pollution, and the health benefits from policy interventions, are linked to population exposure, i.e., how many people are exposed to different levels of $PM_{2.5}$. For 2015, the model analysis suggests that about 616 million people in India have enjoyed air quality that conforms to the national standard, while almost 677 million people have been exposed to higher concentrations (Figure 7). The highest population exposure was found in the states of the Indo-Gangetic Plain.

The highest population exposure was found in the states of the Indo-Gangetic Plain

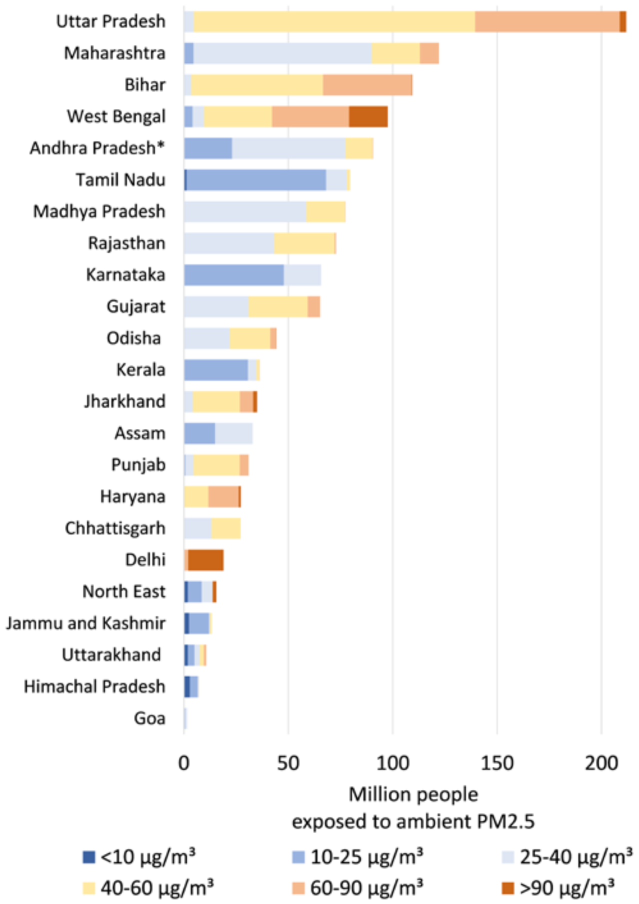


FIGURE 7: Distribution of population exposure to ambient $PM_{2.5}$ in 2015 (GAINS estimates)

Source: IIASA-CEEW analysis, 2019

*Note: *Andhra Pradesh includes Telangana*

3.4 Source apportionment

Source apportionment figures within a particular region quantify the contributions to ambient $PM_{2.5}$ of the various emission sources and from other regions. These figures help inform analyses of (cost-effective) response measures that could reduce exposure and decrease ambient concentrations to national and international air quality standards. The GAINS tool can produce source apportionments for any location or state within the model domain.

For instance, for the National Capital Territory of Delhi (Figure 8), it is estimated that approximately half of the population exposure to $PM_{2.5}$ is caused by emissions within the region. Another 50 per cent of the $PM_{2.5}$ in ambient air in Delhi NCT is transported into the city from outside, out of which about half comes from the surrounding states of Haryana and Uttar Pradesh, and the rest from even more remote anthropogenic sources and natural sources.[3] Furthermore, the sectoral source apportionment indicates that about 20 per cent 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 per cent comes from household fuels and waste management. 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.

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3 Note that the source apportionment presented in this paper is conducted for the meteorological conditions (wind patterns, etc.) in 2015. The analysis presented in Amann et al. (2017)"container-title":"Atmospheric Environment","page":"99-111","volume":"161","source":"ScienceDirect","abstract":"Megacities in Asia rank high in air pollution at the global scale. In many cities, ambient concentrations of fine particulate matter ($PM_{2.5}$ employed the 2010 meteorology, which led to slightly higher figures for inflow from outside sources.

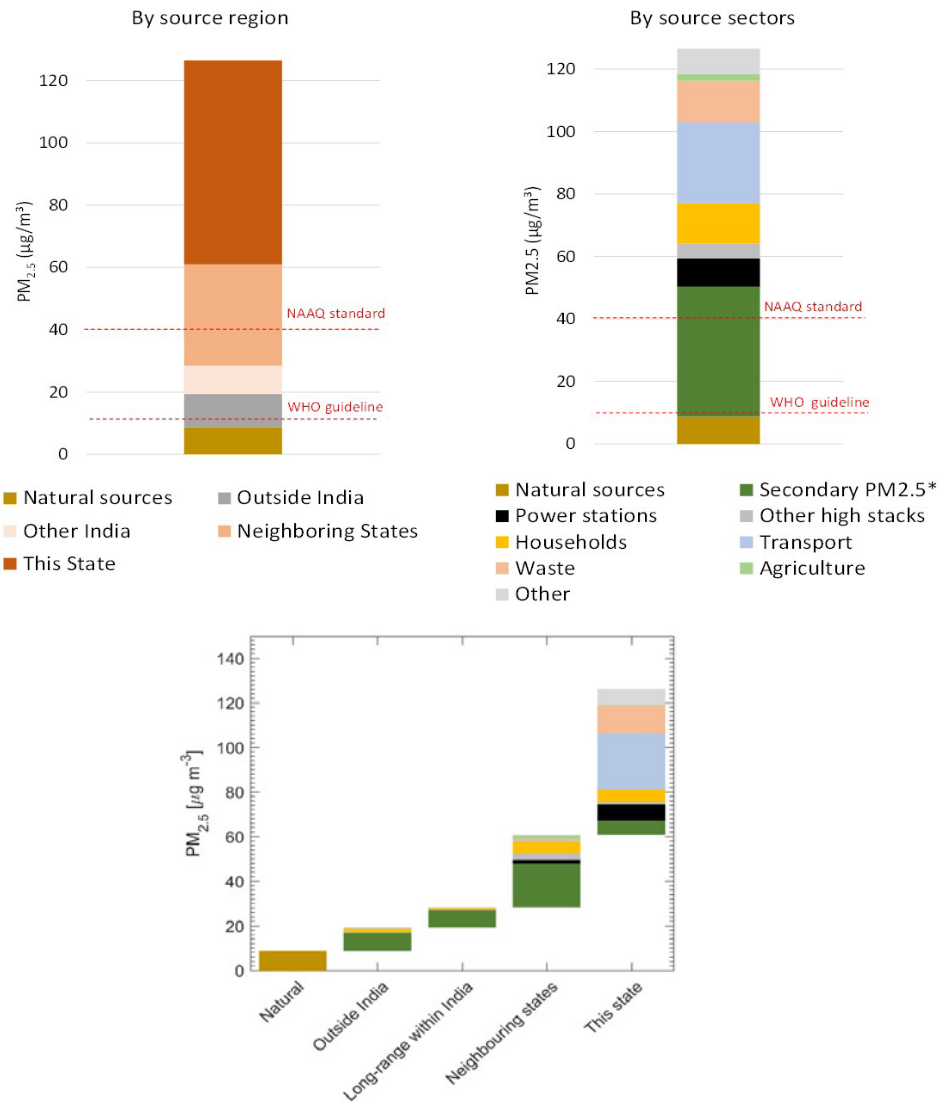


FIGURE 8:
Sources of $PM_{2.5}$ concentrations (population-weighted annual mean) in Delhi NCT in 2015.

Source: IIASA-CEEW analysis, 2019

Note: The x-axis distinguishes the spatial origin of $PM_{2.5}$, i.e., from right to left: (i) emission sources within the Delhi NCT, (ii) sources in the neighbouring states of Uttar Pradesh and Haryana, (iii) emissions from other Indian states, (iv) emissions from other countries, and (v) natural sources

As to be expected, the relative importance of emission sources for ambient $PM_{2.5}$ concentrations varies widely across India due to differences in orographic and meteorological conditions, population densities, and the structure of emission sources.

In general, smaller states—and particularly cities within smaller states—experience a larger inflow of pollution from surrounding states and regions than do larger territorial units (Figure 10). For instance, despite the large population size of Punjab with about 28 million inhabitants, only about 40 per cent of the population-weighted mean ambient $PM_{2.5}$ originates from emission sources within the state (Figure 10). Another 60 per cent of the $PM_{2.5}$ in the ambient air in Punjab is transported from outside the state, out of which about half comes from regions outside India (i.e., Pakistan), and half from other states in India and natural sources. Even in Uttar Pradesh, which currently has about 200 million inhabitants, only about 50 per cent of the population-weighted $PM_{2.5}$ originates from local emission sources. Detailed source apportionment estimates for all states are provided in Annex 2.

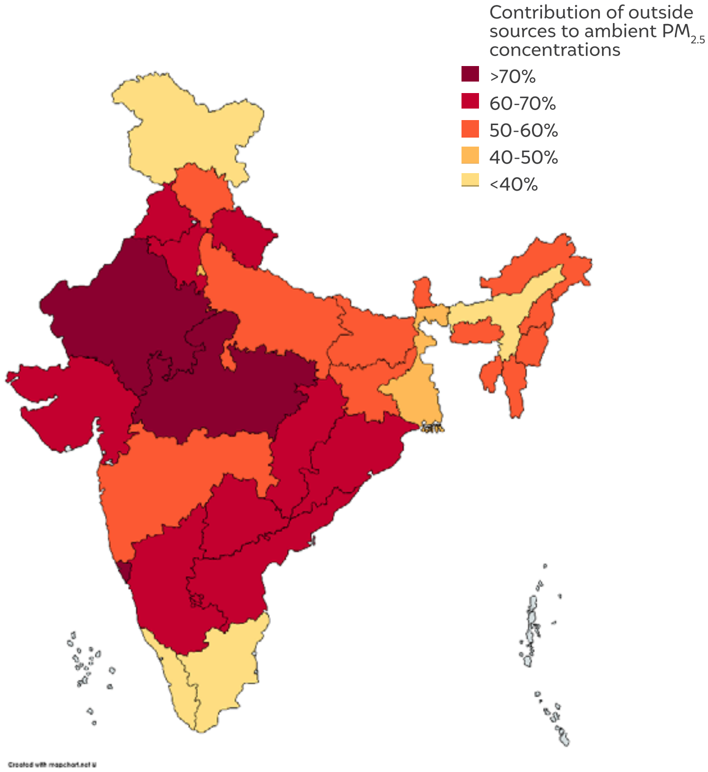


FIGURE 9:
Contributions of emissions from other regions to population-weighted ambient $PM_{2.5}$ concentrations in each state/region

Source: IIASA-CEEW analysis, 2019

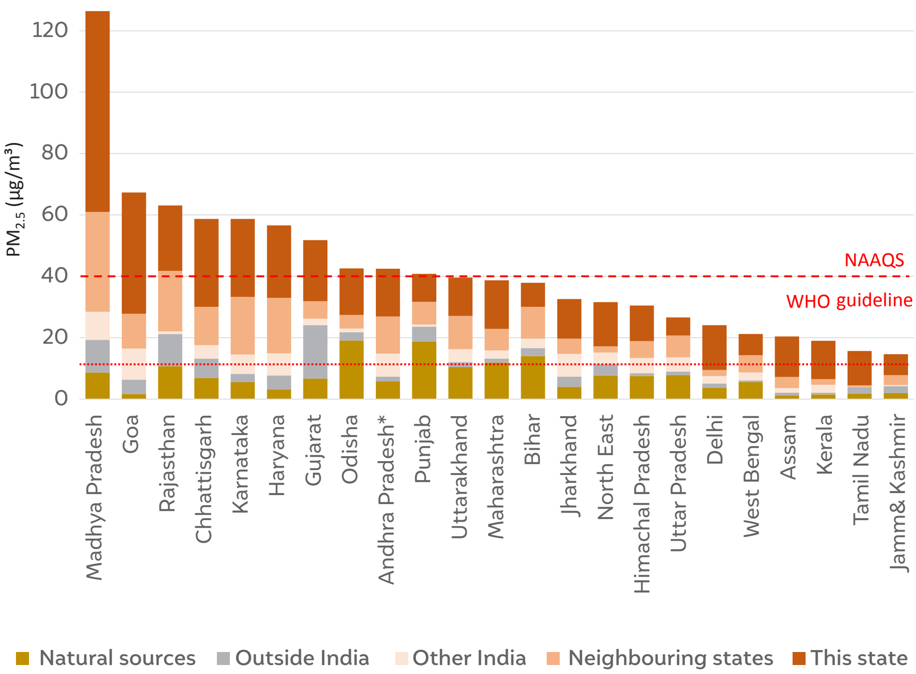


FIGURE 10:
Spatial origin of ambient $PM_{2.5}$ exposure in the Indian states, 2015 (ranked by decreasing shares of pollution inflow)

Source: IIASA-CEEW analysis, 2019

**Andhra Pradesh includes Telangana.*

The share of secondary $PM_{2.5}$ varies from 27 per cent in the North East to 55 per cent in the state of Odisha, due to the high emissions of SO_2, NO_x and NH_3 in the latter (Figure 4). Even in Delhi NCT, one-third of $PM_{2.5}$ is attributed to secondary particles (Figure 8). These secondary particles are formed in the atmosphere through reactions of primary gaseous pollutants (NO_x, NH_3, SO_2, and NMVOCs). Contrary to widespread belief, road traffic is not the dominating source.

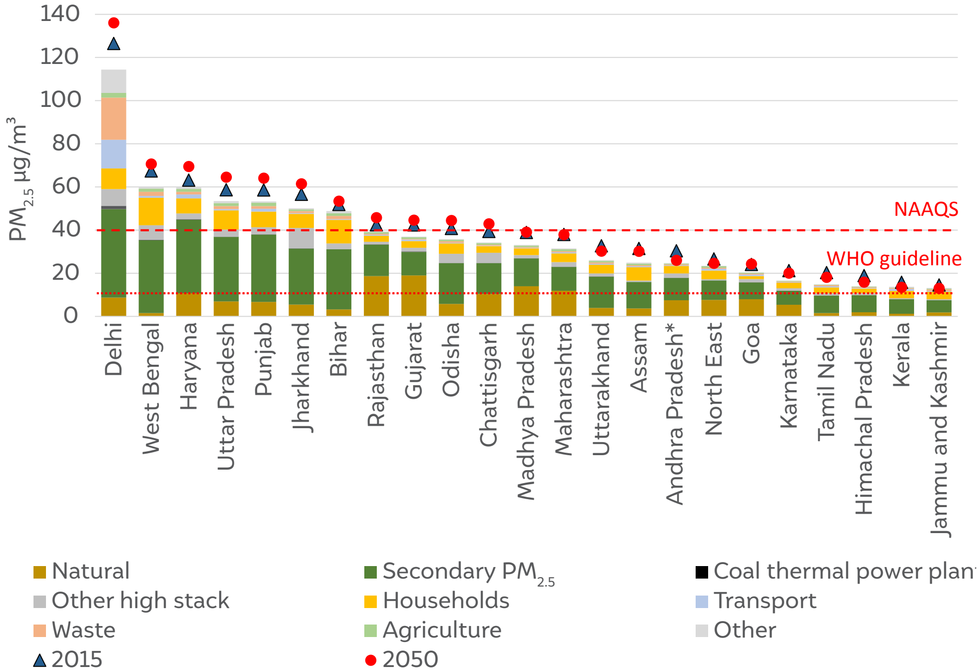


FIGURE 11: Sectoral origin of population-weighted ambient $PM_{2.5}$ exposure in the Indian states in 2015

Source: IIASA-CEEW analysis, 2019

Secondary particles formed in the atmosphere from agricultural NH_3 emissions, through chemical reactions with SO_2 and/or NO_x emissions

** Including Telangana*

3.5 Household pollution

In addition to the exposure to harmful pollution in ambient air, people using solid fuel for cooking without proper ventilation experience additional exposed within their homes. In India, approximately 170 million households, primarily in rural areas, were exposed indoors and near the household to pollution resulting from poor combustion of solid fuels in traditional cook stoves (Bonjour et al., 2013), causing larger health impacts from this source (more than 0.9 million premature deaths annually) than in any other country (IHME, 2015).

Household air pollution (HAP) from solid fuels (such as wood, animal dung, crop residues, charcoal and coal) for cooking and heating is a substantial cause of respiratory illness and death, due to a range of health damaging pollutants such as fine particles, carbon monoxide (CO), nitrogen oxides (NO2), sulphur dioxide (SO2), benzene, butadiene, formaldehyde, polyaromatic hydro-carbons and a number of other chemicals (Naeher et al., 2007) and remains a major public health concern in the developing world (Chafe et al., 2014; Goldemberg et al., 2018; Smith and Mehta, 2003). Prolonged human exposure to HAP especially the fine and ultrafine particles has an increased risk of health: respiratory tract infections, exacerbations of inflammatory lung conditions, cardiac events, stroke, eye disease, tuberculosis (TB) and cancer (Gordon et al., 2014).

In 2015, people in approximately 170 million households in India, primarily in rural areas, were exposed indoors and near the household to pollution resulting from poor combustion of solid fuels in traditional cook stoves (Bonjour et al., 2013), causing larger health impacts from this source (> 0.9 million premature deaths annually) than in any other country (IHME, 2015).

Household air pollution (HAP) from the use of solid fuels for cooking and heating (such as wood, animal dung, crop residues, charcoal, and coal) is a substantial cause of respiratory illness and death

Starting in 2015, the Government of India (GoI) pursued a number of targeted programs to actively promote LPG to the poor. 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 71 million already installed by mid-March 2019.

India's urban transition has increased our energy footprint. Fossil fuels contribute significantly to our energy mix.

4 Future Air Quality

To explore the effectiveness of alternative policy interventions in improving air quality in the context of rapid social and economic development in India, this report 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 macroeconomic development, and illustrate the impacts of different energy and air quality policy interventions.

4.1 Economic development trends

The baseline projections for population and economic development follow the recent estimates of the government, as reflected 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 cent per year until 2030, and a 0.46 per cent growth per year thereafter, resulting in a 31 per cent increase in the population in 2030 compared to 2015 (Table 3). At the same time, economic wealth (expressed as GDP/capita) will improve by five per cent per year, which will result in an almost tenfold increase in total economic output (GDP) by 2050 (Figure 12, first panel).

