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Managing future air quality in Delhi

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Abstract

Indian cities rank high in air pollution at the global scale. This report presents an initial perspective on management options that could efficiently improve Delhi's air quality. Employing the newly developed GAINS-Delhi policy analysis model, it reveals innovative insights into the current sources of pollution that threaten the health of Delhi's citizens. It outlines the likely future development of these sources, and explores potential policy interventions that could effectively reduce environmental pollution and resulting health impacts in the coming years.

The analysis demonstrates that effective improvement of Delhi's air quality requires collaboration with neighboring States and must involve sources that are less relevant in industrialized countries. However, many of the policy interventions will have multiple co-benefits on development targets in Delhi and its neighboring States.

Acknowledgments

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Table of Contents

Introduction

Indian cities rank high in air pollution at the global scale; for PM2.5 which is associated with serious health impacts, four out of the ten cities with highest concentrations are found in India (WHO 2016a). While the World Health Organization (WHO) has established a global guideline value of 10 $\mu g/m^3$ for the annual mean concentrations of PM2.5, it is estimated that only about 1% of the Indian population has been exposed to less than this level in 2015 (OECD/IEA 2016). 62% of the population faced an exposure of more than 35 $\mu g/m^3$, the Target Level 3 defined by the WHO. The National Ambient Air Quality Standards (NAAQS) of the Indian government set a permissible limit of annual PM2.5 concentrations of 40 $\mu g/m^3$ (CPCB 2012), which is exceeded widely in the country.

These high pollution levels cause significant health impacts; estimates for India for 2012 range between 515,000 and 750,000 cases of premature deaths annually from outdoor pollution, and 950,000-1,500,000 cases from indoor household pollution (IHME 2016; WHO 2016b).

While their quantification remains uncertain, it is likely that health impacts impose a significant burden on the economy; a recent estimate of the World Bank suggests for 2013 welfare losses equivalent to 7.7% of GDP ((Lim et al. 2012; World Bank 2016; WHO 2016b).

India's ambitious plans for further economic development imply additional growth in many activities that are currently important sources of pollution. The current governmental policies outline a continued 6-7% growth per year in general economic output. Even larger growth rates are envisaged for activities that are generally believed to be major sources of pollution. The sales of domestically manufactured vehicles have increased by at least 15% per annum since 2008 (SIAM, 2013), and traffic volumes are expected to grow by 10.5%/year in future (MoSPI 2015). Also for power generation, forecasts suggest a 11.1%/year increase in the future (CEA 2015)(CEA 2016). Thus, unless effective countermeasures to control pollution from these increased activities would be taken, ambient air quality is poised to deteriorate further in the future.

Since long, the Indian authorities have imposed regulations on important emission sources that should lead to significant improvements in ambient air quality and eventually to compliance with the Indian air quality standards and international guidelines (see Table 1). Further regulations are under discussion. Focusing on the National Capital Territory (NCT) of Delhi, this report assesses the likely impacts of conceivable additional regulations and strategies on air quality, population exposure and health outcomes.

Methodology

To explore the likely impacts of alternative policy interventions on emission reductions for the NCT of Delhi, we employ a detailed atmospheric chemistry model that quantifies the consequences of reductions of primary particulate emissions from different economic sectors on ambient concentrations of PM2.5 in Delhi. Operated by NEERI, the AERMOD atmospheric dispersion modeling system is a steady-state dispersion model designed for short-range (up to 50 km) dispersion of air pollutant emissions from stationary industrial sources (Cimorelli et al. 2005); Perry et al. 2005). Computations employ a detailed inventory of the PM2.5 precursor emissions in the Delhi region, i.e., PM2.5, SO_2, NO_x, NH_3 and VOC, which has been developed by NEERI based on a wealth of statistical information and local measurements (see SI).

Outcomes of this model are subsequently fed into the Greenhouse gas – Air pollution Interactions and Synergies (GAINS) model that has been developed by the International Institute for Applied Systems Analysis (IIASA,) (Amann et al. 2008; Purohit et al. 2008; Amann et al. 2011). The GAINS model is a widely-applied policy analysis tool to identify cost-effective policy interventions to reduce health impacts of air pollution while maximizing co-benefits with other policy priorities (Hordijk and Amann 2007; Reis et al. 2012). GAINS quantifies the implications of alternative pathways of economic development on precursor emissions of ambient PM2.5, i.e., primary PM2.5, SO_2, NO_x, NH_3 and VOC. It estimates the technical potential for emission reductions at the various sources and associated emission control costs, as well as the contributions from natural sources (e.g., soil dust, secondary organic aerosols, sea salt). The GAINS version that has been developed for this particular project estimates the resulting ambient concentration fields of primary particles as well as of secondary aerosols, considering precursor emissions within the Delhi NCT as well as relevant emissions in the rest of India, which are transported in the atmosphere into the city domain. (Note that, due to their small size, PM2.5 particles remain in the atmosphere for several days and are transported with the wind during this time). The model computes subsequent population exposure to PM2.5 at a 2x2 km resolution, and derives indicative estimates of the resulting impacts on premature mortality, both from ambient pollution as well as the exposure to household pollution within homes (see SI).

Results

Understanding of the current situation

To explore the scope and effectiveness of potential future policy interventions, the analysis starts from a detailed inventory of currently implemented and decided emission control measures (Table 1). Assuming effective implementation of all these measures, the analysis combines technical features (i.e., emission reduction efficiencies) of each measure with economic activities, emission factors, and meteorological and chemical features of the dispersion of pollutants in the atmosphere.

As a result, the analysis closely reproduces not only observations of ambient levels of PM2.5 across the model domain (Figure 1), but also the chemical composition of PM2.5 observations (Figure 2).

