BREATHING CLEANER AIR

Ten Scalable Solutions for Indian Cities

A self-organized task force report for the World Sustainable Development Summit, New Delhi, October 6, 2016

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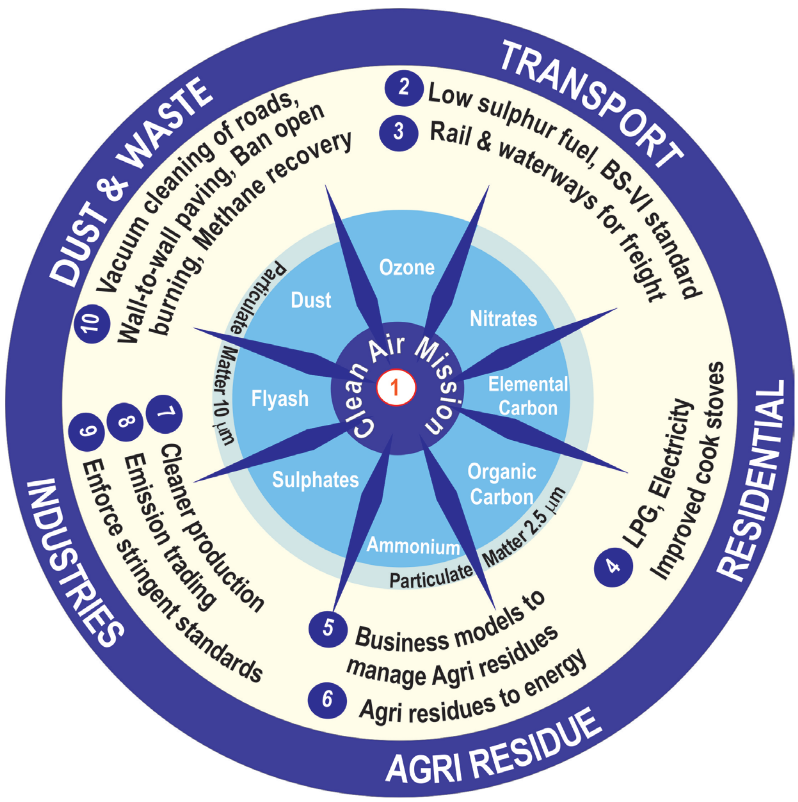

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This report should be referred as Sharma et al (2016).

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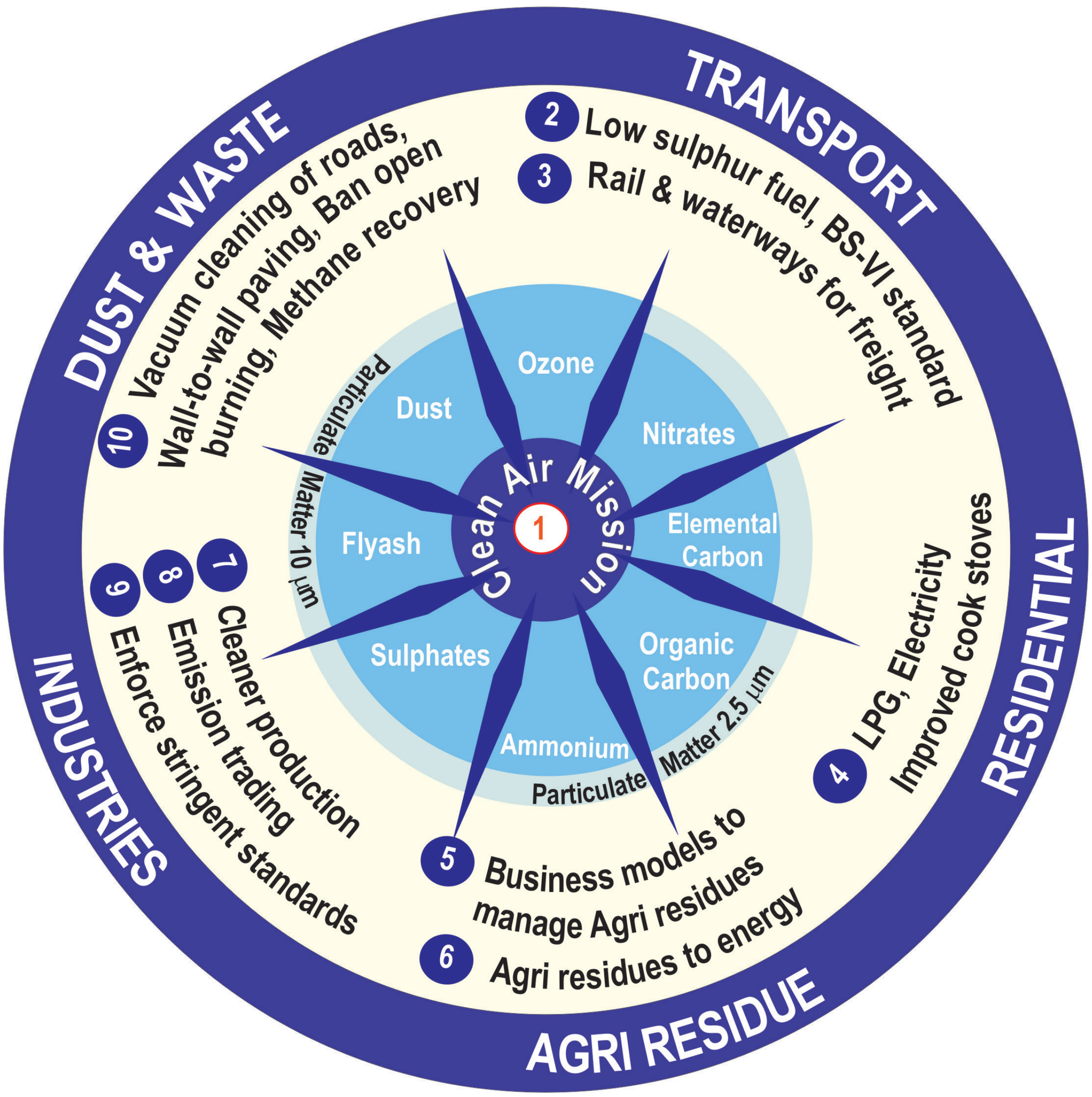
Clean Air Mission for India - Ten Solutions



SUMMARY

Government of India has initiated a major campaign Clean India (Swachch Bharat) that covers its streets, cities, rivers such as Ganga and the vast network of its villages. It is also making concerted efforts to provide energy access to rural women, which is critical for maintaining cleanliness in the villages. Recently, India has implemented similar initiatives to clean the air. There is greater awareness amongst the citizens of the air pollution problem and the Indian government is dedicated to solving the problem, making it an ideal time for India to take action.