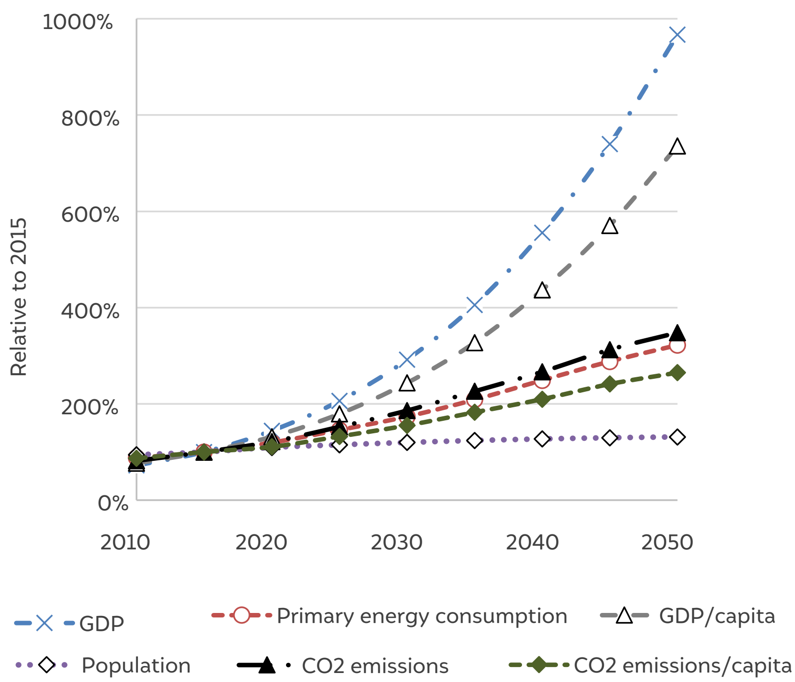


FIGURE 12: Assumed baseline trends of macroeconomic indicators, relative to the year 2015 (left panel) and primary energy consumption (in EJ/year) (panel next page)

Source: IIASA-CEEW analysis, 2019

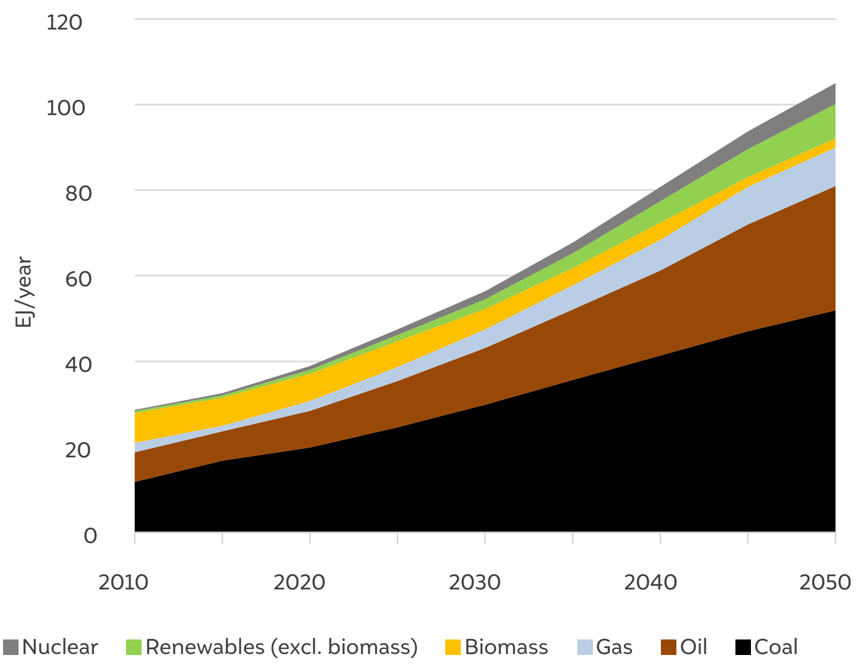


FIGURE 12:
Contd.

Corresponding projections for energy use have been estimated using the GCAM model (Chaturvedi et al., 2018; see Section 2.1.2). Notably, these reflect current climate and energy policies and regulations, as well as the relevant policy intentions of the Indian government, in particular targets set for renewables and coal, and the push to provide universal, reliable electricity access. Using this procedure, it is possible to estimate that total primary energy consumption will increase 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 fuels, particularly LPG, including the provision of 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 by 4.3 and 6.6 times (Figure 12, second panel).

TABLE 3: Macroeconomic development and growth in energy consumption, projected from a 2015 baseline

Source: IIASA-CEEW analysis, 2019

	Unit	2015	Annual growth rate 2015–2030	2030	Annual growth rate 2030–2050	2050
Population[1]	Million	1,263	1.21%	1,513	0.46%	1,659
Per capita income[1]	€	1,336	6.12%	3,252	5.69%	9,830
GDP[1]	Billion €	1,686	7.40%	4,921	6.18%	16,307
Vehicle mileage[2]	Billion km	791	6.28%	1,973	5.35%	5,596
Energy intensity[2]	MJ/€ GDP	19	–3.40%	12	–2.87%	6
Total primary energy consumption[2]	PJ	32,625	3.74%	56,622	3.14%	105,093
Biomass consumption[2]	PJ	6,509	–2.07%	4,753	–3.90%	2,141
Coal use[2]	PJ	16,773	3.91%	29,830	2.81%	51,911
Liquid fuels[2]	PJ	6,825	4.55%	13,306	3.99%	29,062
Gaseous fuels[2]	PJ	1,361	8.01%	4,326	3.71%	8,958
Renewable energy[2]	PJ	558	9.87%	2,293	6.49%	8,061
Other forms of energy[2]	PJ	599	8.78%	2,114	4.36%	4,961

[1] *Assumption, following the medium-growth scenario of NITI Aayog*

[2] *Result from the GCAM model*

4.2 The 2015 policies and measures

In 2015, India implemented a range of emission control measures, mainly controls for primary particulate matter (dust) at large stationary sources (power plants) and measures to reduce exhaust emissions from road vehicles (Table 4). 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.

TABLE 4: Policies and measures considered in the 2015 legislation scenario

Source: IIASA-CEEW analysis, 2019

POWER SECTOR

- Deployment of a mix of subcritical and supercritical technologies in coal power plants after 2015
- Increased efforts to establish the financial viability of all power market participants, especially network and distribution companies
- Strengthened measures, such as competitive bidding, to increase the use of renewables towards the national target of 175 GW of renewables capacity by 2022 (100 GW solar, 75 GW non-solar)
- Established renewable purchase obligation (RPO) and other fiscal measures to promote renewables
- Set particulate matter controls: electrostatic precipitators (ESPs)
- Implemented SO_2 controls: very small share of flue gas desulphurisation (<2%) in power plants (only three power plants).

MOBILE SOURCES

- Passenger cars: Bharat Stage III (nationwide from 2010)
- Passenger cars: Baharat Stage IV (NCR and 13 cities from 2010)
- Light and heavy-duty trucks: Bharat Stage III (nationwide from 2010)
- Light and heavy-duty trucks: Bharat Stage IV (NCR and 13 cities from 2010)
- Two- and three-wheelers: Bharat Stage III (from 2010)
- Agricultural tractors and construction machinery: Bharat Stage III (from 2011)
- FAME[4] scheme 1: Incentives for increasing adoption of electric vehicles (EVs)

Since 2010, these measures have effectively decoupled air pollutant emissions from economic growth (Figure 13). Their impacts on improved ambient air quality, however, are not directly visible since they have been neutralised by the rapid expansion of economic activities. In the future, the already implemented measures will not be sufficient to halt a further deterioration in air quality in view of the tenfold increase in GDP that is expected by 2050.

4 The FAME India (Faster Adoption and Manufacture of (Hybrid and) Electric Vehicles) Scheme was launched by the Ministry of Heavy Industries and Public Enterprises in 2015 to incentivise the production and promotion of eco-friendly vehicles including electric vehicles and hybrid vehicles. FAME India is a part of the National Electric Mobility Mission Plan. The main thrust of FAME is to encourage electric vehicles by providing subsidies. Vehicles in most segments—two-wheelers, three-wheelers, electric, hybrid cars, and electric buses—benefitted from subsidies through this scheme.

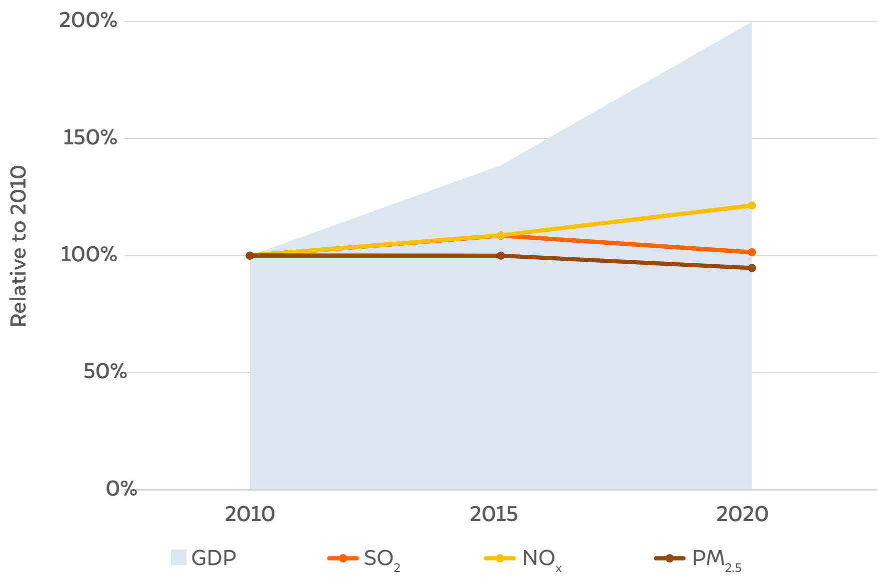


FIGURE 13:
Trends in GDP and emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and primary particulate matter ($PM_{2.5}$) in India, 2010–2020

Source: IIASA-CEEW analysis, 2019

4.3 The '2018 emissions legislation' scenario

To provide a reference for assessing the effectiveness of additional policy interventions, the '2018 emissions legislation' scenario illustrates the impact that the timely implementation and effective enforcement of all emission control measures, regulations, and standards that were in force in mid-2018 will have, in particular those that have been decided after 2015 (Table 4; details are provided in Annex 3).

4.3.1 Emission controls

In particular, this scenario assumes the maximum possible success for the latest policies aimed at providing poor households access to clean fuels (Table 5). For stationary sources, it assumes effective implementation of the current PM emission standards for power plants and industrial combustion activities. For SO_2, the new pollution norms (MoEFCC, 2015) require coal power plants to install and operate flue gas desulphurisation (FGD). For NO_x, new plants will meet the 100 mg/Nm^3 NO_x standard through selective catalytic reduction (SCR). Existing plants will comply with the 300 mg/Nm^3 standard through combinations of primary measures, selective non-catalytic reduction (SNCR), and in some cases SCR (Table A.2 in Annex 3).

For mobile sources (road and off-road), the 2018 legislation scenario considers the Indian Bharat Stage Emission Standards set for previous years, and assumes the extension of the Bharat Stage (BS) VI to all new on-road vehicle categories after 2020 (MoRTH, 2016), and BS IV for non-road machinery from 2020, followed by BS V from 2024.

TABLE 5:
Additional policies and measures considered in the 2018 legislation scenario (over and above the 2015 measures scenario)

Source: IIASA-CEEW analysis, 2019

POWER PLANTS

- Complete move towards supercritical technologies in coal power plants
- Reverse bidding of solar and wind power plants
- Flue gas desulphurisation for SO_2
- Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) for NO_x

MOBILE SOURCES

- BS VI controls (all road vehicles) from 2020 onwards
- Bharat (Trem) Stage IV controls (non-road machinery) from 2020 onwards, and Stage V from 2024
- FAME scheme 1: Incentives for increasing the adoption of electric vehicles and push to remove infrastructure barriers in India

INDUSTRY

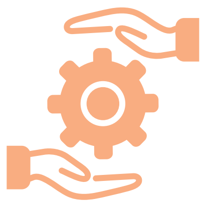
- Full compliance with the PAT-I[5] and PAT-II cycle
- Zig-zag or vertical shaft kilns for all new brick production installations
- New emission standards for SO_2 and NO_x for five industries (ceramics, foundries with furnaces based on fuel, glass foundries, lime kilns, and reheating furnaces)
- Ban of coke and furnace oil in industry in the NCR districts

OTHER SECTORS

- Ban of open burning of waste (trash) in Indian cities and crop residue burning in NCR districts
- Solid Waste Management Rules 2016

4.3.2 Emissions

Timely and effective implementation of the 2018 air pollution control legislation will have significant impact on future emissions in India and will 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 will enable a reduction in emission levels, while beyond 2030, continued economic growth will neutralise some of the positive impacts of current legislation (Figure 14).



Timely and effective implementation of the 2018 air pollution control legislation will have significant impact on future emissions in India

Effective implementation of the recent regulations enacted for the power sector (MoEFCC, 2015) will cut total national SO_2 emissions by half by 2030, although without further controls, continued growth in energy use will thereafter neutralise much of what will have been achieved. 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 NO_x emissions by the power sector and by mobile sources in the coming 20 years, but emissions will rebound thereafter. No trend reversal can be anticipated for industrial sources however, and by 2050, total NO_x emissions in India could be 30 per cent higher than in 2015.

Current policies and plans should deliver large reductions in $PM_{2.5}$ emissions from the

5 Perform Achieve and Trade Scheme (PAT) is a market-based mechanism to enhance energy efficiency in energy-intensive industries through certifications of energy saving, which can be traded. In the 'first cycle' of PAT (ending in 2014–15), 478 industries units in eight sectors (aluminium, cement, chlor-alkali, fertiliser, iron and steel, pulp and paper, thermal power, and textiles) were mandated to reduce their specific energy consumption (SEC), i.e., the energy used per unit of production. Overall, the goal of SEC reduction targets was a 4.05 per cent reduction in energy consumption in these industries, totalling an energy savings of 6.7 million tonnes of oil equivalent (MTOE). The implementation of PAT in large industries has led to energy savings of 8.67 MTOE by year 2014/15, which is about 1.25 per cent of total primary energy supply to the country in the "first cycle". This energy saving also translates into mitigating about 31 million tonnes of CO2 emission. The "second cycle" of PAT was notified in March of 2016, covering 621 designated consumers (DCs) from 11 sectors, including eight existing sectors and three new sectors, viz. railways, refineries, and distribution companies. In its second cycle, PAT seeks to achieve an overall energy consumption target of 8.9 MTOE.

residential sector, mainly due to the enhanced access to clean fuels (LPG, electricity, solar) under the *Pradhan Mantri Ujjwala Yojana* (PMUY) scheme. $PM_{2.5}$ will decrease for the power sector as well, as a consequence of FGD and electrostatic precipitator (ESP) controls. No major net changes are expected for emissions from mobile sources, as the decline in exhaust emissions due to Bharat Stage VI standards will be neutralised by the anticipated increase in

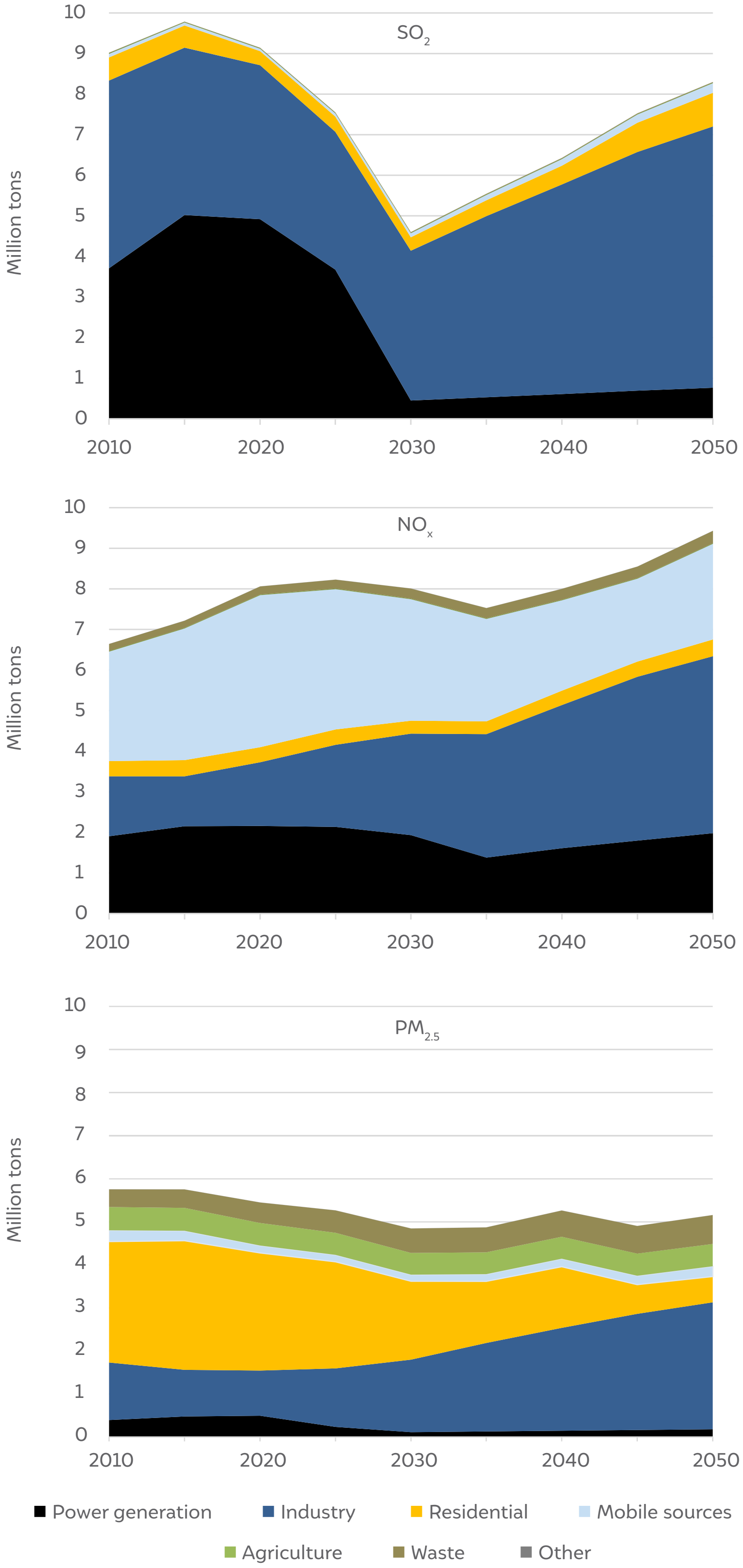


FIGURE 14:
Trends in GDP and emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and primary particulate matter ($PM_{2.5}$) in India, 2010–2020

Source: IIASA-CEEW analysis, 2019

the vehicle fleet, and in particular, by higher non-exhaust emissions (road dust, and tyre and brake wear). Most notably, the absence of stringent regulations will allow $PM_{2.5}$ emissions from the industrial sector to increase by a factor of three following increases in industrial production. (Air pollutant emissions by regions/states are presented in Annex 4.)

4.3.3 Air quality

By 2030, the decrease in $PM_{2.5}$ and SO_2 emissions that are expected to result from the full implementation of the 2018 legislation will have a positive impact on ambient $PM_{2.5}$ levels throughout India (Figure 15). On average, concentrations will decline by about 14 per cent, compared to 2015 (Table 6), and the highest (population-weighted) concentrations—calculated for Delhi NCT—will reduce from 126 µg/m³ in 2015 to 114 µg/m³. After 2030, however, concentrations will rebound again, and will exceed the 2015 levels substantially by 2050.