Table 1: **Air pollution prevention/control policies in India**

Sector	Current status	Current/Planned policies & programs
General	• Air pollution is a serious issue, with most cities violating PM2.5 targets; main sources are fuel wood and biomass burning , fuel adulteration, vehicle emissions, large scale crop residue burning	• National Ambient Air Quality Standards (NAAQS) • Air (Prevention and Control of Pollution) Act (1981) • Air Quality legislation/programs
Power	• Electricity sources: Thermal (Coal, Oil, Gas) – 70%, Hydro (14%), Renewables (wind, bagasse, solar, biomass, waste to power, water mills) - (14%), Nuclear (2%).	• 40 percent non-fossil-based power capacity by 2030 (primarily by renewables and nuclear) • Promotion of renewables and energy efficiency • Use of high efficiency Electrostatic precipitator (ESP) technology in large coal-based power plants (where applicable)

Table 1, continued

Sector	Current status	Current/Planned policies & programs
Industry	• Industries that have the potential to impact air quality: petroleum refining, chemicals, textiles, steel, cement, mining, basic metal industries, non-metallic mineral products, etc.	• Emission regulations for industries • Promotion of renewable energy investment • Incentives to purchase energy efficient equipment; clean production and installation of pollution control technologies • Other actions at national, sub-national and/or local level to reduce industry emissions (i. e. Finance Act 2015 provides incentives for manufacturing facilities to be set up in rural areas of some states).
Transport	• Key transport-related air quality challenges: rapid growth; a number of older vehicles still in use without catalytic converters; some taxis and auto-rickshaws use adulterated fuel (differential taxes encourage this).	• Vehicle emission limit: Euro III (Euro IV in 11 major cities); Euro VI[1] from 2020 onwards • Fuel Sulphur content: 350 ppm (50 ppm in 11 major cities) • Actions to expand, improve and promote public transport, mass transit and non-motorized transport • Shifting of public transport buses from diesel to CNG in Delhi • Other transport - related actions: Incentives for production or purchase of green vehicles[2], such as the electric vehicle incentive program; promotion of biofuels[3], ban on used car import, etc.
Open burning of agric./ municipal waste (outdoor)	• Ministry of Road Transport & Highways has decided to leapfrog from BS-IV to BS-VI emission norms directly by 01.04.2020.	• Legal framework: National Green Tribunal (NGT) has recently directed corporations, authorities and state governments to ensure garbage not burned openly; Cities are not complying with the Municipal Solid Waste (Management & Handling) Rules 2000
Open burning of biomass (indoor)	• Dominant fuels used for cooking and space heating: 82% households use solid fuels	• Promotion of off-grid/grid electrification, cleaner cooking fuels (i. e. LPG, electricity) and cleaner cook stoves

Source: (CPCB 2012; UNEP 2015; MNRE 2016; OECD/IEA 2016)

[1] In January 2016, GoI has decided to leapfrog directly from Euro IV emission norms for petrol and diesel to Euro VI standards. The BS-VI norms will be implemented for new vehicles by April 2020 and for existing vehicles by April 2021 (MoRTH 2016).

[2] The Government of India has set a goal of deploying 6–7 million hybrid and Plug-in electric vehicles (PEVs) on Indian roads by the year 2020 (Sheppard et al. 2016).

[3] National Biofuels Policy proposed a target of 20% blending of transportation fuels — diesel and petrol (gasoline) — with bio-diesel and bio-ethanol by 2017 (Purohit and Dhar 2015).

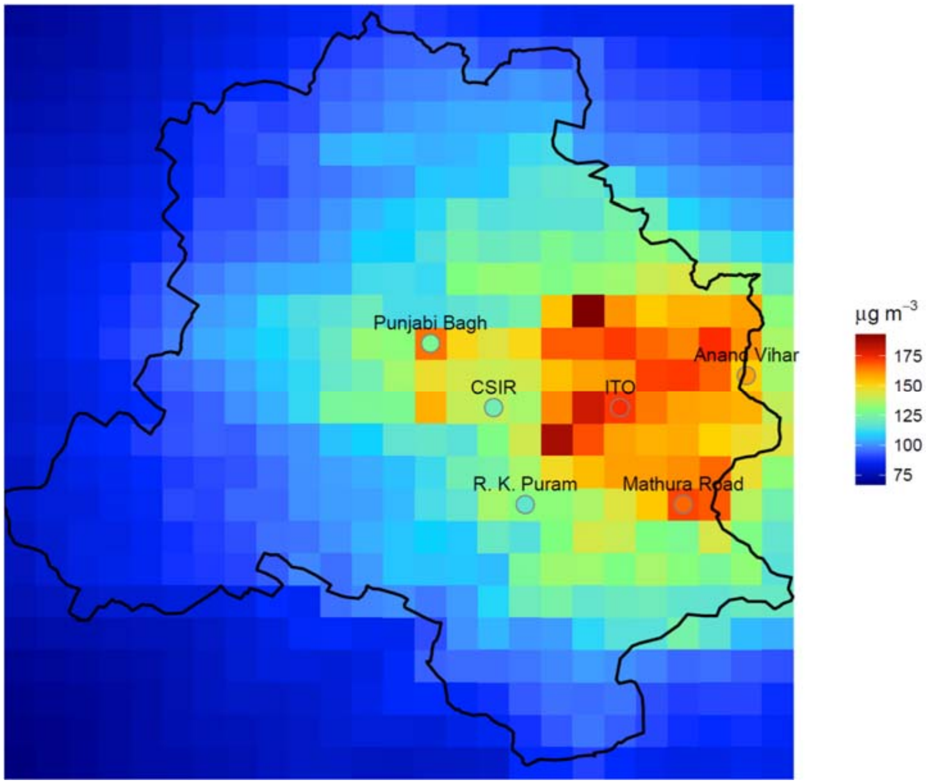

Figure 1: Comparison of ambient PM2.5 concentrations in the Delhi model domain: Modelled results for 2015 (field shading) versus observations (circles) for 2012-2014.