Motivated by the current leadership for a Clean India, we, a self-organized task force, have developed a set of ten scalable solutions to clean the air. We synthesized available data on sources of air pollution, its transport over long distances, its impact on public health, food production, regional climate, to arrive at the solutions that can significantly help reduce air pollution in Indian cities and states. In this interim report, we focus on the winter season in Delhi and Uttar Pradesh, as the winter season experiences the worst pollution episodes and these areas suffer adversely from air pollution. Our strategic thinking is that if we can drastically reduce winter pollution, we can effectively solve the problem for the entire year. We do plan to extend our analyses for all months of the year to all cities and states of India and explore if the ten solutions have to be adjusted or modified on a state-by-state basis.

Our vision is similar to that which transformed the State of California in the US, which had the most polluted cities (perhaps in the world) in the 1960s. With a concerted effort by a team of scientists, technologists, policy makers, and a committed citizenry, California managed to drastically cut its pollution. There are opportunities for India to collaborate with California as it works to tackle similar pollution concerns. As such, a team of experts from India and California collaborated two years ago and produced twelve steps for reducing pollution from the transport sector, which is detailed in Ramanathan et al (2014).

Our highest priority solution relates to improved governance and government initiatives since air pollution emissions arise from many sectors, including power, transport, industry, residential, construction, and agriculture. The resulting air pollution affects health, food production, water, and regional climate. Furthermore, since air pollution from one location travels within days to areas as far away as 1,000 km, coordination across cities and states is required, in addition to multi-sectoral coordination. Therefore, as our Solution 1, we are calling for:

1. ***Launching a National Clean Air Mission for Multi-scale and Cross-sectoral Coordination***

This *Clean Air Mission* [CAM-INDIA] should have the mandate to implement government policies for air pollution mitigation across several ministries dealing with transport, power, construction, agriculture, rural development, and environment, as well as across city and state jurisdictions. The targets for the CAM-INDIA are particles referred to as $PM_{2.5}$ to PM_{10} and Ozone. The term PM (particulate matter) denotes a collection of difference species of particles in the air, while the 2.5 or 10 refers to the radius of the particle in dimension of micrometer (millionth of a meter). The most important ones are: ammonium sulphates, ammonium nitrates, black carbon (elemental carbon), organic carbon, fly ash, and dust (mineral and road dust). To emphasize the point about cross-sectoral coordination, the ammonia in ammonium sulphate comes from agriculture while the sulphates come from sulphur dioxide (SO_2) emissions from the power and industrial sector. The per cent contribution of each of these particles to $PM_{2.5}$ or PM_{10} differs from one location to another, from month to month and at times from one village or city to the next and even, from one day to the next, implying that the science of monitoring, determination of emission inventories, and modeling is crucial to evaluate the efficacy of policies.

The rest of the nine solutions deal with various sectors that contribute to pollution; the technologies required to implement the nine solutions are listed in Table 1. Each of these solutions requires auxiliary measures and these are described in more details in the sections that follows this summary.

2. **Transport:** ***Switch to low sulphur fuel (10 ppm) and implement Bharat VI (similar to Euro VI) standards for engine emissions which require tail-pipe controls like diesel particulate filters for PM and selective catalytic reduction for NO_x.*** This will also call for engine optimization and technologies like exhaust gas recirculation. The Government of India has already announced these norms and timely implementation of these norms will be important. We further recommend that legacy vehicles that are still in use are retrofitted with these control technologies. This solution will cut down soot (black carbon) emissions by up to 90% and drastically reduce oxides of nitrogen (NO_x which is a main precursor for ozone formation), carbon monoxide (CO), and hydrocarbon emissions.
3. **Transport:** ***Shift freight transport from road to lower-emission modes such as rail, inland waterways, and coastal shipping.*** The Government of India places great emphasis on developing rail-based and inland waterways freight transport and efforts need to be scaled up. This involves several auxiliary measures as detailed in the subsequent section on solutions. It is relevant to point out that Solutions 2 and 3 will mitigate emissions of primary particles, such as black and organic carbon, and toxic gases such as NO_x, CO, and hydrocarbons.
4. **Residential:** ***Provide cleaner fuels (LPG, Electricity) and biomass stoves with an efficiency of 50% or more and with a forced draft fan to those who cannot afford LPG.*** This strategy calls for rapidly expanding the access to clean fuels (such as LPG; Electricity) to households reliant on solid fuels. For those who cannot afford LPG in the near term, market access should be increased to biomass/biogas stoves that are compliant with emission rates recommended by the World Health Organization (WHO, 2014). There is a need to adopt business models to reward women who mitigate emissions from traditional biomass stoves. This solution has the potential to mitigate emissions of black carbon and organic carbon particles by as much as 90% and CO2 emissions by more than 50%.
5. **Agriculture:** ***Develop business models for collection, transport, and storage of agriculture residues and farm manure.*** This strategy aims at reducing open burning of agricultural residue, instead, we recomend them to be used as a source of energy. Business models focussing on the economic viability of this strategy are required.
6. **Agriculture:** ***Convert agriculture residues and farm manure to electricity for rural power and biomass pellets for women who depend on biomass stoves.*** This strategy aims at developing and customizing gasification technologies for converting agricultural waste into useful energy. Solutions 5 and 6 will eliminate black and organic carbon particles from open fires and reduce ozone formation by cutting methane, VOCs and CO emissions.
7. **Power and other Industry:** ***Adopt cleaner and efficient production technologies*** such as supercritical technologies in power sector, vertical shaft kilns, hoffman kilns, and tunnel kilns for brick manufacturing. For urban households, it is recomended to improve energy efficiency of room air conditioners. This solution will reduce emissions that produce sulphates, nitrates, and black carbon.
8. **Power and other Industry:** ***Deploy National Emission Trading Schemes (ETS) with cap and trade for power generation and other large polluting industries.*** The government is already experimenting with ETS in three industrial clusters in Gujarat, Tamil Nadu, and Maharashtra, which needs to be scaled up.
9. **Power and other Industry:** ***Implement stringent emission standards to control gaseous pollutants (NO_x, SO_2) and fine particulate (black carbon and fly ash) emissions from both power plants and big industries.*** Solutions 7, 8, and 9 will reduce PM levels due to reductions in sulphates, nitrates, fly ash, and black carbon and will also mitigate ozone formation through reduction of NO_x.
10. **Dust and Waste:** ***Implement wall-to-wall paving of streets and vacuum cleaning of roads; enforce ban on open burning of solid waste; manage waste and recovery of methane from landfills.*** Dust and waste burning are major sources of PM in cities and Solution 10 will drastically cut their contributions to city PM levels.

Other than these ten solutions, India's efforts to meet its Paris INDCs (Intended Nationally Determined Contributions) will significantly reduce air pollution due to the nexus between air pollution mitigation and climate mitigation. For example, India's ambitious target of 100GW power generation from solar energy by 2022 can help reduce the power sector's overall emissions of $PM_{2.5}$, NO_x, and SO_2, compared to its current coal-based power generation. Similarly, improving the energy efficiency of room air conditioning units can sufficiently reduce energy demand to avoid the need for 60–140 medium-sized peak power plants in India by 2030 (Shah et al., 2015a). This would mitigate climate change by preventing nearly 100 Gt CO_2 by 2050 globally. Similarly, reducing fugitive methane emissions from landfills, manure, and gas pipes is important as methane is 25 times more potent greenhouse gas than CO_2; this will also lead to a significant reduction in ozone concentrations, as methane is an ozone precursor.