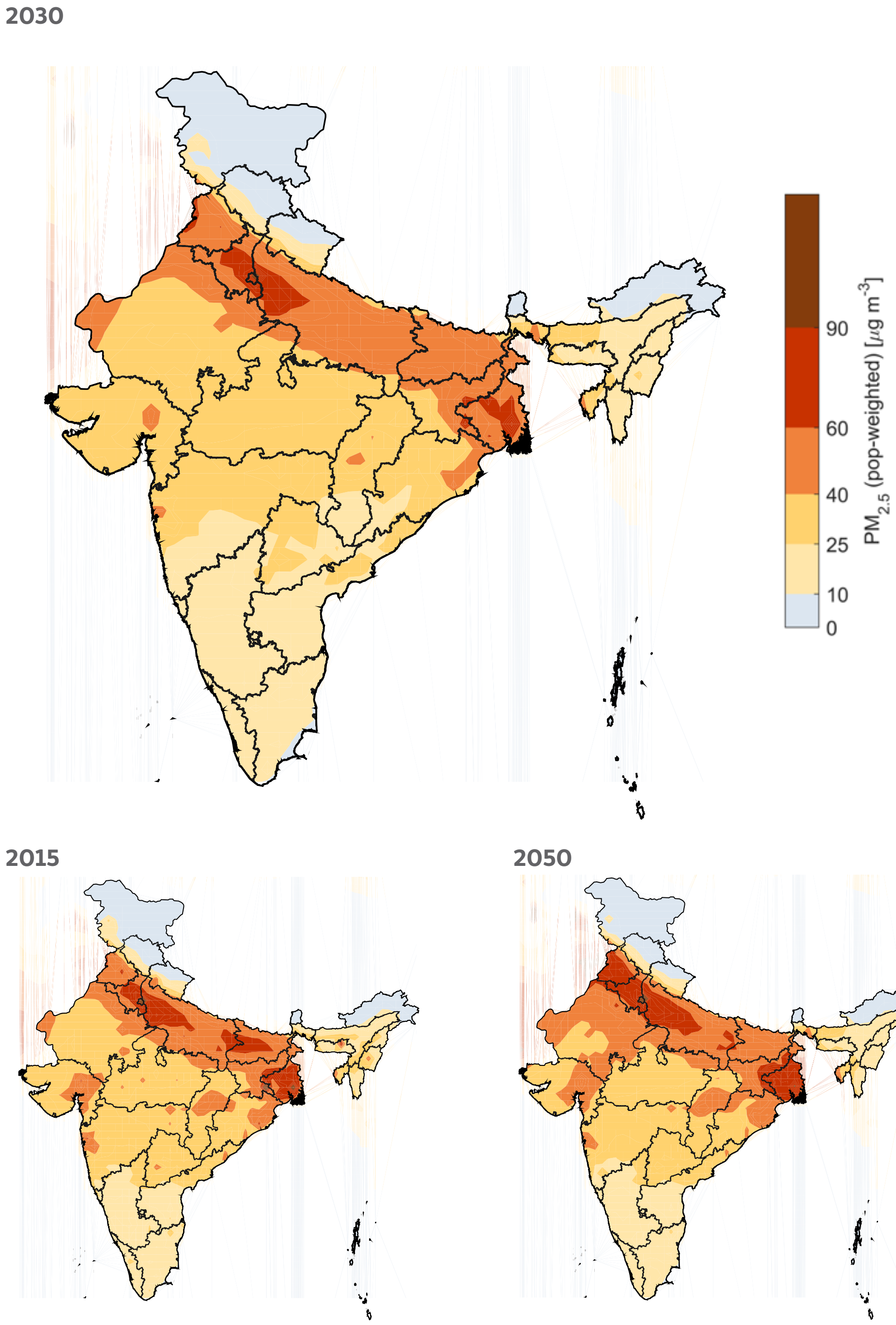


FIGURE 15: Ambient concentrations of $PM_{2.5}$, in 2015, and for the 2018 legislation scenario in 2030 and 2050

Source: IIASA-CEEW analysis, 2019

TABLE 6:
Population-weighted annual mean $PM_{2.5}$ concentrations expected in Indian states under the 2018 air quality legislation scenario

Source: IIASA-CEEW analysis, 2019

Regions	$PM_{2.5}$ concentration (μg/m³)		
	2015	2030	2050
Delhi	126.5	114.4	136.1
West Bengal	67.4	60.1	70.7
Haryana	63.2	59.8	69.5
Uttar Pradesh	58.7	53.4	61.5
Jharkhand	58.6	50.1	64.6
Bihar	56.6	48.8	53.4
Punjab	51.9	53.3	64.1
Gujarat	42.5	37.0	44.6
Odisha	42.4	35.8	44.5
Rajasthan	40.8	39.4	45.8
Chhattisgarh	39.4	34.3	42.9
Maharashtra	38.9	31.5	37.9
Madhya Pradesh	38.0	33.1	39.1
Uttarakhand	32.7	26.1	30.2
North East	31.5	23.5	26.0
Andhra Pradesh*	30.4	24.7	30.3
Goa	26.6	20.4	24.6
Assam	24.1	24.9	24.3
Karnataka	21.2	16.6	20.1
Kerala	20.3	13.7	13.5
Tamil Nadu	18.9	14.9	18.1
Jammu and Kashmir	15.8	13.2	13.0
Himachal Pradesh	14.6	14.0	15.9

Source: IIASA-CEEW analysis, 2019

*Note: *Andhra Pradesh includes Telangana*

4.3.4 Population exposure to $PM_{2.5}$

By 2030, stringent implementation of 2018 legislation will reduce the exposure levels of approximately 55 per cent of the population (833 million people) to within NAAQS limits (≤40 μg/m³), as compared to 516 million people in 2015 (Table 7). By 2050, however, the number of people with access to clean air that meets the NAAQS limits will decrease to 44 per cent (745 million people). Approximately 930 million people will be exposed to concentrations above NAAQS limits if no further action is taken.

TABLE 7:
Distribution of population exposure in 2015, and for the 2018 legislation scenario in 2030 and 2050 (million people exposed to different levels of $PM_{2.5}$)

Source: IIASA-CEEW analysis, 2019

Exposure	2015	2030	2050
Above 40 μg/m³	677	674	930
Between 40 μg/m³ and 25 μg/m³	389	466	404
Less than 25 μg/m³	227	367	341

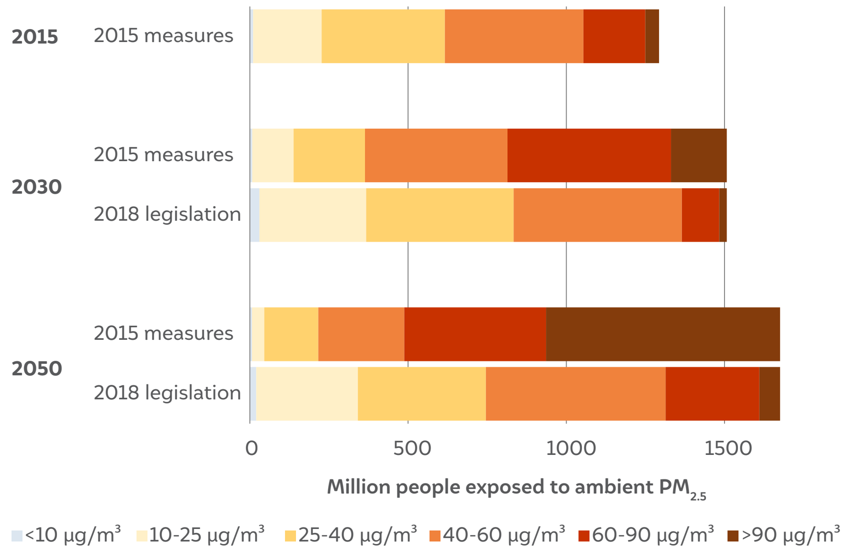


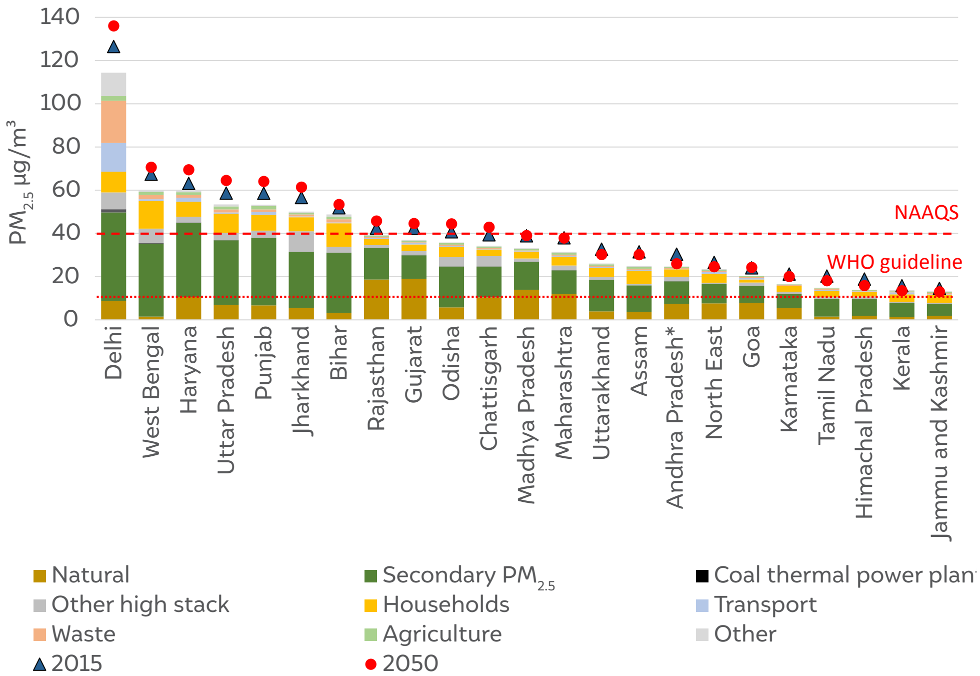
FIGURE 16: Population exposure distribution to $PM_{2.5}$ in 2015, 2030, and 2050, with the 2015 measures and for the 2018 legislation scenario

Source: IIASA-CEEW analysis, 2019

4.3.5 Source contributions of ambient $PM_{2.5}$

Economic development, combined with the source-sector-specific emission controls of the 2018 legislation, will lead to differentiated trends in sectoral emissions across India, and consequently will also alter the (relative and absolute) contributions made by different emission sources to ambient $PM_{2.5}$ concentrations.

Full implementation of the 2018 legislation should deliver an overall decline in ambient $PM_{2.5}$ levels of about 10 per cent by 2030. However, this improvement will be a composite result of diverging trends in different sectors: current regulations are expected to decrease the contribution of primary PM emissions from the power sector by up to 90 per cent, and that of the transport and residential sectors by approximately 40 per cent. By contrast, the absence of emission controls for industrial sources will increase the contribution of that sector by approximately 50 per cent (Figure 17). Secondary particles will still contribute a significant share of $PM_{2.5}$ in large regions in India (up to 60 per cent in Punjab), while natural



** Including Telangana*

Secondary particles formed in the atmosphere from agricultural NH_3 emissions through chemical reactions with SO_2 and/or NO_x emissions

FIGURE 17: 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

Source: IIASA-CEEW analysis, 2019

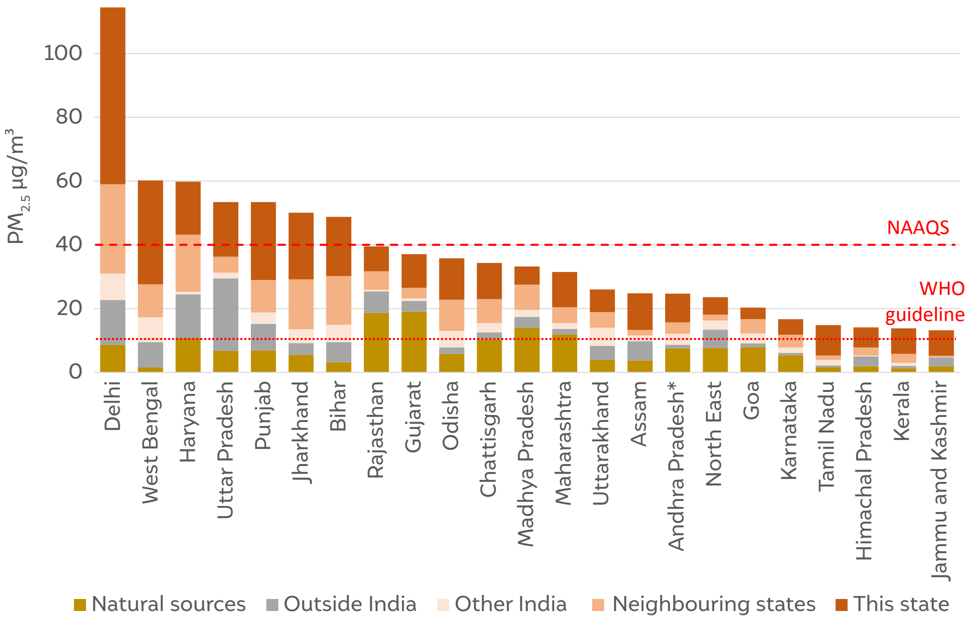
sources will continue to dominate in Rajasthan and Gujarat. This source attribution provides relevant input for the prioritisation of additional policy interventions aimed at improving air quality such that it meets national and international air quality standards.

Furthermore, current policies will not alleviate the interstate transport of pollution in the atmosphere, so effective air quality management in India will continue to require coordination and cooperation between states. Emissions from transboundary transport are a dominant source of secondary pollution (Figure 17), while local pollution is a major source of primary PM emissions. Hence, reductions in both primary PM and precursor emissions of secondary aerosols will be needed to bring down $PM_{2.5}$ to safe levels.

Especially in the Indo-Gangetic Plain where many states significantly exceed NAAQS limits, the transport of PM and precursor gases from neighbouring states will remain a major contributor to urban $PM_{2.5}$ levels (Figure 18).

While the 2018 legislation will enable significant economic growth without major changes in current air pollution levels, effective implementation of the regulations and policies introduced after 2015 will be critical. Without these measures, ambient $PM_{2.5}$ concentrations levels will increase by 40 per cent in 2030, and will double by 2050, reaching unprecedented levels of more than 250 µg/m³ (Figure 19).

Emissions from transboundary transport are a dominant source of secondary pollution



** Including Telangana*

FIGURE 18:
Source contributions to (population-weighted) annual mean concentrations of $PM_{2.5}$ for the 2018 legislation case in 2030

Source: IIASA-CEEW analysis, 2019

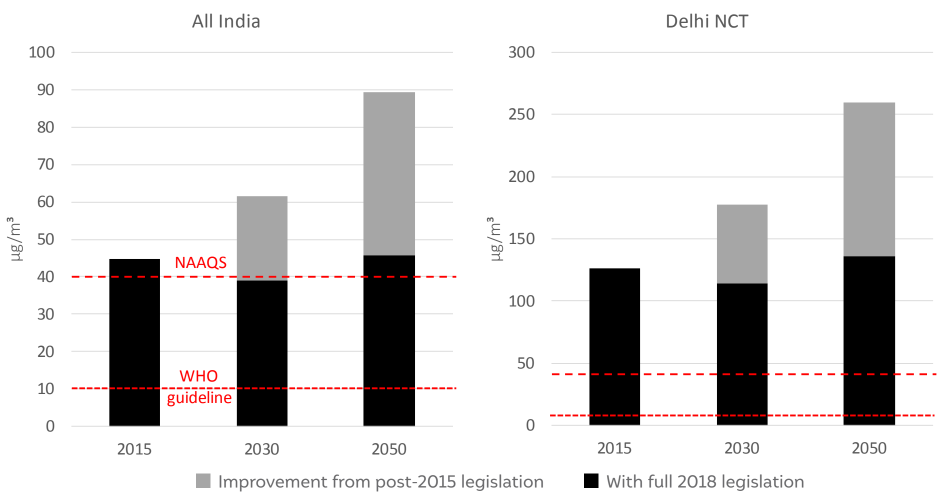


FIGURE 19:
Population-weighted $PM_{2.5}$ concentrations for the full and effective implementation of the 2018 legislation, and the benefits from the post-2015 legislation, for India (left panel) and Delhi NCT (right panel)

Source: IIASA-CEEW analysis, 2019

4.4 The scope for further air quality improvements

4.4.1 Advanced technical measures

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

An illustrative 'advanced technology' scenario explores the potential benefits that could be realised by using the latest emission control technology that has already been widely adopted in many industrialised countries (e.g., in the European Union and Japan). Compared to the '2018 legislation' case, this scenario assumes stricter emission limit values for large point sources of SO_2, NO_x, and PM/total suspended particles (TSP). For mobile sources, tighter controls would be introduced for non-road mobile machinery, while for road vehicles, the standards would follow the Euro-VI introduction schedule as assumed in the 2018 legislation scenario. It is assumed that reduction of ammonia emissions will be achieved by following European procedures of improved manure management practices in livestock production, and efficient application of urea-based mineral fertilisers.

This advanced technology 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-year delay as compared to other industri-

POWER PLANTS

- High-efficiency PM controls at power plants
- Selective catalytic reduction at existing and new oil and gas power plants

INDUSTRY

- High-efficiency PM controls for boilers
- More stringent PM controls for furnaces
- Combustion modification and selective catalytic reduction in oil and gas boilers and furnaces
- Stringent emission controls for industrial processes, including:
  - Ferrous and non-ferrous industries
  - Refineries
  - Coke plants
  - Carbon black production
  - Fertiliser plants
  - Brick kilns (by increasing capacity of tunnel kilns)
- Improved control of flaring in refineries
- Suppressing fugitive emissions during coal handling

HOUSEHOLDS

- Annual inspection and maintenance of residential oil boilers
- Replacement of wick kerosene lamps with hurricane lanterns
- Nationwide ban on open burning of solid waste (trash)

AGRICULTURE

- Improved enforcement of bans on burning of agricultural waste
- Improved manure management in livestock production
- Efficient use of urea-based mineral fertilisers
- Suppressing dust emissions from storage and handling of agricultural crops
- Low-till farming, alternative cereal harvesting

TABLE 8: Additional policies and measures assumed in the advanced measures scenario (additional to 2018 legislation)

Source: IIASA-CEEW analysis, 2019

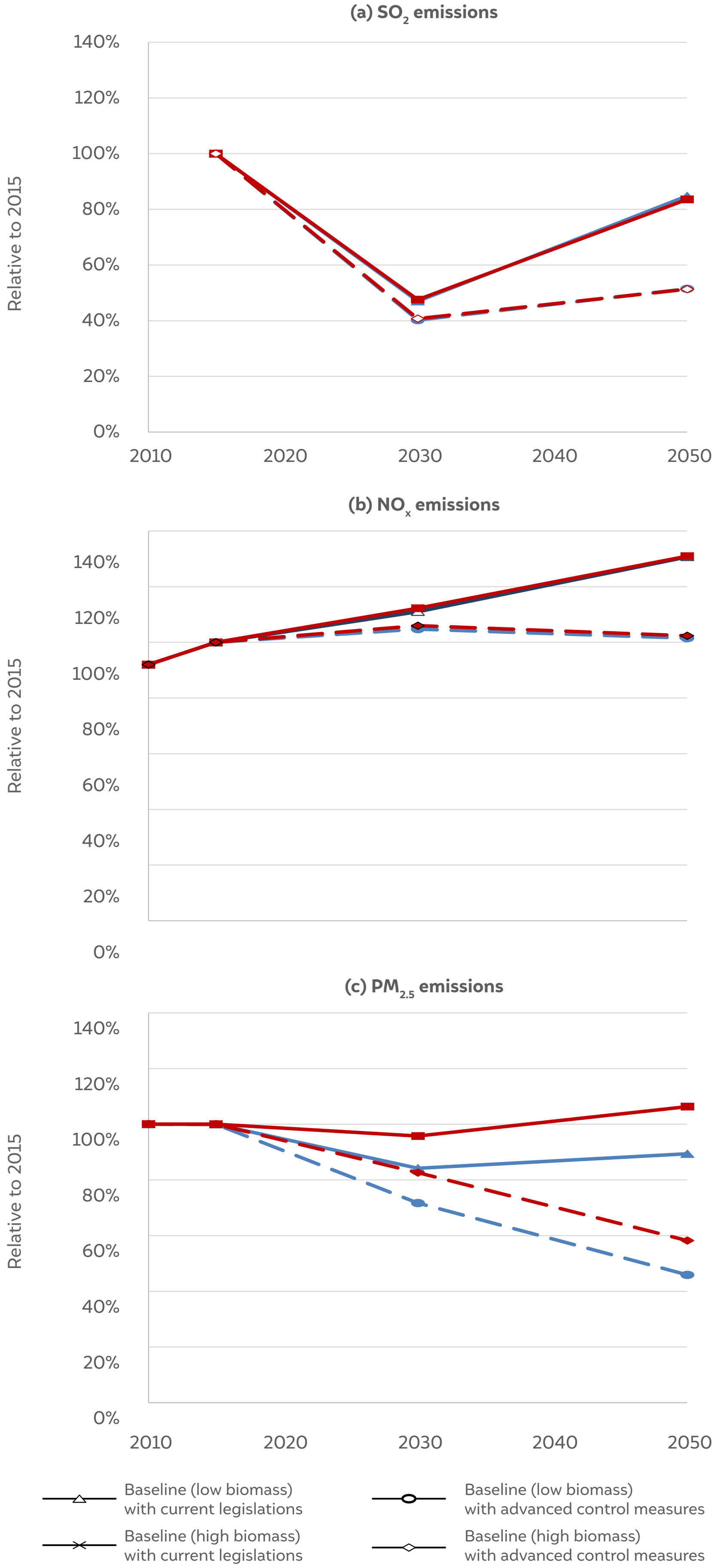


FIGURE 20:
Air pollutant emissions for the 2018 legislation and the Advanced Control Technology scenarios, for the baseline case assuming successful introduction of clean household fuels, and for a less optimistic variant

Source: IIASA-CEEW analysis, 2019

alised countries, so that, for example, the current EU legislation (Amann et al., 2014) would be fully introduced in India by 2025. This scenario, however, restricts the scope of advanced technology only to emission control equipment, but does not consider further structural changes in the economy caused by the introduction of other advanced technologies, such as energy efficiency improvements and advanced production processes.