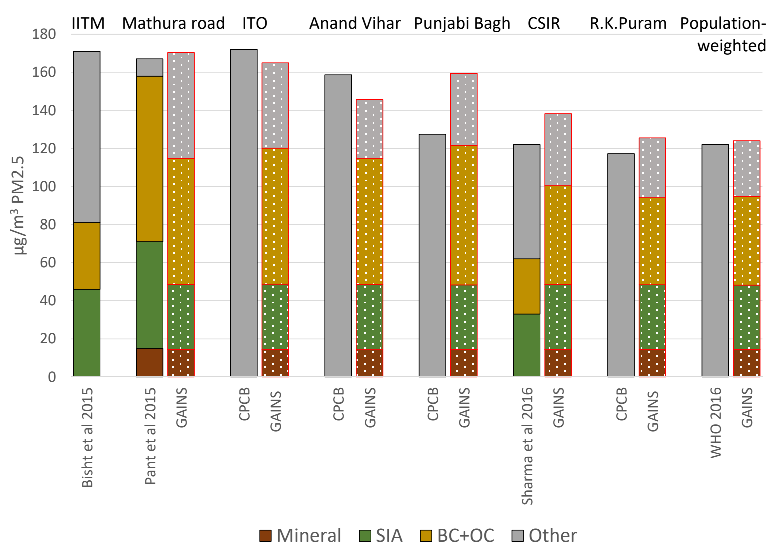

Figure 2: Chemical composition of PM2.5: Observations (Bisht et al. 2015; Pant et al. 2015; Sharma et al. 2015; CPCB 2016) against GAINS model results for 2015

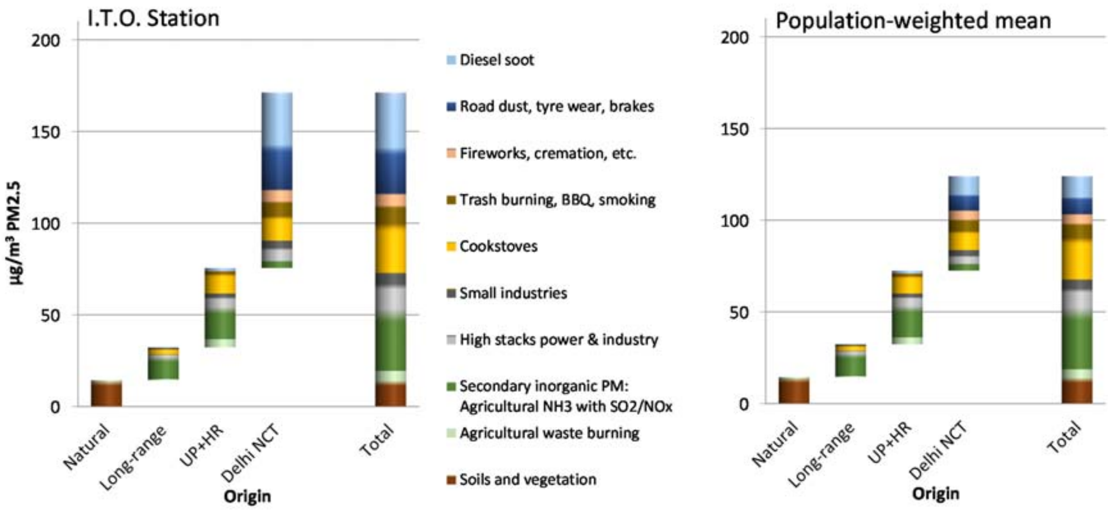

Figure 3: Source contributions in 2015; left panel: I.T.O. monitoring station, right panel: population-weighted mean exposure.

Most instructive, however, is the source attribution that quantifies contributions to ambient PM2.5 from the different sources. Figure 3 shows the contributions to ambient PM2.5 concentrations computed for 2015 for the I.T.O station, which is located in the city center close to a road side (left panel) and the contributions to population-weighted PM2.5 exposure in the Delhi National Capital Territory (right panel). The x-axis distinguishes the spatial origin of PM2.5, i.e., (i) from natural sources, (ii) pollution originating from the long-range transport of emissions from sources in India outside Delhi, Haryana and Uttar Pradesh, as well as from Punjab, Rajasthan and Pakistan, (iii) from emission sources in the surrounding States Haryana and Uttar Pradesh (HR+UP), and (iv) from emissions originating from the Delhi NCT region. The y-axis indicates the amounts originating from emissions of the different economic sectors.

Strikingly, despite the large size of Delhi NCT with about18 million inhabitants, only about 40% of population-weighted exposure to PM2.5 originates from emission sources within the domain (at traffic hot spots, the share increases to about 55%). 60% of PM2.5 in ambient air in Delhi is transported into the city from outside, out of which about half comes from the surrounding States Haryana and Uttar Pradesh, one quarter from even more remote anthropogenic sources, and one quarter from natural sources.

At the ITO traffic hot spot site, about one third of ambient PM2.5 was caused by emissions from road traffic, out of which about 55% emerge from exhaust gas (diesel soot) and 45% from non-exhaust emissions (road dust, brake and tire wear). On a population-weighted basis, transport emissions contributed about 17% to total PM2.5 in ambient air; other important sources include solid fuel combustion in cook stoves (mainly from the surrounding rural areas) with a 20% contribution, 23% from secondary inorganic aerosols formed from reactions of SO_2 emissions (emitted in power plants and industry) and NO_x (from traffic) with NH_3 from agricultural activities, 14% from dust emitted at high stacks, 12% from the burning of agricultural and municipal waste, and 9% from natural sources (soil dust).

It is noteworthy that this source allocation (which is supported by the chemical analysis of PM monitoring) contradicts wide-spread misbeliefs that the majority of air pollution in Indian cities emerges from vehicles (Badami 2005; Gurjar et al. 2010). While at traffic hot spots vehicles contribute the largest share, still about two-thirds of PM2.5 at such locations originates from other sources. Furthermore, currently only slightly more than half of traffic-related PM2.5 comes from exhaust emissions, while the other fraction is non-exhaust, e.g., road dust, tire and brake wear, etc. As a consequence, policy interventions that focus only on exhaust emissions will have limited impact on PM2.5 concentrations in ambient air, especially when a rapid growth in traffic volumes will cause similar increases in non-exhaust emissions.

In addition, while air quality at traffic hot-spots is relevant for compliance with ambient air quality standards, actual health impacts of air pollution in the total population is more closely related to the population-weighted exposure to PM2.5. The right panel of Figure 3 clearly indicates that traffic-related (exhaust and non-exhaust) emissions make an even smaller contribution to the long-term exposure of the total population in the city. At the same time, it highlights the importance of emission sources that receive less attention in current emission control strategies for urban air quality, such as the uncontrolled burning of biomass and waste, road dust, as well as SO_2 and NO_x emissions from large plants and traffic.