These ten solutions also require a combination of new policies off-the-shelf available existing technologies, new technologies (Table 1), behavioural changes, most of all cooperation among a myriad of agencies and ministries. It is a very complex problem but there are many successful living laboratories in the world which gives us confidence that the solutions listed in this report will have a major impact on reducing the toxins that enter the lungs of the men, women, and children of India.

Table 1: Key Technologies for CAM-INDIA

Sector	Sub-sector	Technology
Transport	Vehicles	Diesel particulate filters; selective catalytic reduction; exhaust gas recirculation; on-board diagnostics for inspection and maintenance; high energy density batteries and technologies for electric vehicles
	Fuel	Hydro-desulfurization at refineries
Industries and power plants	Tail-pipe control	Electrostatic precipitators; bag filters, cyclones; flue gas desulphurization; wet scrubbers; selective catalytic reduction
	Process improvement	Low NO_x burners; efficient super critical combustion technologies; advanced brick manufacturing technology (vertical shaft kilns, hoffman kilns, tunnel kilns)
Residential	Stove	Tier-4 cook stoves with higher thermal efficiencies (50% or more) and emissions conforming to WHO guidelines
	Fuels Lighting	Processed biomass for high efficiency combustion; replace kerosene with LEDs powered by solar
Open burning of agricultural residues	Agri. residues	Biomass gasifiers
Waste management	Waste	Methane recovery at landfills and sewage treatment plants;
	Live stocks	Anaerobic digesters and methane recovery in livestock farms

How Did We Get Here?

The burning of fossil fuels, biofuels, and agricultural crop residues, is the primary source of air pollution. Air pollution is an undesirable side effect of industrialized life and ongoing developments, with immense negative impacts on human health, including increased rate of heart and lung diseases. WHO (2016) concludes that 92% of the world's population lives in places where the air quality levels exceed WHO limits. Air pollution also damages natural and managed ecosystems, and has a substantial impact on regional and global climate, including disruption of precipitation patterns. Food and water security is also threatened. Unfortunately, air pollution is often mistakenly thought to be unavoidable, hindering efforts to reduce pollutant levels.

Contrary to prevailing opinions, however, several regions have demonstrated that air pollution can often be curbed drastically without apparent negative impacts on economic growth or development. For example, in the 1960s, when California was building its economy after World War II, there were many cities wherein the air quality had severely deteriorated. In particular, Los Angeles and neighbouring cities, like Riverside, were competing with London for the infamous title of the most polluted city in the world, not unlike the situation with Delhi and Beijing, two historic and magnificent cities in the world. California has made tremendous progress in reducing air pollution levels since the 1960s, by combining science, policy, governance, and technology (Ramanathan et al., 2014). Between 1968 and 2008, California reduced emissions of gases like carbon monoxide (CO), oxides of nitrogen (NO_x), and sulphur dioxide (SO_2) by 75 to 90%, and cut its black carbon (BC) emissions by 90%. At the same time, its population, number of vehicles, and diesel consumption increased by 100%, 175%, and 225%, respectively (Ramanathan et al., 2014), and its economy grew enormously (resulting in the largest GDP among all states in the US), in spite of the efforts and financial resources expended to curb air pollution.

Various cities in Europe have also seen similar developments. London is particularly infamous for its pollution episodes in the 1950s and has since substantially reduced its air pollution levels, first through regulations on coal and fire wood burning, and more recently, by introducing reduced-traffic zones. Other regions, such as the industrial Rhine-Ruhr and Benelux regions, as well as many of the former Eastern Bloc states, also experienced high pollution levels in the 1960s to 1990s and have substantially reduced them in the last couple of decades. Overall, emission loads of gaseous pollutants like SO_2, NO_x, CO, and NMVOCs in Europe have come down substantially by 64%, 51%, 66%, and 60%, respectively, during 1990–2012 (EEA-2016). The reduction in PM_{10} and $PM_{2.5}$ was about 19% during 2000–2012 (EEA, 2016). However, air pollution is still an issue in many large European cities, as shown by the pollution episodes in Paris in March 2014.

Likewise, India is now embarking on ambitious plans for effective control of its pollution. A list of major interventions taken by the Government of India in different sectors that already have or will result in reduction of air pollutant emissions, is provided in Table 2. In 2006, India passed its National Environment Policy (MoEF, 2006), which aimed both to adopt an integrated approach for energy conservation and use of renewable energy options and remove policy, legal, and regulatory barriers to establishing decentralized power generation and distribution systems. The Auto Fuel Policy, passed in 2002 (MoPNG, 2002), already laid out the roadmap for the introduction of advanced vehicular emissions and fuel quality norms in India (BS-I to BS-IV) by the year 2010. In 2016, the Government of India again announced the advancement of these norms to BS-VI levels by the year 2020 across the country.

There are several power plants in cities like Delhi that have switched from coal to gas, significantly reducing the total contribution of the power sector to air pollution. Strategies for improving energy security and reducing GHG emissions have also been developed, and are being implemented in India, with important co-benefits for reducing air pollution. Due to stringent actions, some cities like Ahmedabad have shown a 50% decline in PM_{10} levels from 2002 to 2012 (NAMP-CPCB data). Improved vehicular standards, enhancement of public transportation, and industrial pollution control are the major factors responsible for decline in PM_{10} levels.

In spite of these policies, air pollution has remained a significant problem due to both the rapid development pathway of the country and its large population of about 1.3 billion. The National Air Quality Monitoring Programme (NAMP) set up 629 stations in 264 cities/towns, across the country, to regularly monitor PM_{10}, NO_x, and SO_2. The data suggests that about 80% of Indian cities do not meet the prescribed national standards of PM_{10}, while NO_x is exceeded in only 8% of cities. With a growing number of vehicles, NO_x concentrations have shown an increase in big cities like Delhi (NAMP-CPCB data). On a positive note, SO_2 concentrations have been reduced, and now just 1% of the cities violate the national standards (CPCB, 2014). However, sulphates formed from SO_2 still make up a major part of $PM_{2.5}$ concentrations in Delhi. Further, though there has been a decrease in SO_2 concentrations at the city scale (due to reduced sulphur in diesel), overall SO_2 emissions in India have increased with growing coal power generation activities (IEA, 2016; Sharma and Kumar, 2016). Gargava and Rajagopalan (2015) have reported contributions of many sources in PM levels observed in Indian cities.

Ozone is limitedly monitored in India, but simulation-based studies suggest high concentrations in certain regions (Sharma et al., 2016). This suggests that particulate matter (PM) and ozone are the two most critical pollutants that violate the standards frequently, often with high values. Moreover, control over these pollutants will also virtually cover the other pollutants. Notably, like many other countries, Indian standards are much less stringent than the WHO guidelines, which suggest health impacts at very low levels of particulate pollution. The highest levels of pollution in India have been observed in the Indo-Gangetic Plains (IGP), which has a very dense population and is also the most fertile land in the country. IGP has a share of about 50% in the total food grains produced in India and feeds to about 40% of the population of the country (Pal et al., 2009).