Two sensitivity cases are considered which explore the role of increasing access to clean household fuels:

- Advanced emission control technologies combined with the rapid penetration of clean household fuels, as assumed in the 2018 legislation scenario
- Advanced emission control technologies, but slower introduction of clean household fuels

Advanced technologies offer potential for further emission reductions beyond what is proposed in the 2018 legislation. Full and effective implementation could avoid the rebound of SO_2 emissions after 2030, and could stabilise NO_x emissions at current levels. For primary $PM_{2.5}$, they could lower emissions by 20 per cent in 2030 (compared to the 2018 legislation), and by about 40 per in 2050 (Figure 20). For $PM_{2.5}$, however, the success of providing clean household fuels will be another determining factor. Combined, India could reduce its primary $PM_{2.5}$ emissions by 60 per cent in 2050, as compared to 2015.

The emission reductions offered by advanced emission control technologies would have a considerable positive impact on ambient air quality, and they would bring large parts of India into compliance with the NAAQS. However, purely technology-based policy interventions will not be sufficient to achieve the NAAQS throughout the Indo-Gangetic Plain.

TABLE 9: Population-weighted annual mean ambient $PM_{2.5}$ concentrations (µg/m³) by state, in 2015 and for the Advanced Control Technology scenario variants in 2030 and 2050

Source: IIASA-CEEW analysis, 2019

	2015	2030			2050		
		2018 legislation	Advanced controls with clean household fuels	Advanced controls without clean household fuels	2018 legislation	Advanced controls with clean household fuels	Advanced controls without clean household fuels
Delhi	126.5	114.5	108.2	111.2	136.1	110.5	112.6
West Bengal	67.4	60.2	54.6	59.0	70.5	49.9	55.3
Haryana	63.3	59.6	56.5	58.4	69.6	57.9	60.2
Jharkhand	58.7	50.1	44.4	46.8	64.6	42.8	45.8
Uttar Pradesh	58.6	53.4	49.9	52.9	61.6	48.6	52.0
Bihar	56.7	48.8	45.1	48.9	53.3	40.5	44.9
Punjab	51.9	53.3	50.8	52.3	63.9	55.5	56.8
Gujarat	42.6	36.9	35.2	36.2	44.6	37.8	38.7
Odisha	42.4	35.6	32.2	34.0	44.4	30.9	33.0
Rajasthan	41.0	39.6	38.1	38.9	45.7	40.5	41.3
Chhattisgarh	39.6	34.3	31.1	32.3	43.0	30.8	32.1
Maharashtra	38.8	31.3	29.2	30.6	38.1	29.9	31.3
Madhya Pradesh	38.0	33.1	31.3	32.5	38.9	32.2	33.4
Uttaranchal	32.8	26.0	24.4	25.7	30.1	23.6	25.0
North East	31.7	23.5	22.5	23.7	25.9	22.9	24.3

Andhra Pradesh	30.5	24.8	22.6	24.0	30.3	22.4	23.5
Goa	26.6	20.1	19.0	19.4	24.5	19.5	19.9
Assam	24.2	24.8	23.6	25.1	24.4	20.1	22.1
Karnataka	21.2	16.7	15.4	16.2	19.9	15.2	16.0
Kerala	20.1	13.7	12.5	13.7	13.4	10.2	11.6
Tamil Nadu	19.1	14.8	13.4	14.5	18.0	13.2	14.0
Jammu and Kashmir	15.7	13.2	12.4	13.6	12.8	10.7	12.0
Himachal Pradesh	14.7	14.1	13.2	13.8	16.0	12.3	12.9

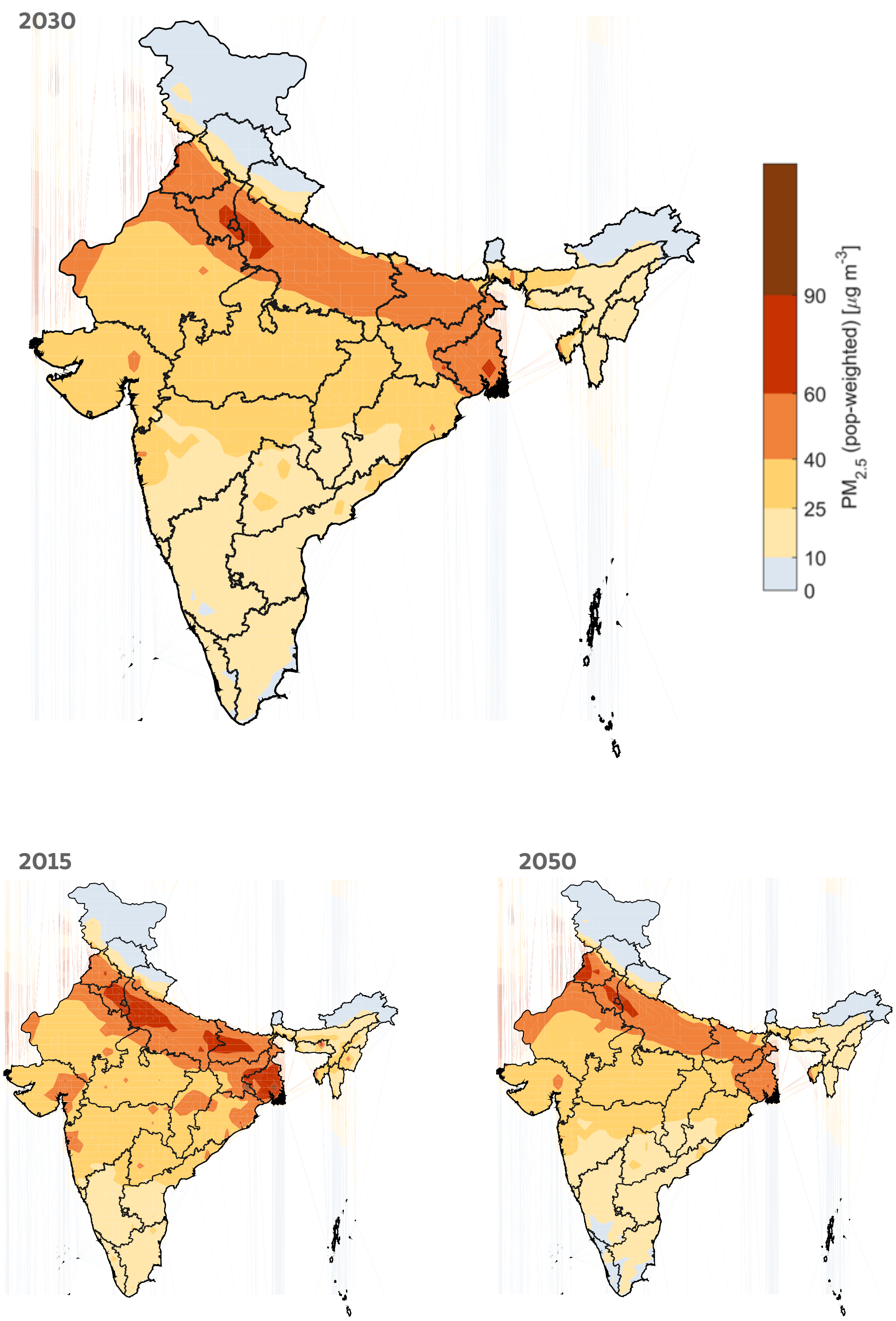


FIGURE 21: Ambient concentrations of PM2.5, in 2015, and for the advanced technology scenario in 2030 and 2050 (assuming enhanced access to clean fuel as in the 2018 legislation case)

Source: IIASA-CEEW analysis, 2019

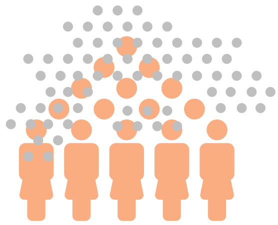
4.4.2 Development measures

As indicated above, even advanced technological solutions, despite their potentially high costs, will not be sufficient to meet the NAAQS standards in important regions in India, as they do not effectively address some emission sources that are of particular importance. Concentrations will also remain substantially above the global WHO guideline value that has been established as an aspirational target to protect human health.

As shown in the sectoral source apportionment analysis (e.g., Figure 17), after the implementation of the 2018 legislation, non-industrial emission sources (e.g., road dust, household fuel use, agricultural activities, and waste management) will still make large contributions to population exposure. However, these are not effectively addressed in the advanced technology scenario because, while they are strongly linked to social and economic development, they have lost importance in developed countries

While India is pursuing ambitious development policies which might eventually eliminate emission sources that are related to poverty, the strong benefits these policies imply for air quality, in themselves, constitute an additional incentive to accelerate such policies.

An illustrative 'development measures' scenario explores the potential air quality gains from policy interventions that are aimed at a wider development context (Table 10). To this end, the scenario projects onto the energy sector the anticipated energy use, energy systems transformation, and economic activities that have 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 advanced technology scenario. Most importantly, this scenario considers additional emission controls for non-industrial sources (e.g., clean cookstoves, efficient enforcement of bans on burning of agricultural and municipal waste, and road paving) that are important for Indian conditions.



After the implementation of the 2018 legislation, non-industrial emission sources will still make large contributions to population exposure

TABLE 10: Policies and measures assumed in the development measures scenario (additional to 2018 legislation and the advanced measures case)

Source: IIASA-CEEW analysis, 2019

POWER PLANTS AND INDUSTRY

- Variable renewable energy (VRE) integration costs will be borne by the government
- No carbon capture and storage (CCS) technology introduction due to its high technology costs as compared to conventional technology
- Increase in domestic manufacturing of solar panels
- Industrial energy efficiency improvements through 54 per cent penetration of electricity in total fuel mix
- Increase in energy efficiencies in the industrial sector
- Near doubling of non-fossil electricity generation capacity by 2050
- Increased share of renewables in industry

AGRICULTURE

- More stringent policies for manure management and fertiliser application
- Efficient enforcement of ban on agricultural waste burning

MOBILE SOURCES

- Improvements in energy efficiency
- Increased incentives for greater adoption of electric vehicles
- Improved public transport infrastructure and capacity in cities
- Road dust control (road paving, street cleaning, increasing green areas)

HOUSEHOLDS

- Increased efficiency improvements in buildings and appliances
- Replacement of kerosene lamps with LED lamps for domestic lighting
- Advanced cookstoves for households still using solid fuels for cooking
- Phase out of biomass use in domestic cooking by 2040 in rural areas, and by 2030 in urban areas

The far-reaching transformative changes of energy systems in the development measures scenario, together with advanced technical emission controls and development measures, will lead to substantially lower emissions of $PM_{2.5}$ precursors by 2050. Compared to 2015 levels, SO_2 emissions will decrease by 50 per cent. Similarly, by 2050, NO_x emissions will decline by about 50 per cent, and $PM_{2.5}$ by 80 per cent.

These emission changes will have profound impacts on air quality and will bring large parts of India into compliance with the NAAQS for $PM_{2.5}$

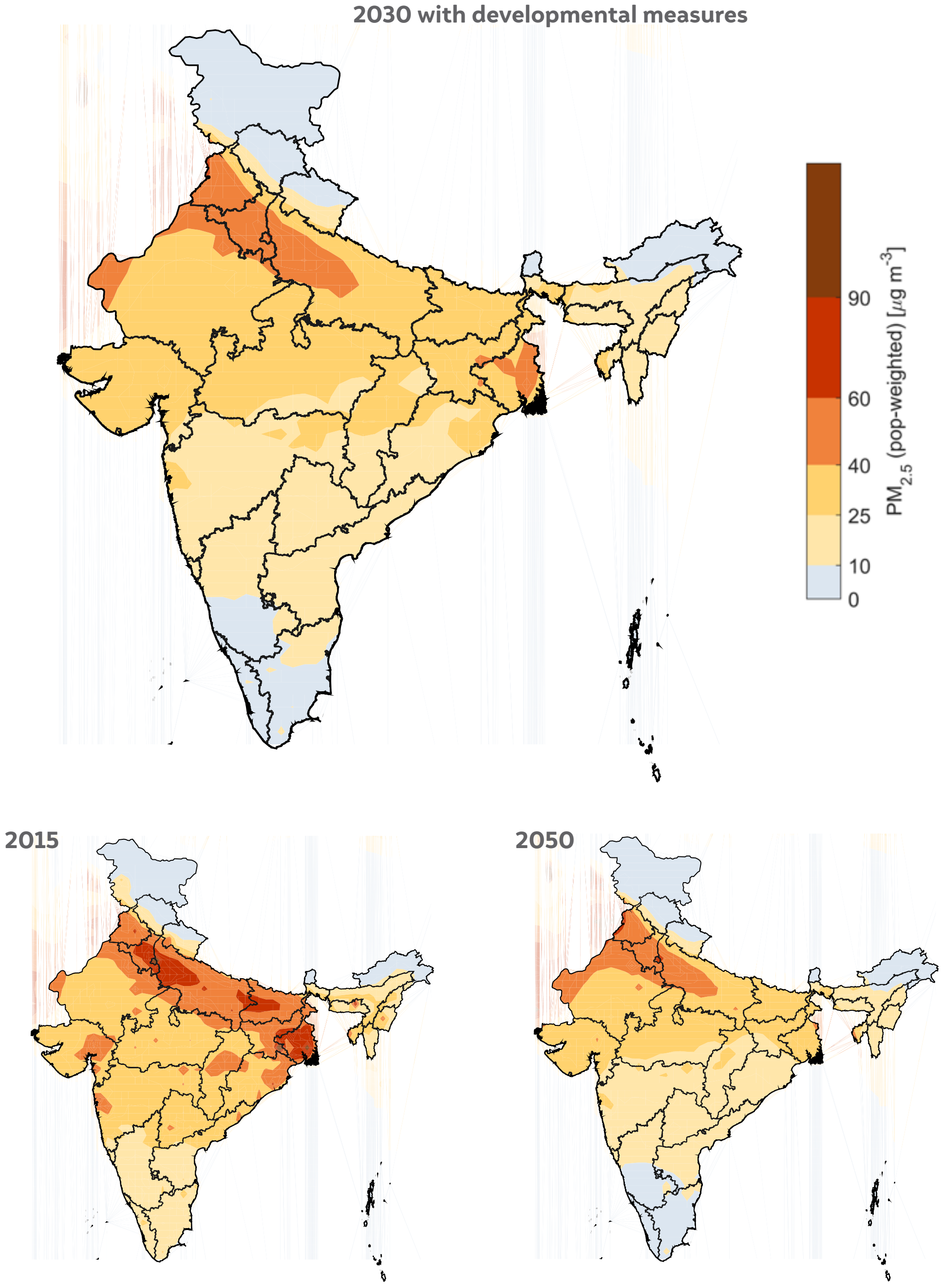


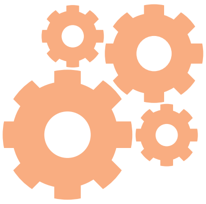
FIGURE 22: Ambient levels of PM2.5 in 2015, and for the development measures scenario in 2030 and 2050

Source: IIASA-CEEW analysis, 2019


Image: iStock

4.4.3 Impacts on population exposure to $PM_{2.5}$

By 2030, population exposure to $PM_{2.5}$ will be strongly determined by the degree of compliance with recent policies and emission control regulations. In particular, the effective implementation of the post-2015 legislations will reduce population exposure to $PM_{2.5}$ in India by up to 50 per cent by 2050, compared to a hypothetical case without these regulations (Figure 23). Further improvements can be realised through the use of advanced control technologies (about 10 µg/m³ by 2050) and development measures (about 7 µg/m³ by 2050).



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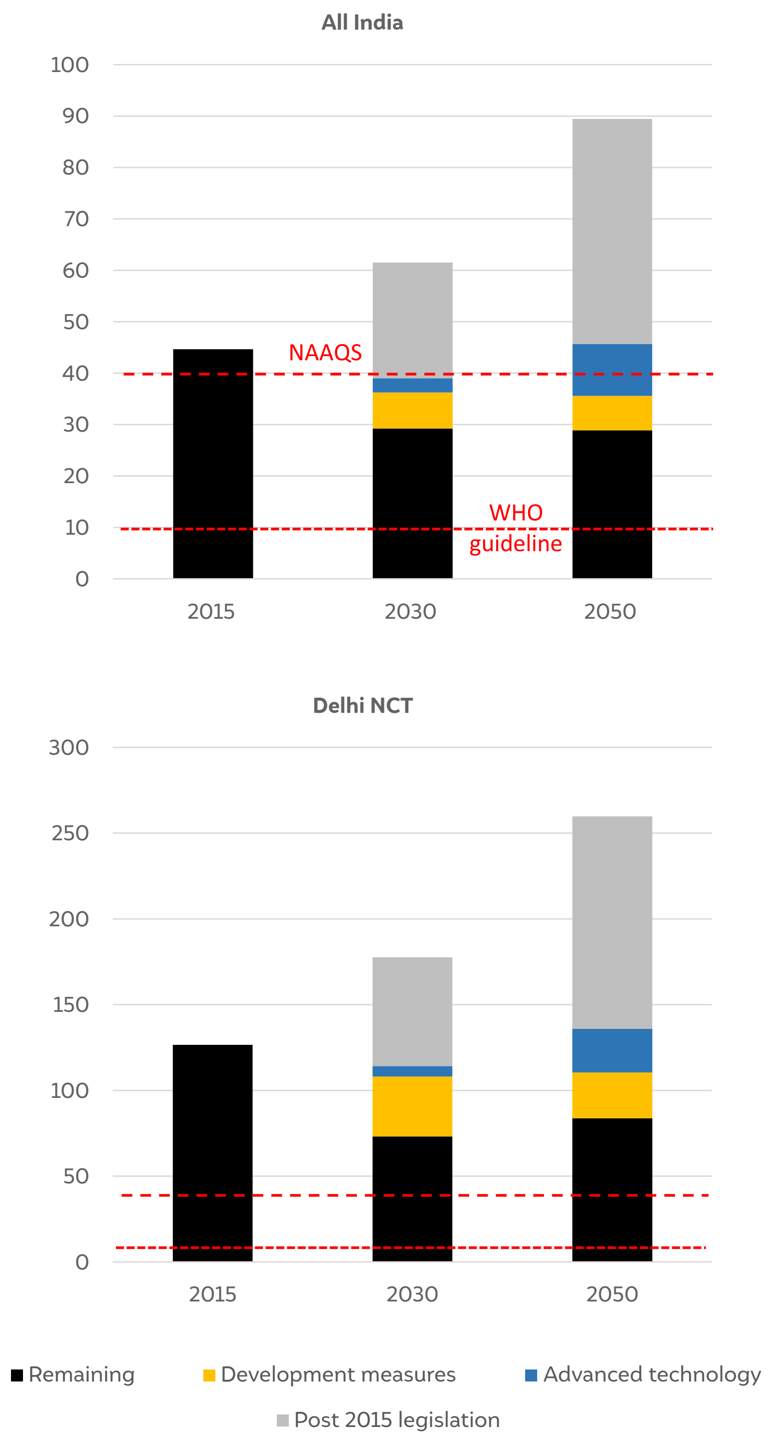

FIGURE 23: Potential benefits of emission control packages on population-weighted $PM_{2.5}$ concentrations, for all of India (left panel) and Delhi NCT (right panel)

Source: IIASA-CEEW analysis, 2019

These improvements in ambient air quality will be mirrored by levels of population exposure (Figure 24). In 2015, more than 50 per cent of the Indian population (677 million people) experienced air quality that did not conform to the NAAQS. Development measures, combined with technical emission controls, could reduce this number by two-thirds (i.e., to 236 million people, or 16 per cent of the total population) by 2030, and to 270 million people by 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 (Figure 18).