Future trends

To explore the likely future development of air quality in Delhi and the effectiveness of alternative policy interventions, we analyze an economic projection provided by NEERI for the year 2030. This projection assumes an annual growth of the population in the Delhi National Capital Territory by 2.8%, resulting by 2030 in a 50% larger population than in 2015. At the same time, economic wealth (expressed as GDP/capita) will improve by 5%/year, resulting in an 8% annual growth of economic output in the region, i.e., a doubling compared to 2015. Transport demand is assumed to follow the same growth path (Table 2).

The economic projection is accompanied by an energy forecast that predicts a significant decline in the energy intensity (3.6%/year), so that total energy consumption in Delhi will grow by only 4.2% by year. Most of the increased energy demand would be supplied by natural gas (+7.3%/year) and liquid fuels (+2.9%/year), while the consumption of coal and biomass will remain at current levels.

Table 2: Assumed development of key indicators in Delhi NCT between 2015 and 2030

	Annual growth	**Change 2015-2030**		**Annual growth**	**Change 2015-2030**
Population	+2.8/yr	+50%	Energy intensity	-3.6%/yr	-40%
GDP/capita	+5%/yr	+110%	Natural gas	+7.3%/yr	+190%
GDP	+8%/yr	+200%	Liquid fuels	+2.9%/yr	+80%
Transport demand	+8%/yr	+200%	Coal, biomass	± 0%	± 0

For the regions outside Delhi, we employ the assumption of an economic growth of 6.2%/year and the energy projection presented by the International Energy Agency (IEA) in its special report on Energy and Air Quality (IEA 2016).

As a baseline air quality projection, we assume full and effective implementation of the emission control legislation that is currently in force for Delhi and the neighboring States (see Table 1).

With these assumptions, population-weighted exposure to PM2.5 in the Delhi region would rise by about 9% to 132 µg/m^3. The anticipated expansion of transport volumes would cause an even larger growth of PM2.5 concentrations at traffic hot spots (e.g., to 195 µg/m^3 at the ITO station, which would then exceed the current Indian Ambient Air Quality Standard by almost a factor of five.

It is noteworthy that most of the increase emerges from higher emissions in Delhi. The inflow of pollution would stabilize at the 2015 level, essentially due to the new legislation on SO_2 emissions from large point sources that affect the formation of secondary inorganic aerosols. While the new legislation introduced on emission in Delhi show significant effect (e.g., Bharat VI for exhaust emissions from mobile sources), their benefit will be compensated by higher non-exhaust emissions that emerge in line with the general growth in transport activities.

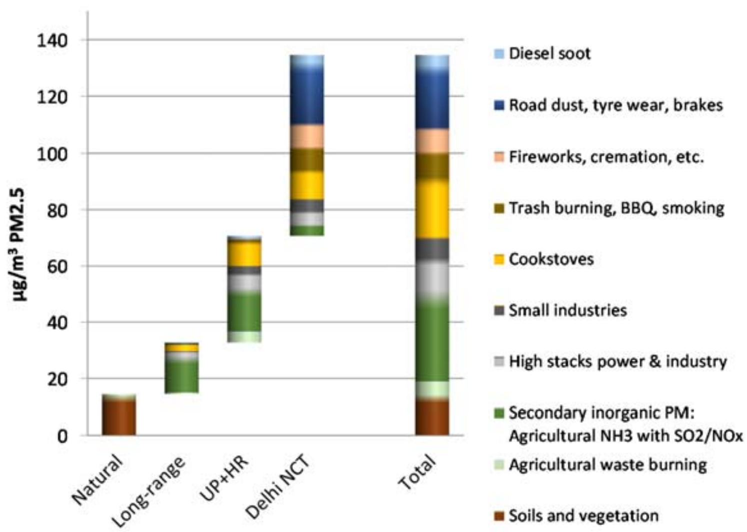

Figure 4: Source contribution to population-weighted PM2.5 in Delhi NCT for the Baseline projection in 2030

The scope for additional measures in Delhi

As the baseline projection does not indicate likely progress towards the achievement of the National Air Quality Standards in Delhi, we use the GAINS-Delhi tool to explore the effectiveness of additional emission control strategies.

An 'Advanced Technology' scenario

As a logical extension of current policies, we analyze an 'Advanced Technology' case which assumes that the Delhi government would strengthen measures that rely on technical emission controls, in line with examples widely adopted in many other countries in the world. In particular, such a scenario would tighten the emission limit values for large point sources for SO_2, NO_x and PM/TSP. For mobile sources, tighter controls would be introduced for non-road mobile machinery, while emission standards for road vehicles would remain at the Bharat VI level that is already assumed in the baseline. Furthermore, cremation would be electric.

Effective implementation of these additional requirements by 2030 would reduce population-weighted PM2.5 to 120 µg/m^3, i.e., by 10% compared to the baseline, and thereby bring it back to the 2015 levels. However, despite the high ambitions for new technology, emission sources from within the NCT area would still contribute about 50 g/m^3 to population exposure, which in itself already exceeds the current National Ambient Air Quality Standard.

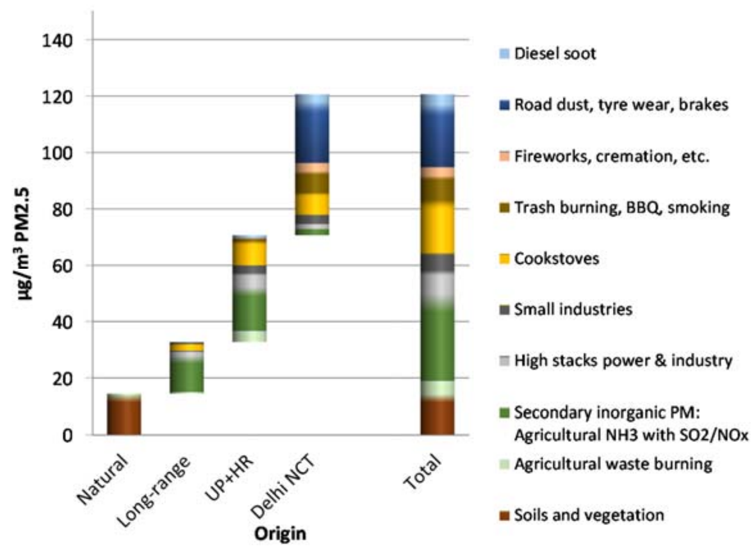

Figure 5: Source contribution to population-weighted PM2.5 in Delhi NCT in 2030 for the 'Advanced Technology' set of measures applied to Delhi

A 'Delhi Clean Air' strategy

An alternative scenario explores the scope for air quality improvements from regulating emissions from such non-industrial activities. As these sources are less relevant in industrialized countries, they are often overlooked in simplistically drawn lessons from international experience. While there is less experience documented, these sources have been controlled in many countries along their development path, although often not with a focus on air quality management.