PM and Ozone Primer

PM includes both primary particles released directly from the source and secondary particulates formed by conversion of gaseous pollutants like sulphur dioxide (SO_2), oxides of nitrogen (NO_x), and ammonia (NH_3) into fine particles. The prime drivers of severely high levels of pollution in Delhi and Uttar Pradesh are their dense population bases, presence of high intensity emission sources, and stagnant meteorological conditions conducive to particle formation and buildup. Other than PM, the IGP region also shows very high levels of ground level ozone, exposing agricultural crops to severe damages, reducing crop yields. Ozone is a secondary pollutant, formed at the ground level by the reactions of NOx and VOCs in the presence of sunlight. Controlling PM and ozone would address the majority of air pollution concerns

Table 2: Major Indian Initiatives to Curb Air Pollution

S.No	Initiatives	Dates
	Transport sector	
1	Notifying advanced vehicle emission and fuel quality standards– BS-IV from 2017 and BS-VI from 2020	2016
2	Introducing gas as an automotive fuel in many cities	Ongoing—2003 onwards
3	Introduction of fuel efficiency standards for cars and in process to decide the norms for HDVs.	2015
4	Plan to introduce a voluntary fleet modernization and old vehicle scrappage programme in India	2016 (currently being discussed)
5	Introducing National Electric Mobility Mission Plan 2020	2012
6	Introduction and enhancement of metro-rail and advanced bus based public transport systems in select cities	Ongoing—2002 onwards
	Residential sector	
1	Push to accelerate the LPG penetration program for cooking in households	Ongoing – special emphasis 2015 onwards
2	Accelerating electrification of villages to reduce kerosene consumption for lighting	Ongoing process
3.	Introducing energy efficiency labeling program for energy intensive home appliances like air conditioners	2006
	Power sector	
1	Ambitious targets for power generation through renewables (100 GW solar by 2022)	2015
2	Shift towards high efficiency super critical technology for power generation	Ongoing process
3	Converting coal based power stations to gas based in select cities	-
4	Notifying more stringent standards for PM and new standards for gaseous pollutants for coal-based plants	2015
5	Notifying new stringent standards for diesel generator sets for stand by power generation	2016
	Industrial sector	
1	Notifying and revising standards for highly polluting industries	Ongoing process
2	Pilot testing of emission trading scheme (ETS) in select industrial zones	Announced in 2010
3	Continuous monitoring of select large industries	Ongoing under the ETS
	Others	
1	Imposition of ban on open agricultural residue burning	2015 (NGT)
2	Imposition of ban on refuse burning in some cities	2015 (NGT)
3	Launch of an official air quality index for Indian cities	2015
4	Setting up the Steering Committee on Air Pollution and Health Related Issues	2014

Analysis Methodology

The analyses and solutions developed here are based on a synthesis of studies and reports done over the last decade. The details are described in depth in a companion report to be released in the near future (Sharma et al., 2016a). A draft copy can be obtained from the Chairs of this summary report.

In particular, we relied on air pollution emission inventories and air quality simulations, as well as studies of regional impacts on health, agriculture and climate, done with meso- and regional scale models by national and international groups including: Sri Ramachandra University; TERI; Indian Institute of Tropical Meteorology; IIT, Delhi, IIT, Kanpur; Max Planck Institute of Chemistry, Mainz; University of Iowa; and University of California at San Diego. We adopted only those aspects of these studies where there is a general consensus among the various groups mentioned above. There are still uncertainties in emission inventories; however, it was encouraging that studies are converging on the impacts of air pollution on health (both qualitatively and quantitatively), impacts on crop yields (qualitative agreement in the sign of the impact), regional climate impacts such as the air pollution impacts on the monsoon (qualitative agreement in the sign of the impact), and the large warming effects of black carbon.

Some of the findings and the recommendations mentioned below were based on targeted simulations conducted for the purpose of this study by adopting WRF-CMAQ model (Byun et al., 1999; Skamarock et al., 2008) at a spatial resolution of 4 km by 4 km for the Delhi and NCR (National Capital Region, consisting of 16 districts around Delhi with a scale of 240 km by 280 km), and 36 km by 36 km resolution for the region outside NCR, including Uttar Pradesh and rest of India. Rest of India is included in the assessment to estimate contributions of these regions to air quality in Delhi and Uttar Pradesh. Emissions of neighbouring countries and boundary conditions have been taken from Chatani et al., 2014, to account for contributions from outside India. All of the targeted simulations were done only for the month of December 2015. In deducing our findings, we took care to adopt only those results that are generalizable. We picked December since it is one of the most polluted periods of the year and hence, control of pollution in this season will ensure much lower levels in other seasons too.

We picked two regions for our analyses—Delhi, as an example of a mega city of India and the state of Uttar Pradesh, as an example of a large polluted region. It is our expectation that measures to reduce air pollution, effective in these regions, will also likely apply to other regions in India.

Policy Relevant Recommendations

- **National air quality standards and WHO guidelines cannot be achieved in all parts of Delhi by just focussing on Delhi's emissions. Multi-sectoral interventions, both inside and outside (over a very large region surrounding Delhi), need to be taken for effective control of pollution in the capital city.**

A regional approach is necessary due to the fast atmospheric transport of pollutants by winds. The same conclusions would essentially apply to all cities in India. Thus, air pollution control, stringent enough to protect public health in India, can be done only with a coordinated effort across the national, state, city levels, and across multiple ministries (transportation, power, industry, rural and urban development, health, agriculture, and others).

- **A 'Clean Air Mission' to enact or coordinate policies related to air pollution is warranted. The mission should focus on developing regional scale plans for air quality improvement with yearly targets and integrate efforts across different Indian Ministries.**

Normally, it is assumed that local sources contribute most to the pollution levels in a city. This study finds that in house sources in Delhi contribute about 32% (10–65%) of the air pollution in Delhi, while NCR (National Capital Region) sources (other than Delhi) contribute an additional 25% (13–37%); the remaining 43% (25–63%) is the background due to sources outside of NCR (Figure 1). Delhi's annual average $PM_{2.5}$ levels show significant variations both temporally and spatially across the city. The monitored annual average $PM_{2.5}$ concentrations have varied between 60 $\mu g/m^3$ to 140 $\mu g/m^3$, as measured by different agencies, such as Central Pollution Control Board (CPCB), Delhi Pollution Control Committee (DPCC), and SAFAR, during the last few years. Even if all emissions from Delhi were to be stopped, the PM levels would still exceed the standards at several locations in the city, mainly due to higher contributions from outside regions to Delhi's air quality. The share of Delhi's local emissions is found to be higher in NO_x, EC (elemental carbon), and OC (organic carbon).