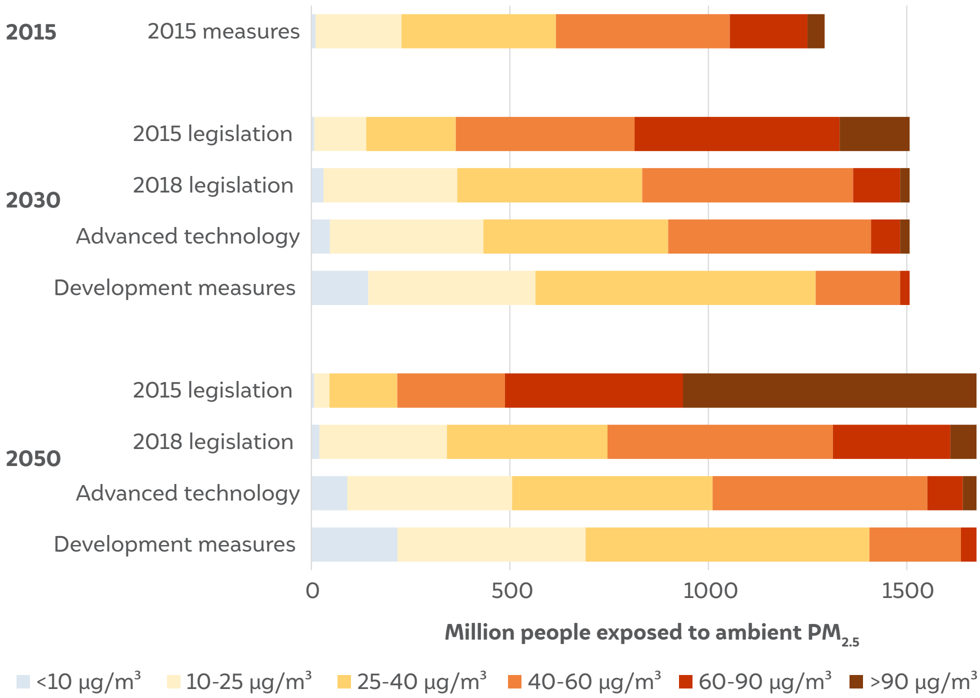

FIGURE 24: Distribution of population exposure in 2015, and projected emission control scenarios in 2030 and 2050

Source: IIASA-CEEW analysis, 2019

To meet the new pollution norms for SO_2, coal thermal power plants are required to retrofit or install flue gas desulphurisation equipment, which removes sulphur dioxide from exhaust flue gases.

5. Costs and Benefits

Based on the scenarios presented, this report estimates the life-cycle costs for emissions reductions, the potential for greenhouse gas mitigation, as well as progress on other Sustainable Development Goals.

5.1 Emission control costs

The GAINS model estimates the life-cycle costs for emission reductions from a social planning perspective, focusing on the diversion of societal resources. This approach excludes transfer payments such as taxes, subsidies, and profits, and balances upfront investments with subsequent cost savings, for example from lower energy consumption. Moreover, the GAINS model estimates the scope for further environmental improvements through the use of commercially available emission control technologies (excluding the potential from structural changes), given their costs, and the implementation of a portfolio of measures that will achieve higher environmental protection at least cost.

It is estimated that in 2015, India spent about 0.7 per cent of its GDP (€12 billion per year) on emission controls, with significant—although often hidden—benefits for air quality and human well-being. More than 80 per cent of the total costs went toward imposing emission controls on mobile sources, i.e., for the nationwide BS III standards and BS IV standards in Delhi and 13 other cities. Control measures for large stationary sources in the power sector accounted for about seven per cent of total costs (Figure 25), followed by five per cent toward non-road machinery, and four per cent toward industrial processes and the combustion sector.

Across all future emission control scenarios, mobile sources will account for the largest share of emission control costs.

Across all future emission control scenarios, mobile sources will account for the largest share of emission control costs. While the additional emission controls considered in this analysis affect mainly stationary sources, their share in total costs accounts for not more than 35 per cent in 2030, and less than 30 per cent in 2050. For the power sector, flue gas desulphurisation accounts for 12 per cent of total costs in 2030, and seven per cent in 2050. In the transport sector, advanced control measures in heavy-duty trucks (viz., HDEUVI, HDSE II and III, and LSMD-II and III) will constitute an increase from 25 per cent of the total emission control costs in 2030 to 27 per cent in 2050, whereas the share of total emission control costs of imposing advanced control measures on cars (LFEUVI and LSMD-II and III) will increase from 18 per cent in 2030 to 29 per cent in 2050. Costs for flue gas desulphurisation in industry increases by 64 per cent between 2030 and 2050 in the 2018 legislation scenario; however, the share in total costs will decrease by half (from four per cent in 2030 to two per cent in 2050).

Notably, since the development measures scenario considers a host of policies aimed at decreasing fossil fuel consumption, the associated emission control costs will be lower than in the advanced technology case.

Overall, air pollution emission control costs accounted for about 0.7 per cent of GDP in 2015. This share will increase to 1.4–1.7 per cent by 2030. By 2050, with an almost tenfold increase in GDP, air pollution controls will consume 1.1–1.5 per cent of the GDP, or 1.5 per cent of the 2015-to-2050 increase in economic wealth (GDP).

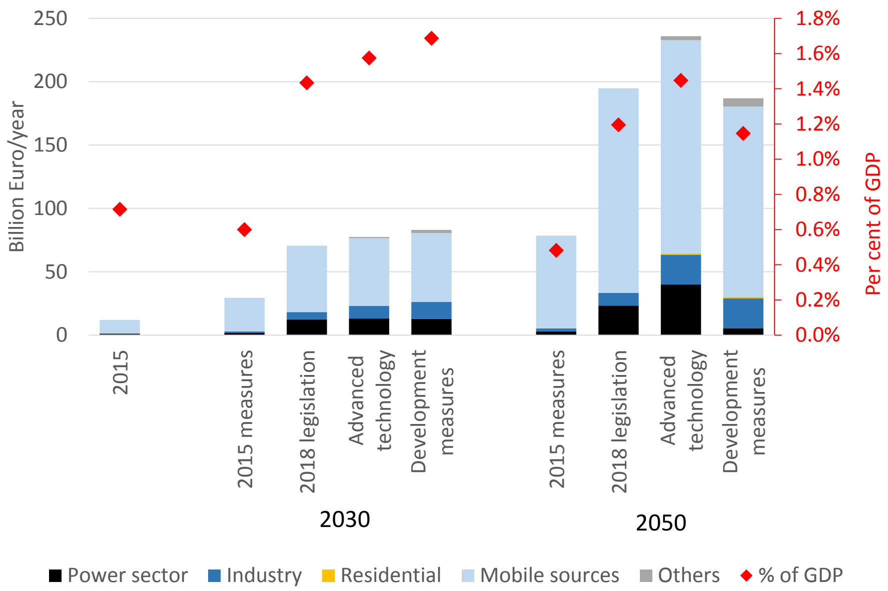

FIGURE 25: Air pollutant emission control costs for the various scenarios

Source: IIASA-CEEW analysis, 2019

5.2 Greenhouse gas (GHG) emissions

Compared to the advanced technology scenario that does not modify economic activity levels, the development measures scenario addresses pollution sources in a more holistic way. It promotes the reduction and substitution of most polluting activities by providing cleaner alternatives without diminishing human welfare, though, for example, 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 development scenario, India's CO_2 emissions would be about 60 per cent lower in 2050 than in the baseline case. Even without dedicated measures focused on methane, CH_4 emissions would be 40 per cent lower in 2050 as compared to the baseline case, and black carbon emissions would decline by 80 per cent as compared to 2015 (Figure 26).

Overall, air pollution emission control costs accounted for about 0.7 per cent of GDP in 2015. This share will increase to 1.4–1.7 per cent by 2030

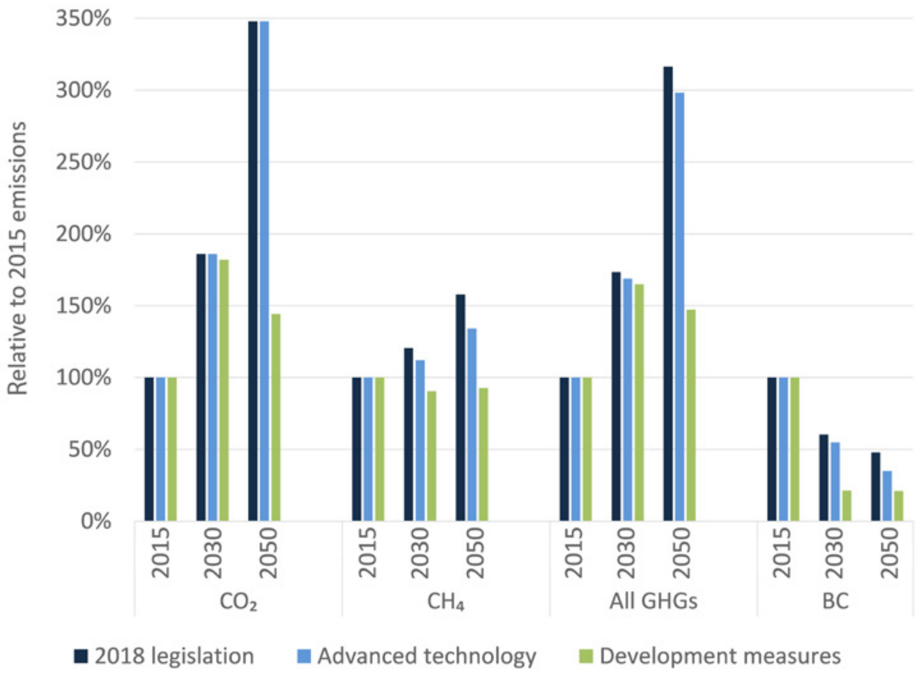

FIGURE 26: Greenhouse gas and black carbon emissions in India for the emission control scenarios

Source: IIASA-CEEW analysis, 2019

5.3 Other SDG benefits

Furthermore, there are additional benefits to other SDGs. A non-exhaustive list of such benefits includes 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 efficient land use due to less ash and soot disposal; lower emissions of other toxic substances such as Hg (mercury) and persistant organic pollutants (POPs), with the subsequent health benefits; improved traffic management; improved protection of historical monuments and buildings; and enhanced economic gains from tourism.

Blue skies in India are possible. Aligning out development goals with stringent pollution control measures will help achieve this.

Image: iStock

6. Conclusion

India's rapid urban transition and the limited control of pollution are causing public health problems, significant environmental degradation of air, water, and land, and an increase in greenhouse gases. Together these undermine the potential for sustainable socio-economic development of the country, and will have dire repercussions for the poor.

Indian cities rank poorly in terms of air pollution globally, and the National Ambient Air Quality Standard of $PM_{2.5}$ of 40 µg/m³ is exceeded at many monitoring stations. It is estimated that in 2015, more than half of the Indian population, i.e., about 670 million people, were exposed to ambient $PM_{2.5}$ concentrations that did not comply with India's NAAQS, and that less than one per cent enjoyed air quality conforming with the global WHO guideline value of 10 µg/m³.

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

After 2015, the Indian government issued a wide range of pollution control policies and regulations. Their actual impact on air quality will critically depend on how effectively they are enforced and implemented. Full compliance could prevent a 70 per cent increase in the number of people living in areas where the NAAQS are exceeded by 2030. These new policies and regulations support economic growth that has the potential to lift millions out of poverty without further worsening air quality. At the same time, these policies and regulations will not be sufficient to deliver significant air quality improvements and, even with full implementation, average population exposure will not decline by more than 10 per cent by 2030. Also, these policies and measures will not be sufficient to avoid a rebound in emissions after 2030, when they will have reached their full impact. Even with the maximum implementation of the 2018 legislation, by 2050, 40 per cent more people will face pollution levels above the NAAQS as compared to today, and implementation failure could double that number.

The model analysis for India reveals that in many of the Indian states, emission sources that

> The already implemented measures will not be sufficient to halt a further deterioration in air quality in view of the tenfold increase in GDP that is expected by 2050

are outside of their immediate jurisdiction make the highest contributions to (population-weighted) ambient pollution levels of $PM_{2.5}$. As a consequence, most states cannot achieve significant improvements in their air quality and population exposure without emission reductions in the surrounding regions, and any cost-effective strategy requires regionally coordinated approaches.

> Most states cannot achieve significant improvements in their air quality and population exposure without emission reductions in the surrounding regions

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

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, though these have shown rapid growth in recent years. In addition, a significant share of emissions still originates from sources related to poverty and underdevelopment, such as solid fuel use in households, waste management practices, and agricultural activities.

There is a wide portfolio of practical intervention options of a technical and non-technical nature that are already being applied in different parts of the world to improve air quality. While they are also employed to some extent in India, wider application could, in theory at least, 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 though a more comprehensive application of advanced technical emission controls, in line with examples widely adopted in many other countries. Additional compliance could provide NAAQS-compliant air quality to 60 per cent of the Indian population, if accompanied by ongoing efforts to provide universal access to clean household fuels.

Development priority measures offer further means for air quality improvements in India, even if they are not primarily targeted at air pollution. These development priority measures fall under the jurisdiction of a range of different authorities and are often discussed in the context of policy frameworks that do not take air quality management into consideration. These include, for example, measures related to economic and social development (such as clean cooking and solid waste management), energy or agricultural policies, and urban management.

If combined with advanced technical emission controls, such development measures could provide NAAQS-compliant air quality to about 85 per cent of the Indian population, and could reduce mean population exposure by about one-third of 2015 levels.

The portfolio of development measures identified in this report promotes reduction of most polluting activities and their substitution with cleaner alternatives, without diminishing human welfare. This can be achieved through, for example, improvements in energy efficiency, enhanced public transport, the use of cleaner cook stoves, the replacement of coal with natural gas and renewables (solar/wind) in power generation and industrial, as well as improved waste management and agricultural production practices. In addition to their air quality and health benefits, these measures will contribute to a number of Sustainable Development Goals. Most obvious are the interactions with greenhouse gas emissions, an essential dimension of SDG 13 (climate action) resulting in decline of CO_2 emissions by about 60 per cent in comparison to the baseline case.

> The portfolio of development measures identified in this report promotes reduction of most polluting activities and their substitution with cleaner alternatives, without diminishing human welfare

Although the portfolio includes certain measures that lead to higher direct CO_2 emissions (e.g., replacement of biomass for cook stoves by LPG, natural gas, or electricity), their net result would be an approximately 50 per cent reduction in greenhouse gas emissions as compared with the baseline scenario.

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 will thereby deliver additional benefits to human health and vegetation, in particular reducing damage to agricultural crops (the quantification of these effects was outside of the scope of this study).

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Annexures

Annex 1:

Data sources and assumptions for the GCAM scenarios

Energy supply

The GCAM-IIMA version starts with the base year 2010 and operates at five years' time steps till 2100. For 2015, data on electricity generation and capacity are based on the publicly available statistics from the Central Electricity Authority (CEA) and Energy Statistics.

The future demand for electricity generation and other forms of energy is determined in each end-use sector, where the penetration of electricity-based technologies (e.g., air conditioning) and other-fuel-based technologies (e.g., oil-based cars) grows with increasing income. The distribution of electricity generation across different technologies is determined by the relative cost of generating electricity, based on stakeholder consultations with power sector experts (including renewable energy developers, National Thermal Power Corporation Limited, and experts from the Ministry of Power).

Energy demand

The building sector comprises commercial buildings and the rural residential and urban residential subsectors. Energy service demand is modelled for air conditioning (high and low efficiency), cooking (biomass, coal, electricity, LPG, and natural gas), lighting (fluorescent bulbs, incandescent bulbs, kerosene lamps, and LEDs), refrigeration (high and low efficiency), ventilation (low- and high-efficiency ceiling fans), televisions, water heaters (electricity, LPG, solar) and 'other appliances'. The demand for each energy service responds to changes in income levels, service prices, and growth in floor space. Data on electricity demand for the building sector in 2015 was provided by CEA.

For the transport sector, energy demand is modelled for passenger transport (road, rail, and aviation), freight transport (road and rail), and international shipping, driven by per capita GDP and population.

The industrial sector is modelled in an aggregate way in GCAM-IIMA. The demand for industrial services responds to income growth and fuel prices. Fuels (biomass, coal, electricity, natural gas, and oil) compete on the basis of the relative prices for providing energy services to meet industrial energy demand. The current GCAM model version only tracks the energy mix and emissions at an aggregated level for all industrial sectors. This category also includes the agricultural sector, whose electricity consumption is almost half of that of the industrial sector.

Socio-economic variables

In GCAM, population and income (GDP) act as exogenous drivers of energy supply and demand. For GDP, the assumptions for this study follow the medium economic growth rate projections of NITI Aayog, with an annual growth rate of 6.7 per cent from 2012 to 2047.

Energy access

GCAM contains a detailed representation of energy service demands for the urban and rural residential sectors. Demands are responsive to costs as well as income. As the affordability of services increases, the demand for energy services increases both in urban and rural areas. The current policies related to energy access are represented in the analysis in the following way:

(i) **Urbanisation rate:** The rate of urbanisation is modelled as a function of economic growth – the higher the economic growth, the higher the transition towards urbanisation. Coherent with the data in GAINS, an increase in urbanisation to 50 per cent by 2050 is assumed for the medium economic growth scenario.

(ii) **Urban–rural income divide:** While the framework can model increasing inequalities in incomes, a stylised representation has been adopted for this study, reflecting an optimistic assumption of the state of the future urban–rural divide in India.

(iii) **Clean cooking access:** The Indian government has embarked on an ambitious programme to provide clean fuel, mainly LPG, to Indian households. For this study, we assume that biomass will be entirely replaced by alternative cooking fuels by 2040. We also model an alternative policy-failure scenario in which biomass use remains significant for meeting cooking energy demands even until 2050.

(iv) **Efficient lighting:** We assume that the penetration of LEDs increases rapidly. Incandescent bulbs will be phased out of household use by 2030 across all scenarios. Incandescent bulbs will be replaced by LEDs as well as CFL bulbs.