In particular, this 'Delhi Clean Air' strategy copnsiders road paving, improved waste management with a ban on open trash burning, fewer fireworks in the city, and promotion of electric barbecues (to replace 50% of current BBQ activities). Furthermore, it is assumed that solid fuel use for cook stoves will be phased out in Delhi up to 2030 and replaced by electricity or natural gas.

Such a strategy would lead to significant improvements in air quality in Delhi, with population-weighted PM2.5 exposure dropping to about 90 µg/m^3, i.e., by 30% below today's levels (Figure 6).

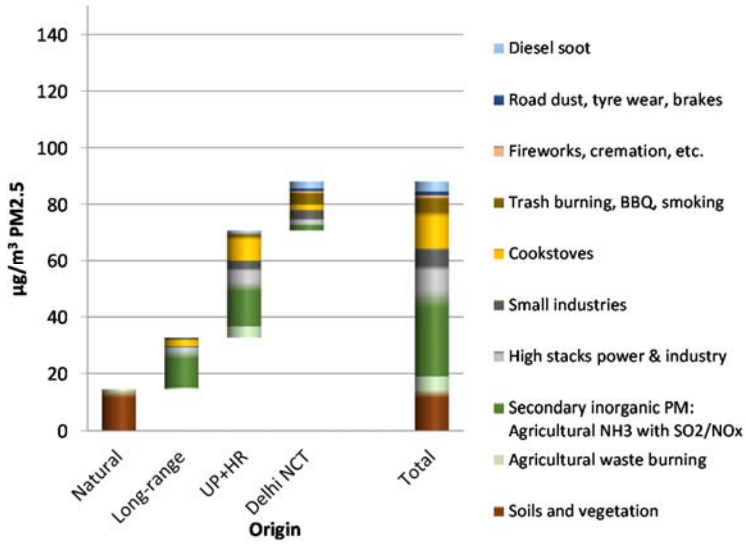

Figure 6: Source contribution to population-weighted PM2.5 in Delhi NCT in 2030 for the 'Delhi Clean Air' measures applied to Delhi NCT

Regional cooperation with neighboring States

Although addressing the traditional emission sources that are characteristic for Indian cities will enable a significant improvement in air quality, it will only solve part of the problem as a large share of pollution will remain, imported from the surrounding areas. For the scenario above, 80% of particulate matter in Delhi's air will be imported from outside, so that a further strengthening of regulations within Delhi would have only very limited impact on local air quality. As shown in Figure 6, after Delhi would have taken all practical measures, the majority of pollution would be transported from the surrounding States Haryana and Uttar Pradesh. About 40% of the import from these areas would result from large point source emissions of SO_2 and NO_x (forming secondary inorganic aerosols), while the more conventional emission sources account for about 60%.

Thus, following the Western standard model for air quality management, i.e., tightening emission standards for large industrial emission sources and transportation in Haryana, Uttar Pradesh and Delhi, would reduce PM2.5 levels in Delhi to about 107 μg/m^3, which is less improvement than the 'Delhi Clean Air' strategy in Delhi would deliver (Figure 7).

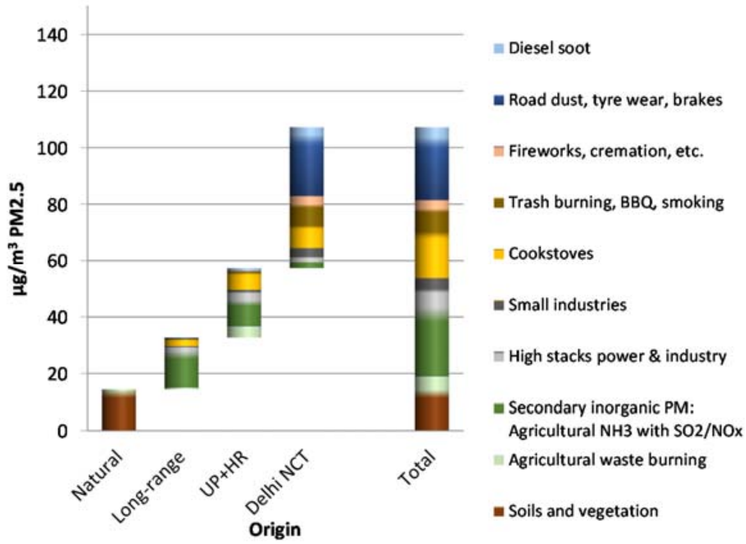

Figure 7: Source contributions to population-weighted PM2.5 in Delhi NCT in 2030 for the 'Advanced Technology' set of measures applied to Delhi, Haryana and Uttar Pradesh

Much larger benefits could be achieved from extending the 'Delhi Clean Air' strategy to the three States, enhanced by an organized recycling of agricultural waste to substitute coal and oil in the industrial sector, to be accompanied by a ban on agricultural waste burning. Furthermore, it is assumed that biomass for cook stoves will not only be substituted by electricity and natural gas (as in Delhi), but in rural areas also by LPG.

Such a cooperative strategy would have major impacts on air quality in Delhi, and could halve current exposure levels for PM2.5 to around 60 µg/m^3 (Figure 8). In addition, it would also lead to significantly lower pollution levels around Delhi, and thereby deliver even larger benefits in surrounding areas.