The other two recent studies for Delhi (Marrapu et al., 2014; IITK, 2015) also arrived at similar findings regarding significant contributions from outside of the city to local Delhi pollution. For example, the joint study by IITM, and University of Iowa (Marrapu et al., 2014) showed that outside sources contributed 30–80% to air pollution in

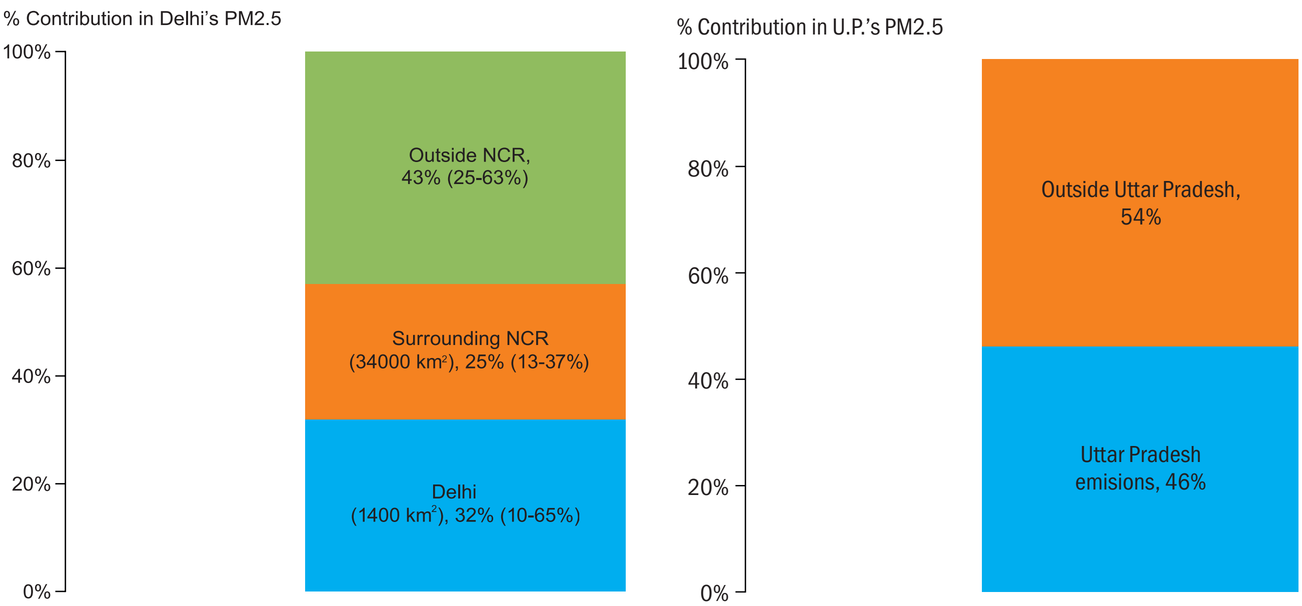


Figure 1 Percentage contribution of different regions to simulated $PM_{2.5}$ concentrations in Delhi (December 2015) and Uttar Pradesh (December 2012)

different parts of Delhi. IITK (2015) also showed significant contributions (~56%) from secondary particulates and biomass burning, which mainly originate from regions outside Delhi. The simulations conducted as part of this task force report reproduce the percentage share of different species (like elemental carbon, organic carbon, ions, other elements) as measured in the IITK (2015) report (see Sharma et al., 2016a). Figure 2 shows the chemical speciation for $PM_{2.5}$ samples in winter season as reported in IITK (2015), which again points towards contributions from different sectors (from both close and distant sources). In the case of Uttar Pradesh (UP), in house sources contribute 46% of UP's pollution and the remaining 54% is from sources outside the state.

- **Targeting emissions from the transport sector, residential energy use in rural areas, power, agriculture and refuse burning and industrial sectors, as well as road dust, will have the largest impact towards reducing air pollution in Delhi and most cities of India.**

We next examine the major sources that have to be curbed (again focussing on Delhi) by comparing 3 recent India-based studies [Marrapu et al., 2014 for year 2010; IITK, 2015 for year 2013–14; TERI analysis, 2016, for year 2015]. The major sector in NCR (National Capital Region) that contributes to Delhi emissions are discussed in the following paragraph.

The transport sector (both tail-pipe and road dust) contributions to $PM_{2.5}$ concentrations at Delhi are estimated to range from 10% to 50%, with higher shares in the centre and lower towards the outskirts of the city. In this, tail-pipe emissions have a share of about 5% to 21%. Other contributions in the city are from, the residential sector (7–21%), mainly cooking, lighting and heating with biomass, kerosene and other solid fuels, industries (1–13%), agricultural residue burning (5–13%), and power (2–5%). The rest of the contributions to $PM_{2.5}$ concentrations in Delhi are from outside NCR. The shares will be somewhat different in the months when there is no agricultural burning.

Uttar Pradesh's $PM_{2.5}$ concentrations are largely from the residential and industrial sectors (21% and 24%, respectively). The transport sector contributes about 9%, while power plants and DG (diesel generators) contribute about 10% to $PM_{2.5}$ concentrations. Open burning of agricultural residue is more prevalent in the north-western part of the IGP and varies seasonally. December is one of the months when burning takes place, and this burning contributes heavily—approximately 26%—to $PM_{2.5}$ concentrations in Uttar Pradesh. Figure 3 shows primary emissions of $PM_{2.5}$ in Uttar Pradesh, highlighting a distinct rural-urban contrast with Delhi and India. With

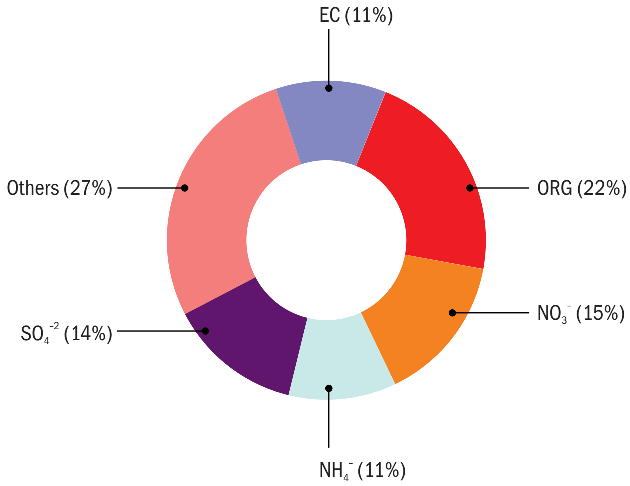


Figure 2 Filter-based $PM_{2.5}$ composition in Delhi (Winters) (IITK, 2015)

higher vehicular activity, shares of transport and road dust are higher in Delhi. Uttar Pradesh, with a significant rural population shows high shares of residential sector emissions, based on biomass use and emissions from agricultural residue burning. Please note that the shares in primary $PM_{2.5}$ emissions will not match with the aforementioned sectoral shares in $PM_{2.5}$ concentrations, as the ambient concentrations also include secondary particulates formed by gases and atmospheric transport from outside Uttar Pradesh.