Annex 2:

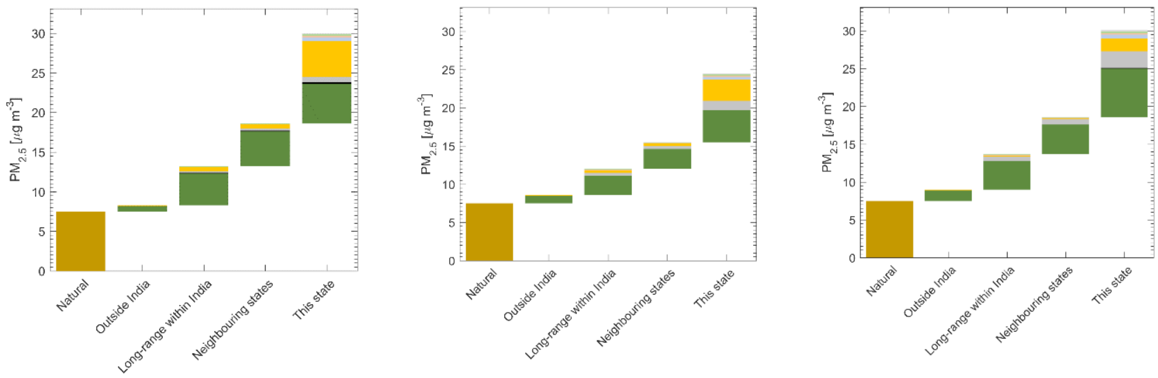
Source contributions to $PM_{2.5}$ annual concentration by state/region

Figures in this annex show source contributions to population-weighted annual mean ambient $PM_{2.5}$ concentrations under the 2018 legislation scenario for all states (GAINS regions). Contributions are specified by spatial origin (x-axis), chemical speciation (PPM/secondary aerosols), and economic source sector for primary PM (colours).

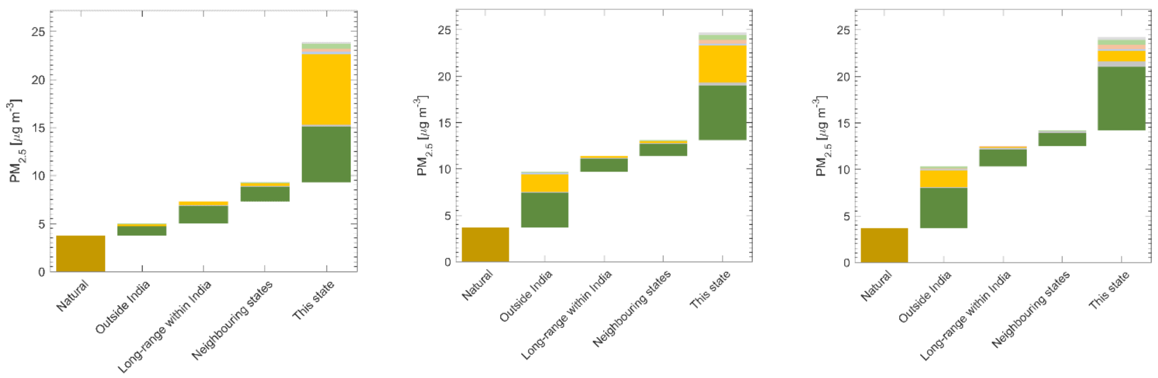
Natural	Secondary PM2.5⁺⁺	Coal thermal power plants
Other high stack	Households	Transport
Waste	Agriculture	Other

2015	2030	2050

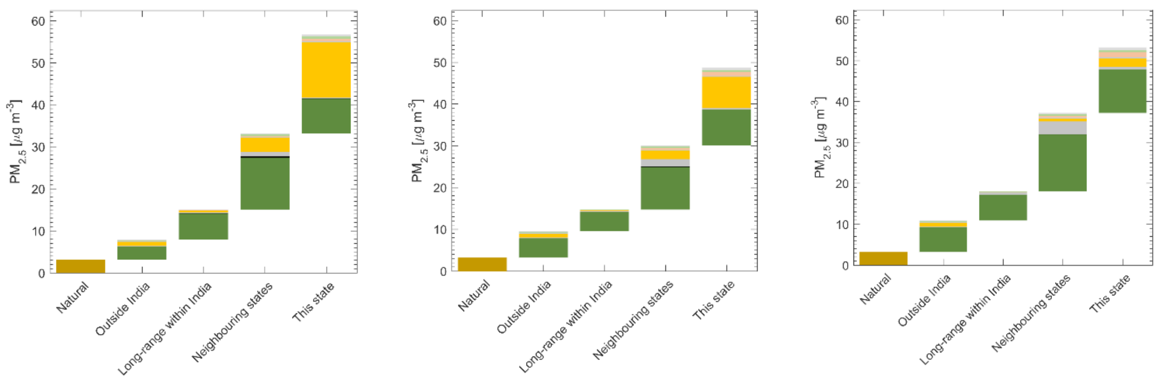
1. Andhra Pradesh



2. Assam

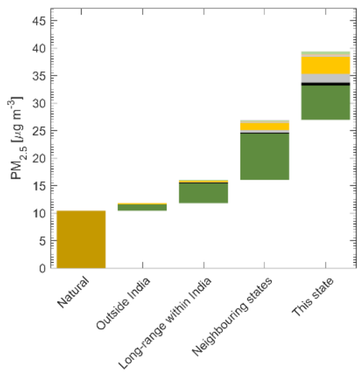


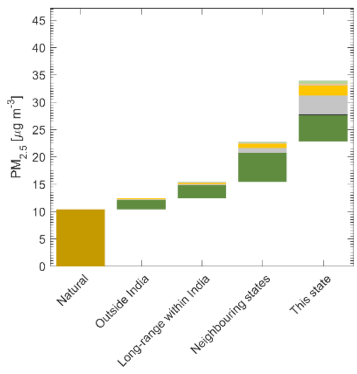
3. Bihar

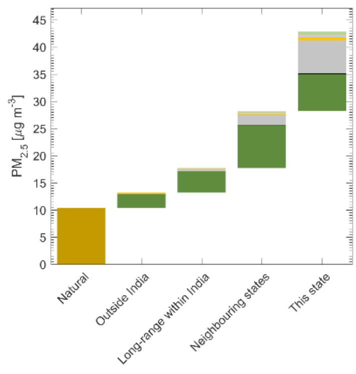


2015	2030	2050

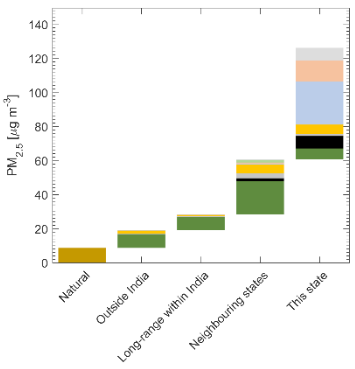
4. Chhattisgarh

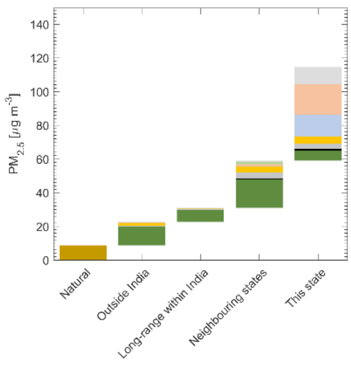


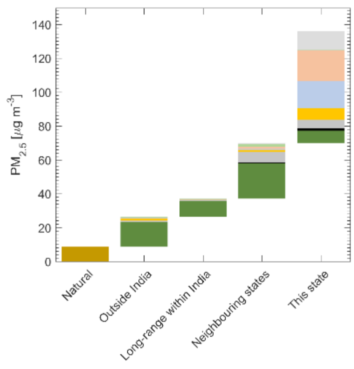




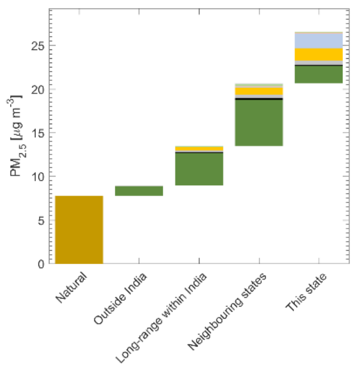
5. Delhi

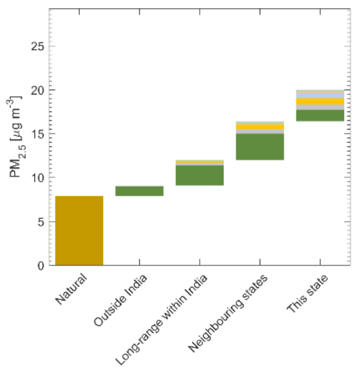


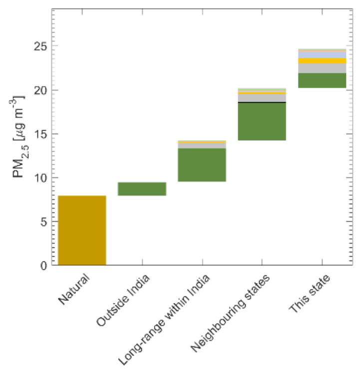




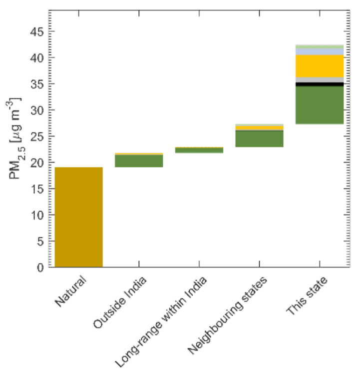
6. Goa

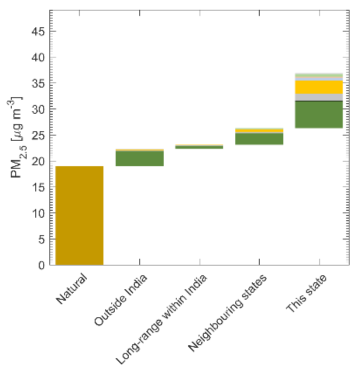


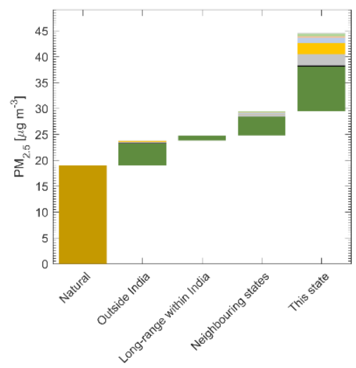




7. Gujarat

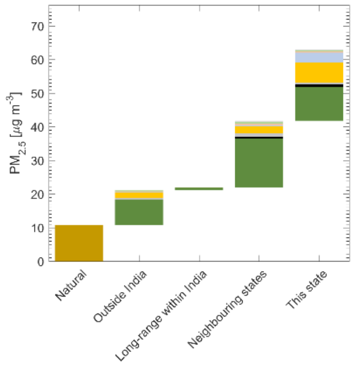


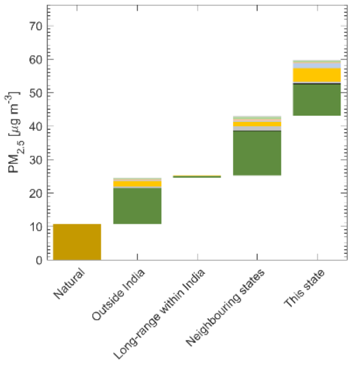


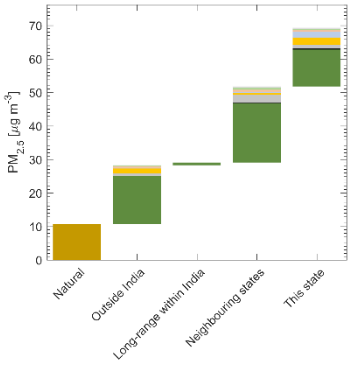


2015	2030	2050

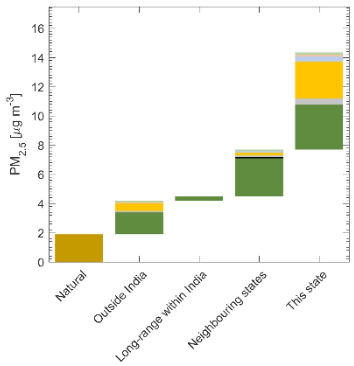
8. Haryana

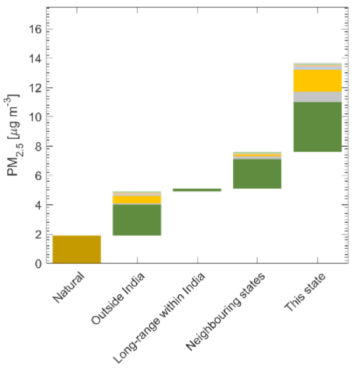


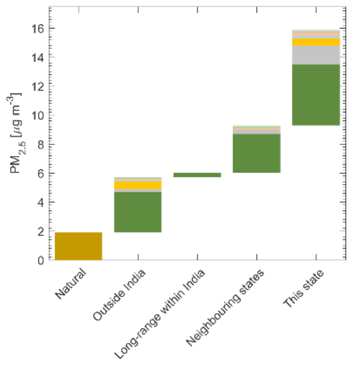




9. Himachal Pradesh







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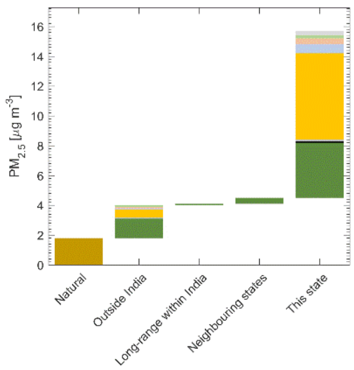

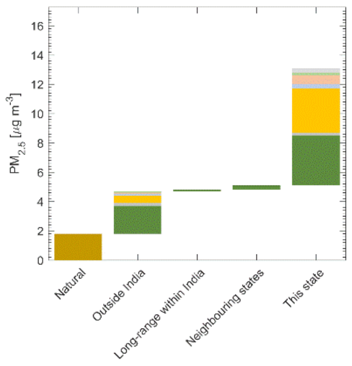

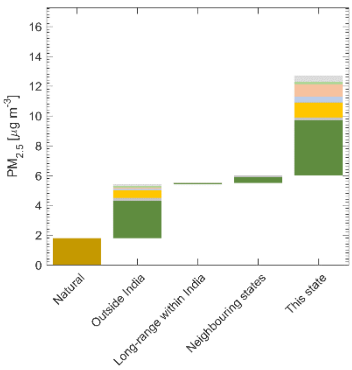

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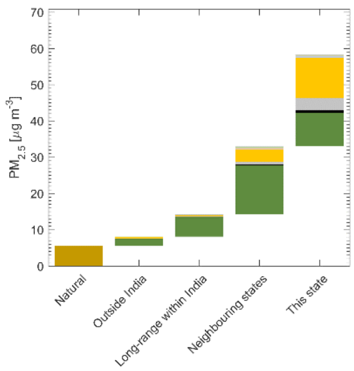
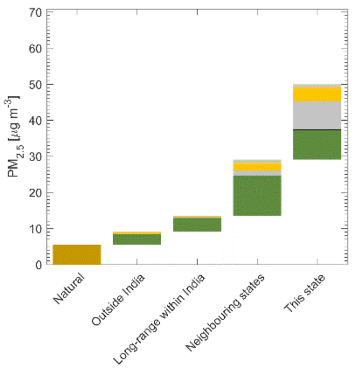
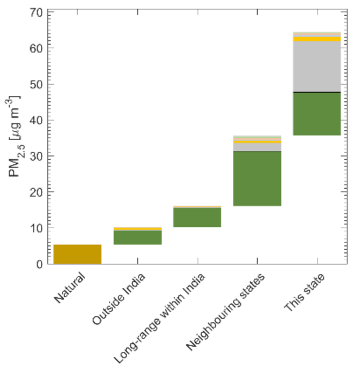
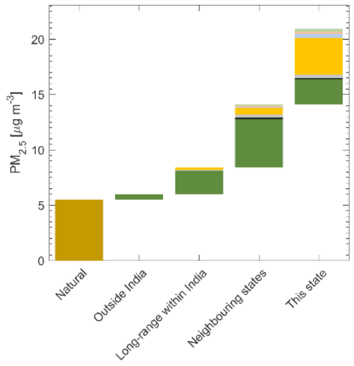