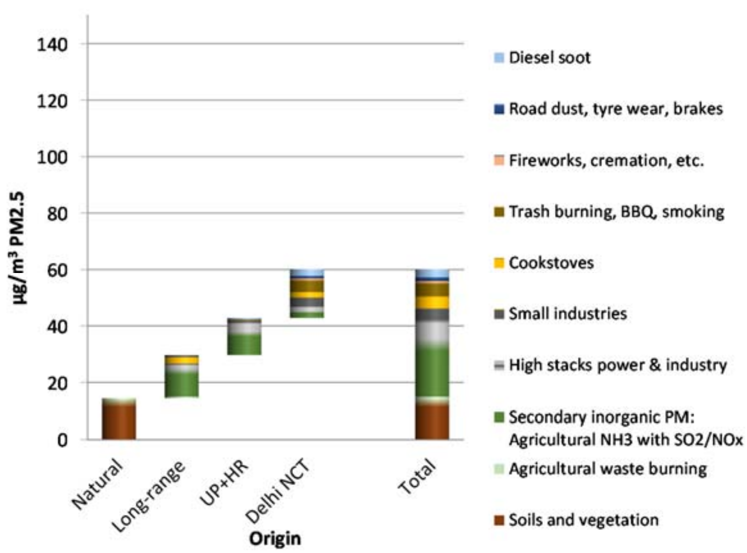

Figure 8: Source contribution to population-weighted PM2.5 in Delhi NCT in 2030 for the 'Delhi Clean Air' set of measures applied to Delhi, Haryana and Uttar Pradesh

Benefits from the air quality measures

The above analysis explored the response of a health-related exposure metric, i.e., population-weighted PM2.5 concentrations in Delhi NCT towards different emission control assumptions. Obviously, both the population distribution and concentrations of PM2.5 in ambient air show significant spatial variation within the model domain. Such distributional aspects are important for an analysis of the compliance with air quality standards, which typically refer to concentrations at specific locations.

Compliance with National Ambient Air Quality Standards

As mentioned above, the GAINS-Delhi model computes concentrations and population exposure with a 2x2 km spatial resolution, to be compared with the corresponding distribution of (today's and future) population.

For the year 2015, the analysis reveals that within the Delhi model domain essentially all people faced pollution levels that exceeded the (annual) National Air Quality Standards of 40 µg/m^3 . About 2.5 million people were exposed to air that exceeded the NAAQS by more than four times (>160 µg/m^3), 7.5 million people experienced exceedance between a factor of three and four (i.e., between 120 and 160 µg/m^3), and 10 million between 40 and 80 µg/m^3. For the baseline case in 2030, the group with the largest exposure (>160 µg/m^3) would increase to more than 8 million people, and 19 million people (i.e., almost the current population of Delhi) would be exposed to more than 120 µg/m^3. Compared to today's situation, only the joint implementation of the 'Delhi Clean Air' scenario in Delhi, Haryana and Uttar Pradesh could reduce total population exposure in absolute terms, i.e., reduce the number of people that face exceedances of the current Indian National Air Quality Standards (Figure 9).

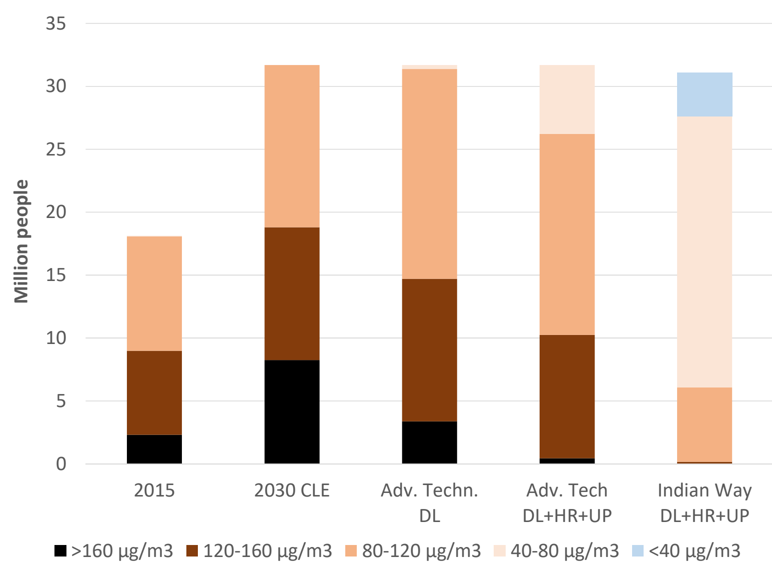

Figure 9: Population exposed to different levels of PM2.5 in Delhi NCT

Health impacts

Although a precise quantification of health impacts from air pollution remains uncertain, the GAINS-Delhi model has implemented the current methodologies that are widely used to estimate the global burden of disease from exposure to ambient and household air pollution around the world (Lim et al. 2012), (WHO 2016b), (World Bank 2016), (Burnett et al. 2014).

These methods would suggest that in 2015 ambient air pollution caused about 8,900 [6,230-11,570] cases of premature deaths in Delhi. In the baseline case, this number would increase to about 15,000 [10,630-19.640], a combined effect of the 50% growth in population size and the higher exposure as a result of higher emissions. While the 'Advanced Technology' scenarios would reduce population exposure to some extent, the current health impact methodologies suggest even smaller improvements in health effects, essentially due to the assumptions of declining health effects under high pollution levels. Even the regional application of the 'Advanced Technology' scenario would lead to an increase in the number of premature deaths by about 50% compared to 2015, an aspect that will be relevant for the future planning of public health authorities. Larger health benefits are expected for improvements at lower exposure levels, e.g., from the 'Delhi Clean Air' scenario (Figure 10).