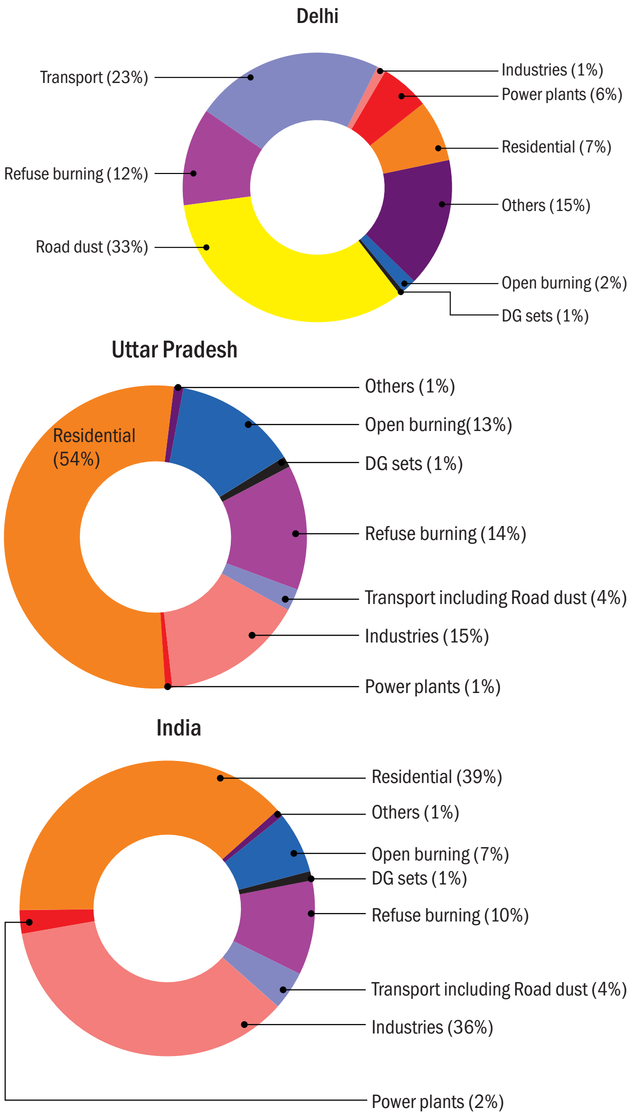


Figure 3: Share of different sectors in the inventory of annual primary $PM_{2.5}$ emissions in Delhi, Uttar Pradesh, and India (2011–2012).

Note: Please note these are primary emissions of $PM_{2.5}$, while in the text we are referring to $PM_{2.5}$ concentrations that also include secondary particulates formed by gaseous pollutants such as SO_2, NO_x, and VOCs. In most instances, the secondary particles contribute as much or more than the primary particles to $PM_{2.5}$ and PM_{10}.

- **At the regional scale, controlling NO_x rather than VOCs should result in more reductions in ozone in India. Other than trans-boundary contributions, transport and methane emission are the two most important local factors for control of ozone in India (Sharma et al., 2016). About 60–80% of ozone concentrations, across Delhi, are attributed to atmospheric transport from outside the city (based on Marrapu et al., 2014, TERI Analysis). Among the local factors in Delhi, the transport sector emerges as the most important one to control, followed by the residential and power sectors.**

Regional-scale ozone in India: Similar to $PM_{2.5}$, ozone is also high in India and especially in the IGP region, due to the presence of high emissions of precursors like NO_x and VOCs (volatile organic compounds). Studies confirm that NO_x sensitive conditions prevail generally across India, and therefore, controlling NO_x should result in more reduction in ozone at the regional scale than controlling VOCs. The transport sector's contribution to ozone in India is highest among all sectors (Sharma et al., 2016). Overall, reducing solely local emissions in India will cause only 28% reduction in ozone.

Urban-scale ozone (Delhi): In contrast to the regional scales, in the urban regions, VOC-limited conditions prevail and the titrating reaction of ozone with NO (released from vehicles) leads to lower ozone concentrations in the centre of cities than in the surrounding downwind regions. Some of the ozone simulation studies conducted for Delhi (Marrapu et al., 2014 [for year 2010]; TERI analysis [for year 2012]) concluded that the contributions from outside the city are the major factors contributing to ozone concentrations in Delhi.

- **We find that the health impact of air pollution estimated by studies from Indian institutions (IITM, SRU, and TERI) and by three international groups (WHO, Max Planck Institute, University of Washington) converge to the similar numbers and the conclusion that air pollution is one of the major causes of premature deaths in India. It is understood that these studies are based on dose-response functions empirically developed in US and Europe. Further research is required to develop and use dose-response functions pertinent to Indian conditions. In spite of this data gap**

for India-pertinent dose-response data, there is a clear consensus that improving health is a primary driver to reduce air pollution.

The Government of India has constituted an expert committee under the Ministry of Health and Family Welfare (MoHFW), Government of India, which came up with a report (MoHFW 2015) outlining key source-specific measures to reduce exposure to air pollution in India. The Ministry has taken a lead in recognizing air pollution as a national health concern.

- **We find that agricultural impacts of ozone pollution assessed by research groups in India (IITM and TERI), and by international groups (UCSD, Princeton University, Stockholm Environment Institute, European Commission) converge on the science. They all show that air pollution (ozone) exposure significantly decreases crop yields for almost all crops; some (e.g., wheat) are impacted more severely than others (e.g. rice). The magnitude of impacts, however, differs between studies, suggesting further research in this direction. Nevertheless, all studies concur with the finding that curbing ozone pollution can substantially increase the crop yields.**
- **The impact of aerosols on dimming and other related climatic changes in India have also been studied by a number of research groups across the world, including Indian scientific institutes. All studies again converge to state that aerosols have led to significant amounts of dimming of solar radiation, the net effect of which is to reduce monsoon rainfall as summarized in a new international study (Li et al., 2016) by authors from US, China, India, and Europe. The studies vary in the magnitude of impacts and their regional patterns, and hence, further studies are required. However, the compelling evidence is that curbing air pollution particles (aerosols) is likely to increase monsoon precipitation (Krishnamurti et al. 2013).**
- **Black carbon is a major climate warming pollutant, in addition to its impact on health and regional climate. New studies (by Stockholm University and IIT, Kanpur) have reduced the uncertainty surrounding the radiative forcing by black carbon. They are also quantifying the warming effect of brown carbon emitted by the burning of biomass. Due to the short lifetime of BC particles in the atmosphere, the reduction of BC can bring nearly immediate benefits in terms of health and climate.**
- **Improving the energy efficiency of room air conditioning units can reduce energy demand, equivalent to avoiding the need for 60–140 medium-sized peak power plants in India by 2030 (Shah et al., 2015a). These energy efficiency gains would avoid related air pollution, save lives, and otherwise improve health (Guttikunda and Jawahar, 2014; Lim et al., 2012). They also would mitigate climate change by preventing nearly 100 Gt CO_2 by 2050 globally. In India, improved A/C efficiency, along with the transition to low-GWP refrigerants, would amount to roughly twice the commitment in India's National Solar Mission (Shah et al., 2015a).**
- **Air conditioning contributes 40–60% of summer peak loads in cities such as Delhi. Thus, a large fraction of the pollution related to diesel generator sets that are used during blackouts could also be indirectly attributed to AC use. Improving grid reliability, while tightening the stringency of the A/C star rating programme administered by the Bureau of Energy Efficiency (BEE), can, thus, further mitigate air pollution. For example, Shah et al. (2016) finds that improving the A/C efficiency up to an Indian Seasonal Energy Efficiency Ratio (ISEER) level of 3.5 has a payback period of 1.1 years and up to 5.2 will have a consumer payback of less than 3 years.**
- **Nexus between energy, air pollution, and climate change—Energy use is the primary cause of the release of GHG and air pollutants in India. As a result, switching from fossil fuels to renewables (solar, wind, geothermal, hydro, and nuclear) for power generation to mitigate emissions of CO_2 and other greenhouse gases, will also eliminate air pollutant emissions. On the other hand, reducing air pollution emissions through end-of-pipe measures will not necessarily reduce greenhouse gas emissions. In this context, India's ambitious target of 100GW power generation through solar by 2022 will contribute significantly to reducing PM, especially sulfates, fly ash, and nitrates. Similarly, switching to electric cars fueled by batteries or hydrogen fuel cells would eliminate both air pollution and greenhouse gas emissions, provided the primary power (for batteries and fuel cells) is generated by renewable (e.g solar) and not fossil fuels. There are significant opportunities to reduce air pollution by mitigating climate change. Likewise, there are significant opportunities to mitigate climate change by curbing air pollution.**