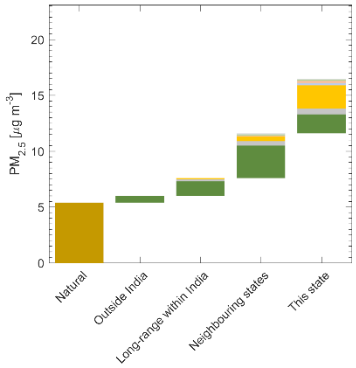


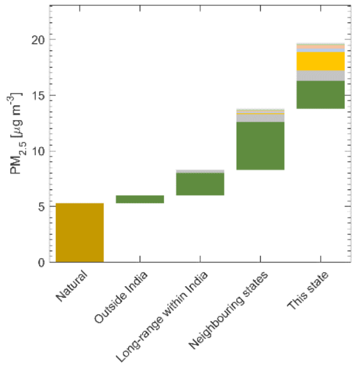


2015	2030	2050

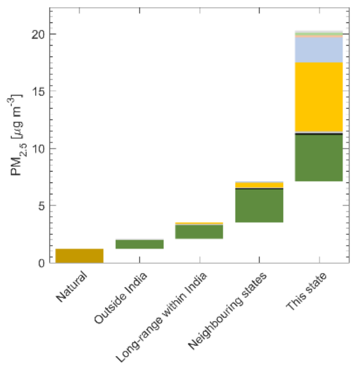
12. Karnataka

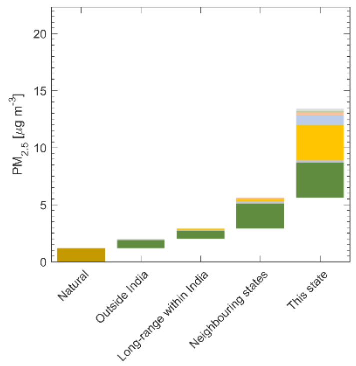


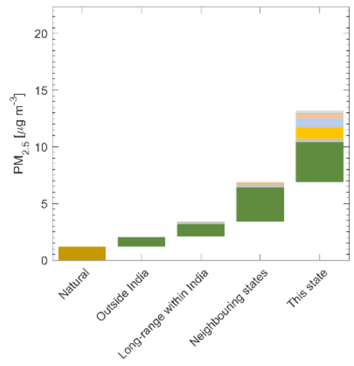




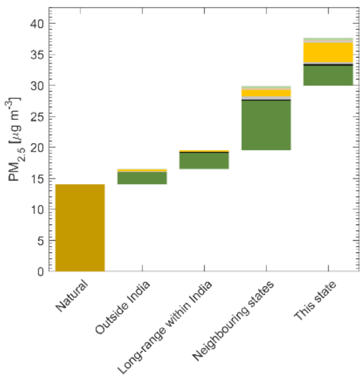
13. Kerala

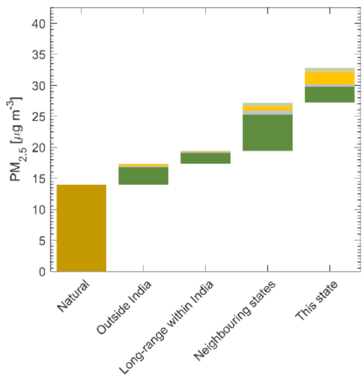


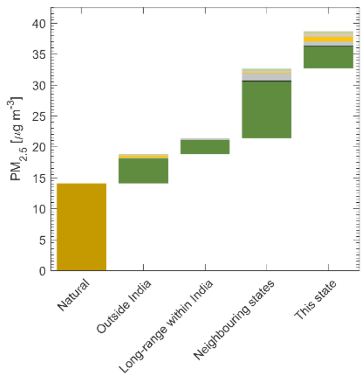




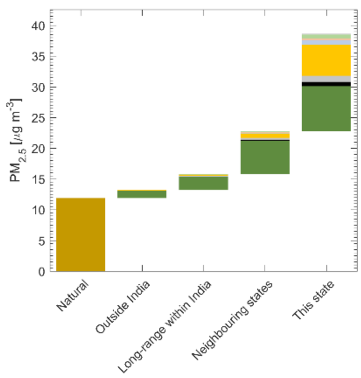
14. Madhya Pradesh

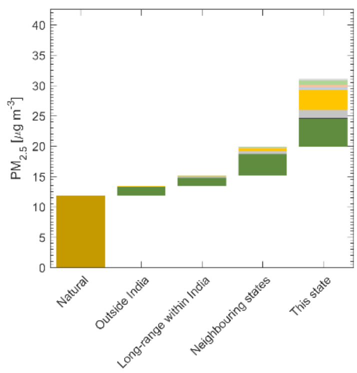


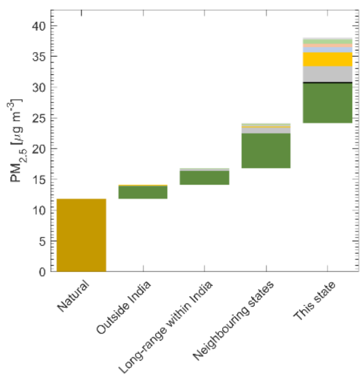




15. Maharashtra

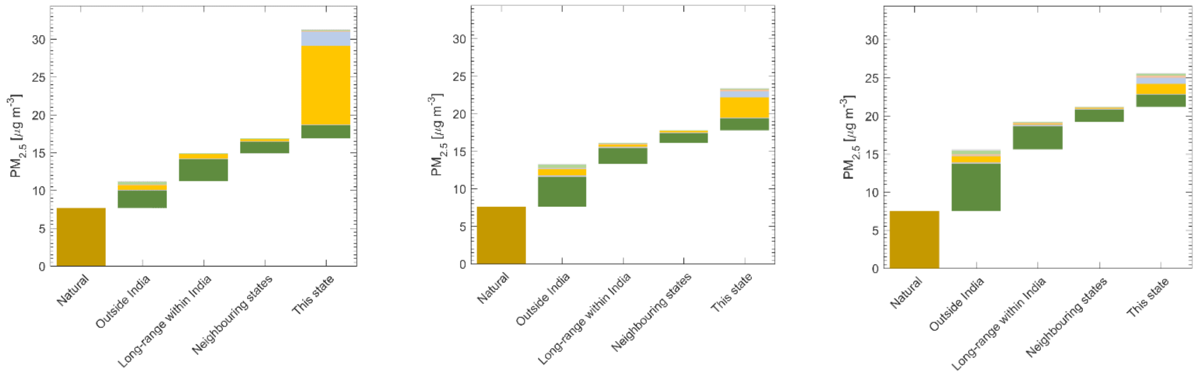




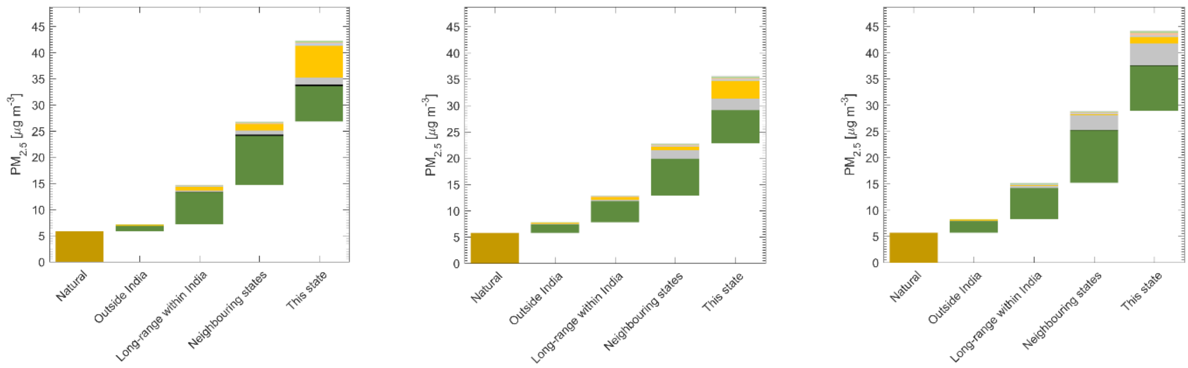


2015	2030	2050

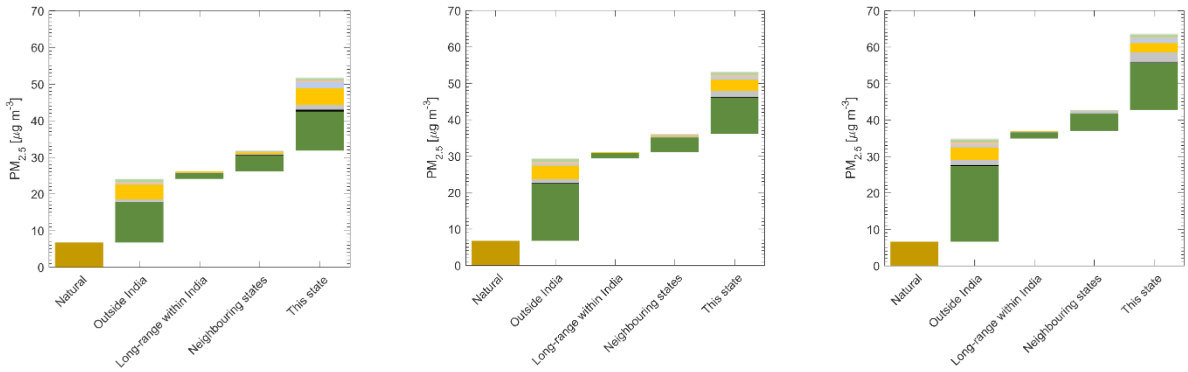
16. North East (excl. Assam)



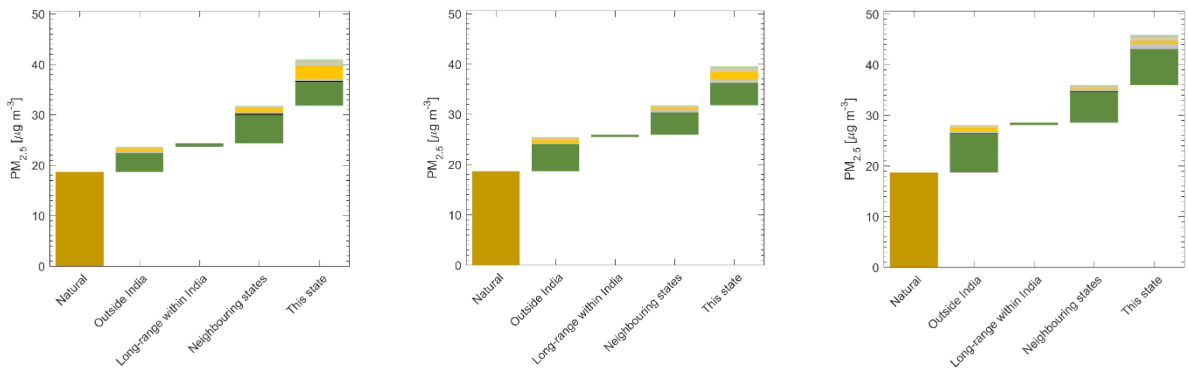
17. Odisha



18. Punjab

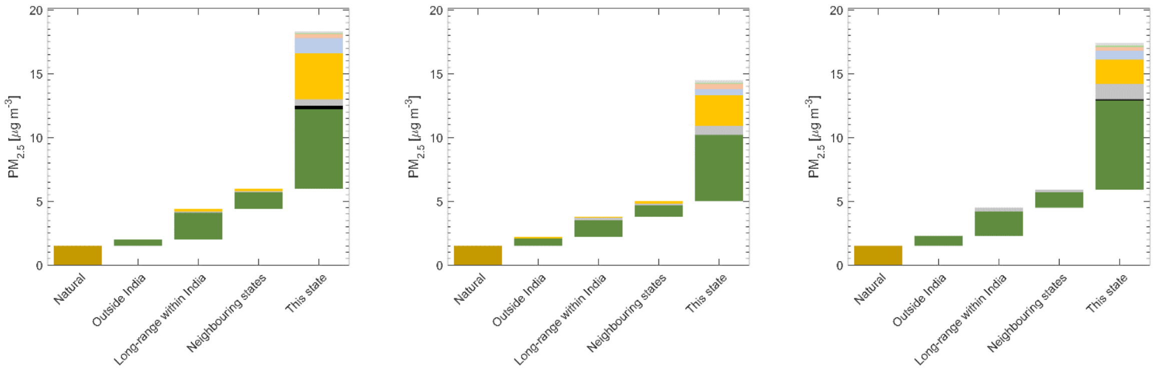


19. Rajasthan

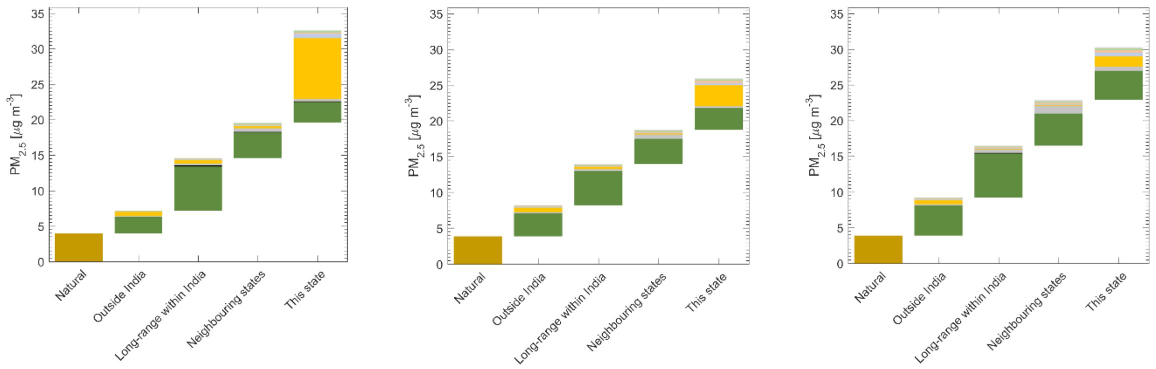


2015	2030	2050

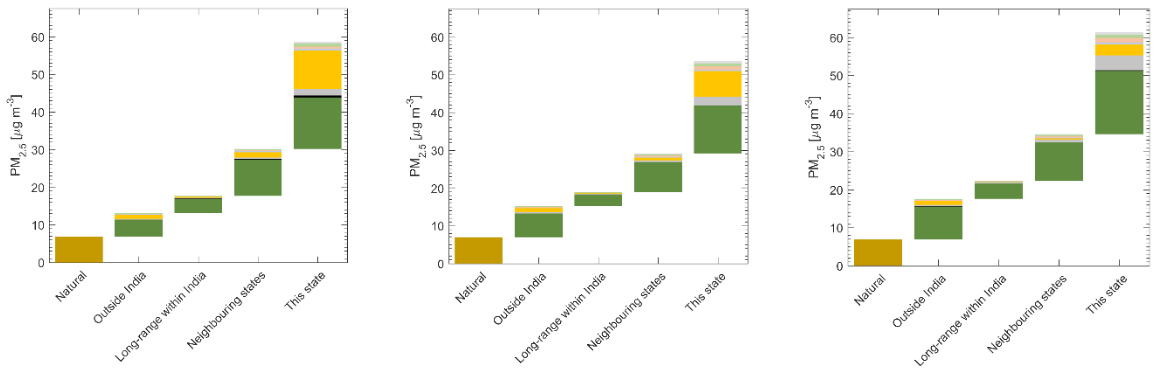
20. Tamil Nadu



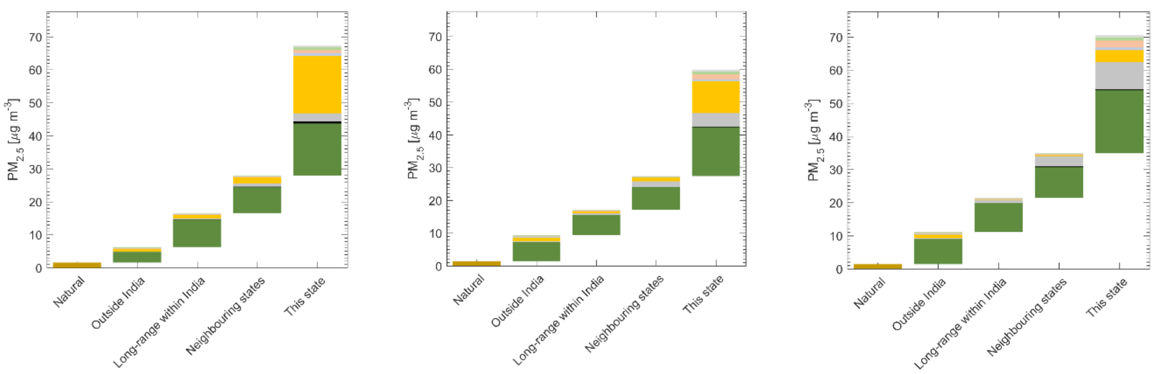
21. Uttarakhand



22. Uttar Pradesh



23. West Bengal



Source: IIASA-CEEW analysis, 2019

Annex 3:

Policies and measures considered in the scenarios

This annexure highlights the different policies considered across the different scenarios.

Annex 3A: Sectoral policies and measures incorporated into the energy baseline projection

TABLE A.1: Policies/measures incorporated into the baseline scenario

Source: GoI, 2014, 2008; GoI, 2006; MNRE, 2010; MoEFCC, 2015; MoP, 2014; UNFCCC, 2015

Policies/measures	Policy
Cross-cutting	▪ National Mission on Enhanced Energy Efficiency (GoI, 2008) ▪ National Clean Energy Fund to promote clean energy technologies, based on a levy of INR 400 (USD 6) per tonne of coal (Purohit, 2014) ▪ 'Make in India'[6] campaign to increase the share of manufacturing in the national economy ▪ Nationally Determined Contributions (NDC) GHG target: reduce emissions intensity of GDP to 33–35 per cent below 2005 levels by 2030 (UNFCCC, 2015) ▪ NDC energy target: achieve about 40 per cent cumulative installed capacity from non-fossil fuel sources by 2030 with the help of technology transfer and low-cost international finance (UNFCCC, 2015) ▪ Make efforts to expedite environmental clearances and land acquisition for energy projects ▪ Open the coal sector to private and foreign investors
Power sector	▪ Renewable purchase obligation (RPO) and other fiscal measures to promote renewables ▪ Increase use of supercritical coal technology ▪ Environmental (Protection) Amendment Rules ▪ Universal electricity access by 2025 ▪ Strengthen measures such as competitive bidding, to increase the use of renewables to meet the national target of 175 GW of renewables capacity by 2022 (100 GW solar, 75 GW non-solar) ▪ Expand efforts to strengthen the national grid, upgrade the transmission and distribution network, and reduce aggregate technical and commercial losses to 15 per cent ▪ Increase efforts to establish the financial viability of all power market participants, especially network and distribution companies

6 "Make in India" is a major new national programme of the Government of India designed to facilitate investment, foster innovation, enhance skill development, protect intellectual property, and improve India's manufacturing infrastructure.

Transport sector	▪ Increase blending mandate for ethanol (Purohit and Dhar, 2015) ▪ Support alternative-fuel vehicles, including 2020 National Electric Mobility Mission Plan; subsequent support for electric two- and three-wheelers, cars and buses ▪ Increase support for natural gas in road transport, particularly urban public transport ▪ Establish dedicated rail corridors to encourage shift away from road freight
Industrial sector	▪ Energy Conservation Act: • Mandatory energy audits • Appointment of energy managers in seven energy-intensive industries ▪ National Mission on Enhanced Energy Efficiency (NMEEE): • Cycle II and III of the Perform Achieve Trade (PAT) scheme, which benchmarks facilities' performance against best practices and enables trading of energy savings certificates • Income and corporate tax incentives for energy service companies, including the Energy Efficiency Financing Platform • Framework for Energy Efficient Economic Development (FEEED), offering a risk guarantee for performance contracts and a venture capital fund for energy efficiency ▪ Energy efficiency intervention in selected clusters of small and medium-sized enterprises (SMEs), including capacity building ▪ Further implementation of the NMEEE's recommendations including: ▪ Tightening of the PAT mechanism under Cycle III ▪ Further strengthening of fiscal instruments to promote energy efficiency ▪ Strengthen existing policies to realise the energy efficiency potential in SMEs
Building sector	▪ Rural electrification under Deen Dayal Upadhyaya Gram Jyoti Yojana (DDUGJY) scheme ▪ Improve clean cooking access with LPG, including provision of free connections to poor rural households through Pradhan Mantri Ujjwala Yojana ▪ Energy Conservation Building Code 2007 with voluntary standards for commercial buildings ▪ 'Green Rating for Integrated Habitat Assessment' rating system for green buildings ▪ Promotion and distribution of LEDs through the Efficient Lighting Programme ▪ Standards and Labelling Programme, mandatory for air conditioners, lights, televisions, and refrigerators, voluntary for seven other products and LEDs ▪ Phase out incandescent light bulbs by 2020 ▪ Voluntary star ratings for the service sector ▪ Measures under the National Mission on Enhanced Energy Efficiency ▪ Enhance efforts to increase electricity access for households

Annex 3B: Pollution control legislation considered in the 2018 legislation scenario

The 2018 legislation scenario considers all measures and standards that were in force in mid-2018. In particular, it includes measures to control dust emissions from power plants and industrial combustion sources (MoEFCC, 2015). To meet the new pollution norms for SO_2, coal thermal power plants are required to retrofit or install flue gas desulphurisation equipment, which removes sulphur dioxide from exhaust flue gases. In order to meet the 100 mg/Nm^3 NO_x standard, new plants will have to employ selective catalytic reduction to achieve compliance. For existing plans, the 300 mg/Nm^3 standard can potentially be attained through a combination of primary measures such as combustion controls, and selective non-catalytic/catalytic reduction. Table A.2 presents the key air pollution prevention policies in the power and industry sectors considered in the 2018 legislation scenario for India.

Controlling emissions from mobile sources (road and off-road, including non-exhaust sources) is essential for air pollution abatement in India. Unit emissions from road vehicles depend mostly on the fuel used (gasoline, diesel, or CNG) and on the emission control technology. Adoption of emission control technologies is in turn driven by legislation. The National Auto Fuel Policy (2003) mandates that all new four-wheeled vehicles in 11 cities meet Bharat Stage III emission norms for conventional air pollutants (similar to Euro III emission norms), and comply with Euro IV standards by 2010 (MoPNG, 2003). The Auto Fuel Vision and Policy 2025 was published in May 2014 to update the 2003 document with more stringent fuel and emissions standards (MoPNG, 2014).