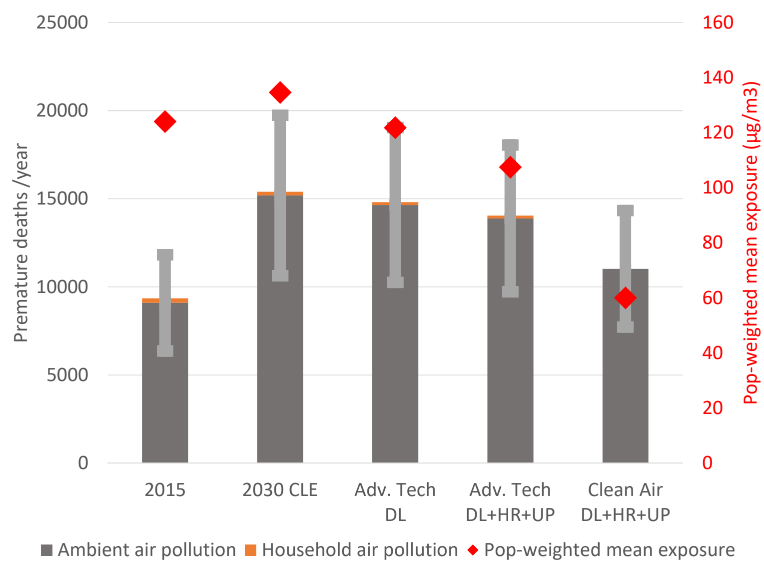

Figure 10: Premature mortality attributable to ambient and household air pollution, and population-weighted exposure to PM2.5 in Delhi

Greenhouse gas emissions

Compared to the 'Advanced Technology' scenario that does not modify the levels of any economic activities, the 'Delhi Clean Air' strategy addresses pollution sources in a more holistic way. It promotes reduction and substitution of most polluting activities by cleaner alternatives without diminishing human welfare through, e.g., energy efficiency improvements, enhanced public transport, use of cleaner fuels for cook stoves, and the replacement of coal with natural gas.

The 'Delhi Clean Air' strategy does not, per se, aim at a reduction of greenhouse gas emissions. If beneficial for air quality purposes, it even adopts certain measures that lead to higher direct CO_2

emissions (e.g., replacement of biomass for cook stoves by LPG, natural gas or electricity). At the same time, the analysis accounts for associated changes in the emissions of all greenhouse gases, especially emissions of methane from biomass combustion and waste management. It is noteworthy that, as a side effect of the adopted measures, Delhi's greenhouse gas emissions in the 'Delhi Clean Air' strategy would be more than 20% lower than in the baseline case (Figure 11). Co-controls of air pollution and greenhouse gas emissions in Haryana and Uttar Pradesh are even larger due to the ban of agricultural waste burning, an activity that is not relevant in Delhi NCT.

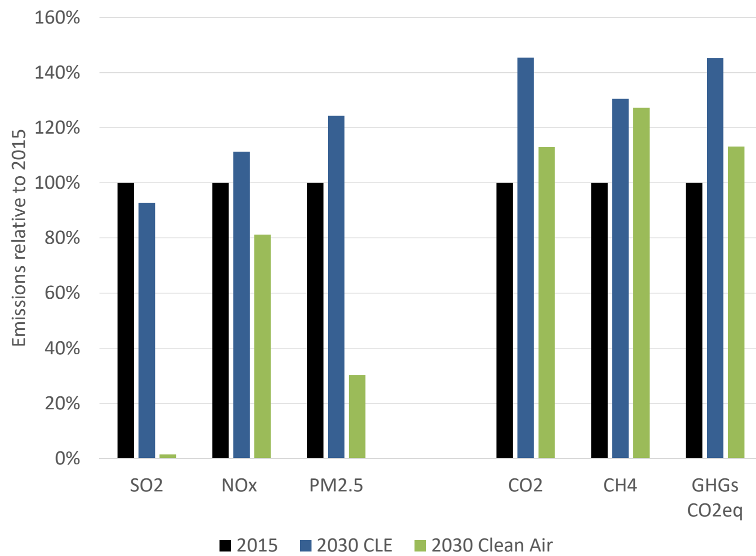

Figure 11: Air pollutant and greenhouse gas emissions in Delhi; 2015 compared with the baseline projection for 2030 (CLE) and the 'Delhi Clean Air' scenario for 2030

Co-benefits on development targets

In addition to the co-control of greenhouse gas emissions, measures of the 'Delhi Clean Air' strategy would deliver a range of benefits on other development priorities (in Delhi and in its surroundings), which however are not quantified in this initial analysis. A non-exhaustive list includes, inter alia, accelerated infrastructure development (power grid expansion, loss reduction, enhanced gas distribution networks, waste management practices), time savings from avoided biofuel collection, additional jobs for the manufacturing of clean technologies (e.g., efficient and electric stoves, renewable energy), more efficient land use due to less ash and soot disposal, lower emissions of other toxic substances (Hg, POPs) with subsequent health benefits, improved traffic management, improve protection of historical monuments and buildings, enhance gains from tourism, etc.

Conclusions

Poor air quality is a major concern world-wide, with a significant burden on public health. Indian cities rank high in air pollution at the global scale; for PM2.5 which is associated with serious health impacts, four out of the ten cities with highest concentrations are found in India (WHO 2016a).

Many emission sources in Delhi and its surroundings contribute to PM2.5 in the city

It is found that, despite the large size of Delhi NCT with about currently about 18 million inhabitants, only about 40% of (population-weighted exposure to) PM2.5 originates from local emission sources (at traffic hot spots, the share increases to about 55%). 60% of PM2.5 in ambient air in Delhi is transported into the city from outside. Transport emissions contributed less than 20% to total PM2.5 in ambient air; other important sources include biomass fuel combustion in cook stoves (mainly from the surrounding rural areas) with a 20% contribution, 23% from secondary inorganic aerosols formed from reactions of SO_2 and NO_x emissions (emitted by power plants, industry and traffic) with NH_3 from agricultural activities, 14% from dust emitted at high stacks, 12% from the burning of agricultural and municipal waste, and 9% from natural sources (including soil dust and biogenic emissions).

This source allocation (which is supported by the chemical analysis of PM monitoring) contradicts wide-spread misbeliefs that the majority of air pollution in cities emerges from vehicles. While at traffic hot spots indeed vehicles contribute the largest share, still about two-thirds of PM2.5 at such locations originates from other sources. Furthermore, currently only slightly more than half of traffic-related PM2.5 comes from exhaust emissions, while the other fraction is non-exhaust, e.g., road dust, tire and brake wear, etc. As a consequence, policy interventions that focus only on exhaust emissions will have limited impact on PM2.5 concentrations in ambient air, especially when a rapid growth in traffic volumes will cause similar increases in non-exhaust emissions.