Ten Scalable Solutions for CAM-India

The ten solutions have been chosen based on their scalability in the Indian context. The most encouraging part is that the experts and expertise needed to implement these solutions are largely available in India. Cooperation from international institutions can be brought when needed. For example, the Governor of California, Jerry Brown, met with India's Prime Minister Shri Narendra Modi in the fall of 2015 in San Francisco and has extended the offer of California's cooperation. These developments, along with India's aggressive pursuit of air pollution mitigation (see Table 2 above on Major Indian Initiatives to Curb Air Pollution), clearly shows that the time has come to clean the air and achieve standards that can protect people's health, agriculture, and overall quality of life.

Governance

1. ***Launching a national Clean Air Mission [CAM-INDIA] for Multi-Scale and Cross-Sectoral Coordination***

A. Multi-scale and Cross-Sectoral Coordination

- Considering the enormity of the air pollution problem and its trans-boundary nature, a national scale **'Clean Air Mission'** would be a signifcant step for cleaning the air**. T**he targets for the CAM-INDIA are particles referred to as $PM_{2.5}$ to PM_{10} and Ozone. The per cent contribution of different particle species (like elemental carbon, organic carbon, sulphates, nitrates etc) to these particles $PM_{2.5}$ or PM_{10} differs from one location to another, from month to month and at times from one village or city to the next and even, from one day to the next, implying that the science of monitoring, determination of emission inventories, and modeling is crucial to evaluate the efficacy of policies.Curbing Delhi's and Uttar Pradesh's PM and ozone pollution requires emission mitigation at regional scales across several sectors. The critical sectors are power; transport, residential energy use, industry, and agriculture. CAM-INDIA should focus on developing regional scale plans for air quality improvement with annual targets. CAM-INDIA should look for ways to integrate efforts across different Indian Ministries (Ministry of Road Transport and Highways, Ministry of Petroleum and Natural Gas, Ministry of Industries, Ministry of Power, Ministry of Non-renewable Energy, and Ministry of Environment, Forest and Climate Change) to take targeted actions recommended by the regional scale air quality management plans. Investments for mitigation actions should be sought through subsidy reallocations, marginal increase in fuel prices, and Corporate Social Responsibility (CSR) activities.

B. Air Quality Management Including Monitoring

- The air quality monitoring network should be strengthened with improved calibration and validation of data, widened spatial coverage, and widened pollutant coverage (including $PM_{2.5}$ and PM_{10} and ozone precursors such as NO_x, CO, and VOCs). Data at selected urban and remote sites should contain chemical speciation of $PM_{2.5}$ (such as sulphates, nitrates, black carbon, etc.) to guide policies and assess efficacy of implemented polices. A national database of high-resolution source emission inventories needs to be developed with lower uncertainties. Emission inventories are important tools to drive political actions in different sectors. They are also essential for developing trading schemes and are immensely important for air quality modelling required for prioritizing actions. The current and future projections of emission inventories need to be developed in consultation with academic institutions specializing in air pollution science. Also, self-reporting by major industrial sources should be made mandatory.
- Air pollution research done at academic institutions and government laboratories needs to be well coordinated. Meteorological data should be collected and used for understanding the influence on air quality values. Air quality modelling tools should be used to predict current and future air quality to enable informed policy decisions. These should be the basis for assessment of strategies for their potential in reducing air pollution. Emergency response plan (ERP) needs to be developed to reduce emissions during episodes and avoid exposure

of high pollutant concentrations to the public. In the entire process, public participation needs to be ensured to share information on air quality and involvement in formulation of a management plan.

- Public awareness needs to be enhanced through display of air quality indices and spatial air quality maps using print and electronic media. Public participation begins with informed citizens with raised awareness levels who can motivate the government for vigorous implementation or adoption of mitigation strategies.

Transport Sector

2. *Switch to low sulphur fuel (10 ppm) and implement Bharat-VI (similar to Euro-VI) standards for engine emissions which require tail-pipe controls like diesel particulate filters (DPF) for PM and selective catalytic reduction (SCR) for NO_x.*

- Other than tail-pipe controls like DPFs and SCRs, this will also call for engine optimizations and technologies like exhaust gas recirculation. The Government of India has already announced these norms and timely implementation of these norms should be carried out. The BS-VI emissions norms mandated by the government will drastically reduce the PM and NO_x emissions from new vehicles. The implementation of BS-VI norms should be supported by fuel quality improvement and refineries should produce low sulphur (10 ppm) fuels by 2019 to enable implementation of BS-VI (Euro-VI equivalent) emission standards by 2020. Indian refineries need significant investments to accomplish this task but the costs can be recovered with marginal increase in fuel prices. We further recommend retrofitting for legacy vehicles that are still in use with these control technologies. This will cut down soot (black carbon) emissions upto 90% and drastically reduce NO_x.

3. *Shift freight transport from road to lower-emission modes such as rail, inland waterways, and coastal shipping*

- The Government of India places great emphasis on developing rail-based and inland waterways freight transport and efforts need to be scaled up. Railway infrastructure should be upgraded to support freight movement in specific trade corridors like the Eastern Dedicated Freight Corridor, extending from Ludhiana to Dankuni in West Bengal. Specific cost-benefit studies should be conducted to drive investment decisions in the railways to shift freight transport from road to rail. The Government of India is already exploring a shift from road to inland waterways and a waterways terminal at Varanasi for freight movement through Ganges.