TABLE A.2: Current legislation and air pollution prevention policies implemented in India

S. No.	Sector	Policy		Source
1.	Power plants	Electrostatic precipitators (ESPs) to curb particulate matter Flue gas desulphurisation to minimise SO_2 and mercury Selective catalytic converters (SCRs) and selective non-catalytic converters (SNCRs) to reduce NO_x.		(MoEFCC, 2015)
2.	Transport	India 2000	2000: Nationwide	(ICCT, 2016; MoRTH, 2016)
		Bharat Stage II	2001: National Capital Region (NCR) of Delhi, Mumbai, Kolkata, Chennai	
			04/2003: NCR, 13 Cities[7]	
			04/2005: Nationwide	
		Bharat Stage III	04/2005: NCR, 13 Cities	
			04/2010: Nationwide	
		Bharat Stage IV	04/2010: NCR, 13 Cities	
			04/2017: Nationwide	
		Bharat Stage V	(To be skipped)	
		Bharat Stage VI	04/2018: Delhi NCR	
			04/2020 (proposed): Nationwide	

7 Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, Lucknow, Sholapur, Jamshedpur, and Agra

3.	Industry	All new brick kilns shall be allowed only with a zig-zag or vertical shaft method of brick making	(MoEFCC, 2018a)
		New emission standard norms of SO_2 and NO_x for five industries: ceramics, foundry industries (furnaces based on fuel), glass, lime kilns, and reheating furnaces	(MoEFCC, 2018b)
		Ban on pet coke and furnace oil in the industrial sector in NCR states[8]	(MoEFCC, 2018c, 2018d)
4.	Agriculture	Bharat (Trem) Stage III A for agricultural tractors from April 2010; Bharat (Trem) Stage III from October 2005	
5.	Waste	Ban on open burning of waste in Indian cities	(MoEF, 2010)
		Ban on crop residue burning in five states: Punjab, Haryana, Rajasthan, Uttar Pradesh, and Delhi.	(CSE, 2017)
		Solid Waste Management Rules 2016	(MoEFCC, 2016)

For past years, we model the actual introduction of the different Indian emission control stages (Bharat);[9] for future years (2020 onwards), measures are accounted for to leapfrog directly to Bharat Stage (BS) VI for all on-road vehicle categories[10] (MoRTH, 2016). For passenger cars, and light and heavy-duty trucks, specifically, BS III is in force from 2010. For two-wheelers, standards equivalent to Euro III have been in force since 2010. More stringent emission controls for cars and trucks (BS IV), and an associated supply of low-sulphur fuels, are mandated in Delhi and in 19 other 'advanced' cities since April 2010. Apart from Delhi, these cities constitute about 10–14 per cent of the population in their respective states, and an even higher share of its vehicles. Heavy-duty vehicles are often registered outside the city where there are less stringent emission controls, thereby effectively circumventing the more advanced controls in place in cities (Cofala et al., 2015). We assume, therefore, that only up to 10 per cent of all states' vehicles are complying with the most advanced controls. BS IV air pollutant emission norms have been in force across India since April 2017. Additionally, India has also adopted nationwide fuel efficiency standards for light vehicles. A transition to BS VI

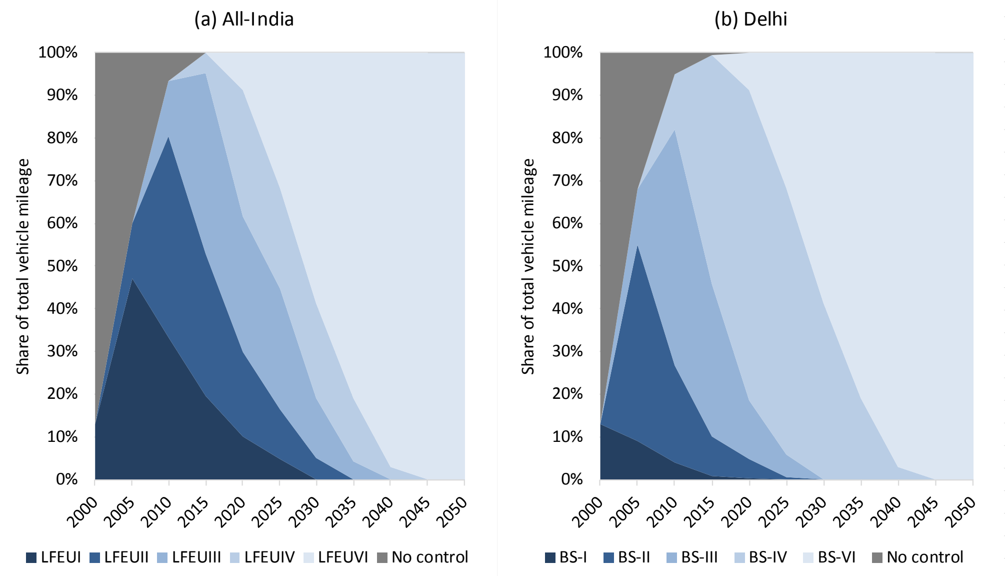


FIGURE A.1: Penetration of Bharat Stage Emission Standards for passenger cars in India

Source: IIASA-CEEW analysis, 2019

8 Including Delhi, Haryana, Rajasthan, and Uttar Pradesh

9 Bharat Stage Emission Standards (BSES) are emission standards instituted by the Indian government to regulate the output of air pollutants from internal combustion engines and spark-ignition engines, including motor vehicles. The standards and the timeline for implementation are set by the Central Pollution Control Board (CPCB) under the Indian Ministry of Environment, Forest and Climate Change (MoEFCC).

10 The Indian Ministry of Petroleum and Natural Gas (MoPNG) has announced a two-year advancement of the BS VI fuel norms; they will be introduced in Delhi from 1 April 2018.

norms is expected from 1 April 2020 (ICCT, 2016). Figure A.1 presents the penetration of the Bharat Stage Emission Standards for passenger cars in Delhi and the rest of the country. The Indian emission control system largely follows the European standards and technologies, with adjusted driving cycle and temperature controls. We therefore use adjusted European emission factors to model exhaust emissions in India (Guttikunda and Mohan, 2014). Emission controls up to BS III are assumed for agricultural tractors and construction machinery, and Stage I for diesel generators.

Similar to the power and transport sectors, all recently implemented environmental pollution control norms at the state and national levels are simulated in GAINS for industry and waste sources. According to the Environment (Protection) Amendment Rules, as of 2018, all new brick kilns should have a zig-zag or vertical shaft method of brick making (MoEFCC, 2018a). Existing brick kilns which are not using zig-zag or vertical shaft methods of brick making should be converted within one year for kilns located near non-attainment cities, and within two years for other kilns. The Environment Ministry has expanded the ambit of emission standard norms of SO_2 and NO_x for five industries: ceramics, foundry industries (furnaces based on fuel), glass, lime kilns, and reheating furnaces (MoEFCC, 2018b).

In the latest effort to curb rising air pollution, India's Ministry of Environment, Forest and Climate Change (MoEFCC) placed restrictions on the use of petroleum coke and furnace oil for powering industries in the National Capital Territory of Delhi and its surrounding region (MoEFCC, 2018c, 2018d). While India plans to propose banning the use of petroleum coke as a fuel nationwide, as part of a long-running programme to clean the country's air, the scenario in this study assumes a ban on petroleum coke in Delhi and the three neighbouring states of Haryana, Rajasthan, and Uttar Pradesh).

The Municipal Solid Waste Management Rules promulgated in 2000 prohibit the open burning of waste in Indian cities (MoEF, 2010). The 2016 solid waste management rules require segregation, processing, and recycling of waste (MoEFCC, 2016). The rules hold urban bodies, administrations, as well as users at source responsible for managing the waste. In November 2015, the National Green Tribunal banned crop residue burning in five states (Punjab, Haryana, Rajasthan, Uttar Pradesh, and Delhi) in which the government plans to spend USD 230 million over two years to prevent crop residue burning (Reuters, 2018).

Annex 4:
Emissions for the scenarios by state/region

TABLE A.3: Sulfur dioxide (SO_2) emissions by state/region

IIASA-CEEW analysis, 2019

State/region	2018 legislation scenario			Advanced control scenario		Development scenario	
	2015	2030	2050	2030	2050	2030	2050
Andhra Pradesh*	853.3	438.3	807.0	363.1	456.2	352.4	264.2
Assam	57.9	38.1	64.8	31.9	37.4	30.5	24.5
Bihar	176.5	79.0	131.9	67.4	75.6	63.3	44.6
Chhattisgarh	497.7	216.6	364.4	186.5	211.8	173.9	88.3
Delhi	79.9	30.2	43.3	25.4	25.0	9.9	5.4
Goa	36.7	12.6	20.8	12.0	15.6	11.6	8.9
Gujarat	1,038.3	585.2	1,092.1	476.2	624.9	429.7	268.5
Haryana	381.1	123.3	245.9	101.4	118.9	177.1	239.2
Himachal Pradesh	23.3	20.8	37.7	16.5	19.2	16.3	12.1
Jammu & Kashmir	27.9	11.3	18.3	10.2	11.6	10.0	7.2
Jharkhand	601.2	298.9	503.1	250.0	269.0	227.1	74.6
Karnataka	438.8	190.4	365.3	153.9	180.4	161.2	117.5
Kerala	170.4	82.8	132.9	70.5	74.5	73.1	43.3
Madhya Pradesh	548.4	203.7	383.2	172.4	223.4	160.1	115.8
Maharashtra	1,222.2	387.3	664.0	344.0	417.0	354.0	275.8
North East**	55.7	21.3	27.9	18.8	15.4	21.0	9.4
Odisha	406.0	239.1	424.5	194.8	224.5	189.6	118.7
Punjab	309.3	132.0	248.1	117.2	147.4	257.7	315.8
Rajasthan	715.3	577.0	1,112.9	533.8	907.6	839.0	1,236.1
Tamil Nadu	708.7	335.9	612.5	289.6	376.8	277.5	175.7
Uttar Pradesh	896.7	345.3	618.9	302.9	386.1	823.9	1,081.5
Uttarakhand	29.3	17.1	30.9	14.3	17.0	14.7	11.8
West Bengal	511.6	210.9	347.4	183.1	201.2	188.5	120.7
Total	9,786.3	4,597.1	8,297.7	3,936.1	5,036.4	4,862.1	4,659.7

**Including Telangana*

***Excluding Assam*

TABLE A.4:
Nitrogen oxides (NOx) emissions by state/ region

Source: IIASA-CEEW analysis, 2019

State/region	2018 legislation scenario			Advanced control scenario		Development scenario	
	2015	2030	2050	2030	2050	2030	2050
Andhra Pradesh*	555.9	710.5	960.7	641.8	678.1	575.5	332.8
Assam	89.0	95.8	97.5	91.3	80.7	84.0	58.5
Bihar	191.1	209.0	263.6	198.9	212.0	170.7	127.9
Chhattisgarh	277.7	358.0	481.5	333.8	386.7	286.5	119.4
Delhi	173.4	145.5	119.5	145.5	111.8	86.8	50.0
Goa	35.7	38.8	38.8	36.3	31.6	34.0	16.4
Gujarat	629.5	689.1	813.9	650.6	646.3	610.7	304.0
Haryana	355.9	357.1	319.3	350.2	268.7	291.3	136.0
Himachal Pradesh	59.8	67.6	73.1	62.5	48.9	58.4	31.2
Jammu & Kashmir	52.0	53.6	48.5	51.6	40.7	47.1	25.7
Jharkhand	306.2	390.6	524.2	383.1	479.8	321.7	113.5
Karnataka	358.7	393.2	461.3	362.6	331.6	338.3	196.0
Kerala	281.3	267.2	165.3	257.5	144.8	251.0	100.0
Madhya Pradesh	388.4	436.1	569.5	392.5	384.0	357.5	185.5
Maharashtra	709.1	769.9	918.0	729.6	737.1	660.2	315.3
North East**	93.5	95.5	73.8	89.6	55.7	86.9	38.8
Odisha	255.1	302.0	387.5	287.6	321.7	249.1	119.7
Punjab	227.4	249.4	298.5	240.4	246.1	196.8	117.2
Rajasthan	478.4	529.3	662.8	486.8	424.0	473.3	462.1
Tamil Nadu	685.8	724.1	717.2	669.3	510.8	632.3	265.2
Uttar Pradesh	582.2	650.9	876.0	642.1	715.8	578.9	457.7
Uttarakhand	37.9	45.5	61.0	41.6	43.0	37.3	25.9
West Bengal	392.9	430.3	498.7	414.9	425.2	359.6	180.9
Total	7,216.8	8,009.1	9,430.3	7,560.1	7,325.2	6,787.9	3,779.5

**Including Telangana*

***Excluding Assam*

TABLE A.5: $PM_{2.5}$ emissions by state/region

Source: IIASA-CEEW analysis, 2019

State/region	2018 legislation scenario			Advanced control scenario		Development scenario	
	2015	2030	2050	2030	2050	2030	2050
Andhra Pradesh*	431.6	377.5	430.9	314.7	187.4	121.9	91.1
Assam	130.2	90.9	62.9	81.0	36.1	22.9	18.0
Bihar	396.0	277.7	175.7	251.3	107.2	65.2	42.3
Chhattisgarh	212.7	246.3	327.3	192.1	128.8	80.9	40.7
Delhi	25.1	19.0	22.5	18.4	18.5	8.4	10.7
Goa	9.8	9.4	13.1	8.1	8.0	4.6	3.8
Gujarat	332.8	255.9	294.8	221.0	172.9	107.8	89.1
Haryana	130.6	92.1	89.9	81.3	55.7	29.1	21.8
Himachal Pradesh	30.2	27.3	31.1	22.8	13.8	9.6	7.7
Jammu & Kashmir	40.6	29.9	23.9	26.8	15.3	8.3	6.8
Jharkhand	277.6	364.3	550.2	261.6	183.6	138.6	31.7
Karnataka	279.9	230.8	253.6	200.0	137.1	80.6	63.3
Kerala	134.9	93.4	63.4	85.0	43.1	28.1	21.1
Madhya Pradesh	368.8	280.3	252.6	242.5	133.4	81.7	57.9
Maharashtra	509.0	414.5	463.8	357.4	272.6	154.3	120.6
North East**	64.7	45.7	35.1	40.1	20.1	12.4	10.0
Odisha	280.6	265.6	324.7	219.3	140.9	88.9	77.1
Punjab	124.2	107.7	123.6	92.1	70.7	32.0	29.7
Rajasthan	357.0	293.7	293.1	250.4	156.0	72.6	71.2
Tamil Nadu	312.1	237.5	250.5	214.3	156.9	91.7	91.6
Uttar Pradesh	820.8	677.2	635.4	597.4	379.6	152.2	123.8
Uttarakhand	37.8	26.9	25.3	23.6	13.4	7.8	7.9
West Bengal	445.2	379.4	400.4	321.8	190.1	112.7	78.6
Total	5,752.3	4,842.9	5,143.7	4,123.0	2,641.2	1,512.4	1,116.5

**Including Telangana*

***Excluding Assam*

TABLE A.6:
Black carbon (BC) emissions by state/region

Source: IIASA-CEEW analysis, 2019

State/region	2018 legislation scenario			Advanced control scenario		Development scenario	
	2015	2030	2050	2030	2050	2030	2050
Andhra Pradesh*	63.2	42.6	42.0	37.3	24.6	15.3	17.1
Assam	27.9	12.6	8.5	11.5	5.5	4.1	3.1
Bihar	71.8	35.1	20.0	32.9	15.1	10.6	7.8
Chhattisgarh	20.8	19.8	21.1	16.1	8.4	5.6	4.6
Delhi	4.9	3.3	3.9	3.4	3.6	2.1	3.0
Goa	1.3	0.9	0.8	0.8	0.7	0.6	0.5
Gujarat	47.4	27.4	24.6	24.9	20.4	12.2	14.6
Haryana	20.3	12.5	8.4	11.5	6.7	4.4	3.8
Himachal Pradesh	5.0	2.9	2.0	2.7	1.6	1.4	1.1
Jammu & Kashmir	8.7	4.0	2.7	3.7	2.2	1.6	1.3
Jharkhand	30.5	11.8	9.1	10.6	5.5	3.9	2.9
Karnataka	41.2	24.5	20.0	22.7	16.2	10.0	11.2
Kerala	25.6	14.5	7.5	13.5	6.3	6.5	3.7
Madhya Pradesh	47.1	30.3	20.4	27.8	15.3	10.3	9.0
Maharashtra	71.9	43.4	40.1	39.3	31.5	17.3	22.0
North East**	16.3	6.3	3.7	5.7	2.8	2.5	1.7
Odisha	35.8	19.9	12.7	18.4	9.5	6.7	5.3
Punjab	18.3	11.1	9.8	10.1	8.0	4.5	5.6
Rajasthan	47.4	30.8	21.6	27.5	14.6	9.1	8.3
Tamil Nadu	50.1	29.9	24.5	28.2	22.4	14.9	16.8
Uttar Pradesh	104.0	75.7	57.3	71.1	47.6	20.7	18.2
Uttarakhand	9.5	3.3	2.4	3.0	2.0	1.3	1.3
West Bengal	68.8	42.6	37.7	37.6	22.1	13.9	13.4
Total	837.7	505.2	400.7	460.4	292.7	179.7	176.3

**Including Telangana*

***Excluding Assam*

TABLE A.7:
Ammonia (NH_3) emissions by state/region

Source: IIASA-CEEW analysis, 2019

State/region	2018 legislation scenario			Advanced control scenario		Development scenario	
	2015	2030	2050	2030	2050	2030	2050
Andhra Pradesh*	714.0	924.9	1154.6	817.8	872.7	710.0	585.4
Assam	187.4	207.9	250.8	189.8	202.4	170.9	154.6
Bihar	501.1	634.7	750.0	568.9	585.7	501.5	421.7
Chhattisgarh	201.3	234.6	274.0	213.8	222.9	193.2	170.8
Delhi	19.8	26.6	29.8	26.2	28.4	25.0	26.4
Goa	5.0	5.9	7.4	5.3	5.8	4.6	3.8
Gujarat	403.1	527.6	612.2	484.3	507.4	438.5	394.4
Haryana	334.4	456.1	541.7	397.3	396.6	197.6	216.1
Himachal Pradesh	56.6	67.1	78.1	63.5	69.2	59.8	60.3
Jammu & Kashmir	98.6	124.5	148.0	116.9	128.6	109.1	109.1
Jharkhand	171.8	198.9	248.7	183.7	207.4	170.4	163.6
Karnataka	383.5	444.4	540.4	392.6	410.2	339.3	277.5
Kerala	61.5	56.4	62.4	53.3	55.0	49.7	47.1
Madhya Pradesh	555.9	666.5	770.6	613.8	641.1	558.2	509.8
Maharashtra	623.5	760.9	909.8	680.0	708.1	595.4	499.0
North East**	84.6	97.3	121.1	87.5	94.5	77.2	68.5
Odisha	286.8	326.6	382.5	300.8	317.2	275.0	251.2
Punjab	342.9	439.3	521.0	374.8	364.2	155.3	172.9
Rajasthan	535.1	663.1	766.7	604.4	624.1	414.8	459.5
Tamil Nadu	400.6	514.7	666.5	456.2	506.5	397.4	339.9
Uttar Pradesh	1,327.7	1,686.9	1,965.4	1,503.6	1,518.4	886.8	975.8
Uttarakhand	76.4	92.0	107.1	84.5	88.5	76.8	69.9
West Bengal	556.3	688.5	842.3	620.2	663.0	551.5	481.5
Total	7,927.7	9,845.4	11,751.2	8,839.0	9,217.9	6,958.5	6,459.0

**Including Telangana*

***Excluding Assam*

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