Despite the adopted policy measures, Delhi's air quality could further deteriorate in the future

The analysis suggests that the increased levels of economic activities following the anticipated economic growth path will counteract the air quality benefits of the ambitious pollution control measures that have been adopted by the authorities. While recent regulations to control emissions at large point sources should stabilize the inflow of pollution from the surrounding areas, the decline in PM exhaust gas emissions from the implementation of the Bharat VI standards in Delhi is likely to be compensated by higher non-exhaust emissions (e.g., road dust, tire and brake wear) that follow the anticipated growth in traffic volumes. As a consequence, it must be expected that (population-weighted) air quality would further deteriorate in the future, despite the adopted policy measures.

Effective improvements of Delhi's air quality require collaboration with neighboring States

The analysis clearly indicates that even the most stringent emission control measures, if restricted to the Delhi NCT area, will not be sufficient to effectively reduce ambient pollution levels in the city and approach the Indian National Ambient Air Quality Standards. The most ambitious scenario for measures in Delhi would reduce ambient levels in the area to about 90 µg/m^3. Since in this scenario about 70 µg/m^3 of pollution would be imported from outside Delhi, coordinated action with neighboring States is indispensable for any effective improvements of air quality within Delhi (Figure 12). Furthermore, achievement of the National Ambient Air Quality Standards or of the even lower target levels issued by the World Health Organization (WHO) would be facilitated by concerted action to address the long-range transport of pollution from other Indian States and Pakistan.

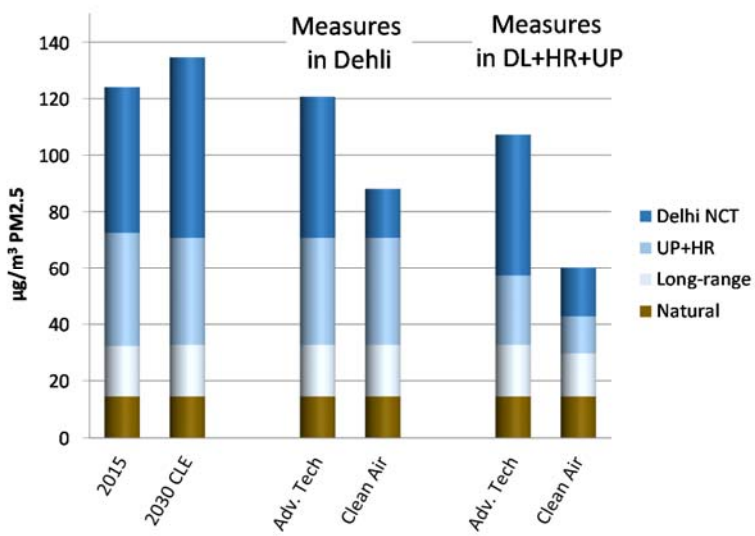

Figure 12: Origin of PM2.5 in Delhi in the different scenarios

Effective interventions must involve sources that are less relevant in industrialized countries

The comparison between the two strategies makes it clear that, in order to solve Delhi's pressing air quality problem, it will be essential that the relevant authorities address emission sources that are not always prominent in air quality management portfolios of other countries and cities. Major emissions and reduction potential exist, inter alia, for road paving to reduce road dust emission, a rapid transition to clean cooking fuels within the Delhi NCT and in the neighboring States, and comprehensive management procedures for municipal and agricultural waste, that should allow for a ban of all open burning of waste. Furthermore, authorities need to develop approaches to reduce pollution from cultural behavior and activities, e.g., less charcoal use for barbecues, fewer fireworks within the city, more environmentally friendly forms of cremation, etc. (Figure 13). While such changed practices will be essential for cleaner air in Delhi, they need to be accompanied by strict control of SO_2, NO_x and PM emissions at large plants in the surrounding area, if the National Ambient Air Quality Standards are to be achieved.

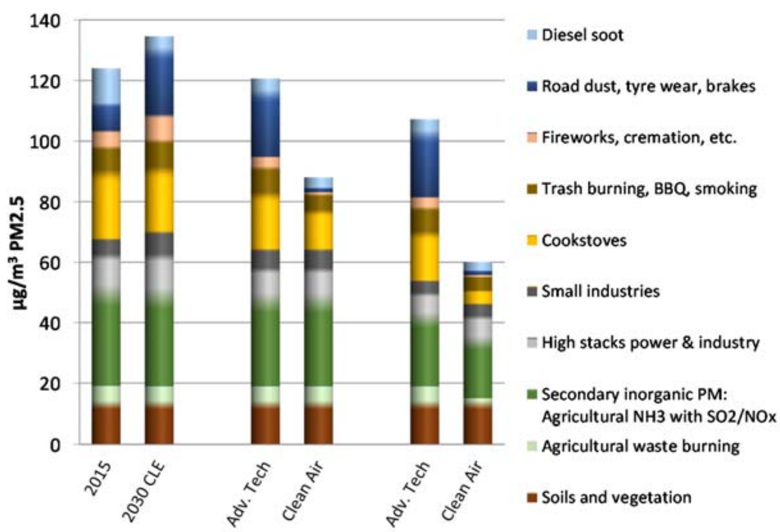

Figure 13: Contributions of different source categories to the population-weighted PM2.5 concentrations in Delhi, for the different scenarios

Many of the policy interventions will have multiple co-benefits on development targets

In addition to the co-control of greenhouse gas emissions, measures of the 'Delhi Clean Air' strategy would deliver a range of benefits on other development priorities (in Delhi and in its surroundings).

Summary and outlook

In summary, this report presents an initial perspective on management options that could efficiently improve Delhi's air quality. It reveals innovative insights into the current sources of pollution that threaten the health of Delhi's citizens, outlines the likely future development of these sources, and explores potential policy interventions that could effectively reduce environmental pollution in the coming years.

While the underlying GAINS methodology is being applied for practical policy analyses throughout the world, many of the Delhi-specific input data that have been compiled in this project might still be imperfect and could be further improved through additional work. Furthermore, the implementation of the economic analysis features of GAINS that allow estimating costs of alternative pollution control strategies, the development of cost-effective policy response packages and exploring the socio-economic heterogeneity of their implications could provide highly relevant information to the policy making process.

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