Solutions 2 and 3 will significantly mitigate emissions of primary particles such as black and organic carbon and toxic gases such as NO_x, CO, and hydrocarbons. However, there are auxiliary measures that will be required to reduce the transport sector emissions. These include enhancement of inspection and maintenance (I&M) systems, fleet modernization, increased distribution of electric and hybrid vehicles, vehicle ownership and usage controls, strengthening of public transport (both bus and rail-based), and local measures like setting-up 'low emission zones'. These options are discussed as follows:

- Inspection and Maintenance System: This needs to be strengthened and the existing pollution control centres should be replaced by modernized and automated centres that can be effectively monitored by state governments. TERI analysis shows that costs to set up these strengthened I&M centres can be recovered within a few years through charges for vehicle inspection. There is also a need for capacity augmentation to undertake vehicle spot checks. With advancement in technology, the On Board Diagnostic (OBD) systems should be included in the new fleet. Vehicle models should be randomly texted to assess on road emission performance, and in the case of violations, further investigations should be carried out; this may lead to recall of vehicles by the manufacturers.

- Encourage Fleet Modernization: The Ministry of Road Transport and Highways, Government of India, is coming up with a voluntary fleet modernization mechanism supported by financial incentives in the form of discounts from the manufacturers and lower excise duties. Gradually, the programme should be strengthened through the mandatory scrapping of very old vehicles. Specific purpose grants could be used to motivate state transport companies and city bus operators to modernize their fleets. Retrofitting options can be explored for 'not so old' vehicles, which can be fitted with tail-pipe treatment technologies. There is a need for a research and development programme for low-cost, robust, easily maintained tail-pipe filters, and other treatment technologies.
- Increase distribution of electric and hybrid vehicles: This should be carried out through necessary financial measures and infrastructural support. The procurement of electric vehicles (EVs) should be mandatory for vehicles for government use and certain public facilities. Research and development activities should be enhanced in the areas of battery cell technologies, electric vehicle power train system integration, electric motors, and power electronics. Availability of citywide support infrastructure for electric vehicles should be ensured.
- Vehicle ownership and usage controls: Strategies like congestion pricing, escalation of taxes and insurances, higher costs of parking, and implementing restrictions on certain areas and times need to be employed to reduce private vehicle usage. A congestion pricing scheme could be employed in big cities like Delhi to discourage private vehicle use. Enforcement can begin with manual processes, which can be later supported by electronic systems. Revenues generated should be used for enhancement of public transport. These measures should eventually lead to a shift towards greater usage of public transportation.
- Strengthening public transport (both bus and rail-based): The public transport system in Indian cities needs to streamline. Efforts should be made to cater to all income classes by provision of safe, economic, and reliable public transport services. For instance, Delhi and Lucknow can be developed as model cities depicting integration of public transportation options based on the PPP model, and later the efforts can be scaled up. There is a need to either preserve the modal share of non-motorized options or, if already depleted, shift from motorized to non-motorized options should be explored. Support infrastructure for non-motorised travel should be augmented. To start with, a Tier-II city like Varanasi can be developed as a model cycling city similar to Amsterdam. In the next 5 years, 100 smaller cities should be developed to 'model cycling towns' through PPP modes.
- Setting up low-emission zones in Delhi and other similar cities by restricting private vehicle entry in highly polluted zones. This needs to be supported by clean public transportation, preferably based on electric vehicles.

Residential Sector

4. *Provide cleaner fuels (LPG, Electricity) and biomass stoves with an efficiency of 50% or more and with a forced draft fan for those who cannot afford LPG.*

- There is a an urgent need to rapidly expand the access to clean fuels (such as LPG; Electricity) to the households reliant on solid fuels. LPG penetration can be enhanced through an aggressive marketing strategy wherein differently sized LPG bottles should be made available to rural households. An LPG subsidy with direct transfer schemes should be made available to all rural customers, with an additional subsidy made available to the lowest expenditure classes in rural areas.

- For those who cannot afford LPG in the near term, market access should be increased to biomass/ biogas stoves that are compliant with emission rates recommended by the World Health Organization (WHO, 2014).Advanced gasification and improved cook stoves should be made available as an intermediate solution. Considering air pollution mitigation and health concern as the primary objective, only stoves with thermal efficiency of 50% or more with a forced draft fan should be promoted, as these drastically cut black carbon emissions and comply with WHO emission standards. Cook stove dissemination programmes need to combine marketing efforts with research and development and should take into account the social, cultural, and economic considerations to ensure higher acceptability and effective adoption. A proper supply chain system for repair maintenance and availability of spares needs to be created as well as a complete market value chain that provides efficient after sales. Finally, cookstoves should be properly monitored for usage as carried out under Project Surya, a joint effort of Nexleaf, University of California, San Diego and TERI. The project pioneered the use of Stove Usage Monitoring System and Result Based Financing wherein users were provided financial credits for use of stoves. This way we can promote business models to reward women who mitigate emissions from traditional biomass stoves.

- Induction stoves (powered by solar or gas) should be made available at a subsidized price, particularly for states with high electrification rates (Himachal Pradesh, Gujarat, Kerala, Uttarakhand, etc.).

Agriculture Sector

5. Develop business models for collection, transport, and storage of agriculture residues and farm manure.

- This strategy aims at reducing open burning of agricultural residues. We recomend using them as a source of energy. Business models focussing on economic viability of these needs should be developed. Village-level institutions need to be involved in collection, storage, and supply of biomass materials and to link with MNREGA (Mahatma Gandhi National Rural Employment Guarantee Act) and other livelihood generation schemes. Bank finance should be made available to CBOs (Community Based Organizations) for setting up biomass supply chain and pellet production facility. Biomass depots should be set up to address fluctuation of raw material prices to support farmers and consumers during season and off-season period.

6. Convert agriculture residues and farm manure to electricity for rural power and biomass pellets for women who depend on biomass stoves.

- This strategy aims at developing and customizing gasification technologies for converting agri-waste into useful energy. Pilot-scale studies need to be initiated in states, such as Punjab and Haryana to test and develop gasification-based facilities for power generation/co-generation using agricultural residues. The studies need to focus on competing uses of agriculture residue and economic viability of power generation from agricultural residue. The second step in this direction has to focus on developing a market value chain for biomass collection, processing, and usage. The third step needs to be on the introduction of state-of-the-art technology for gasification and waste to-energy conversion. Dedicated R&D programmes should be launched for technological improvements to improve suitability for various types of agricultural residues for power generation. There is a need to develop mini grids and generate power with fuel Cells fueled by biogas generated from agricultural waste. Technologies for this exist which need to be scaled up.
- Biomass should be pelletized into short, narrow cylinders that are handled more like a processed solid fuel. Pellets also have a combustion profile similar to liquid fuels and this provide a ready alternative for meeting household, industrial, and institutional fuel demand. The use of pellets and processed fuel should be incentivized for use in thermal and power gasification systems.

Solutions 5 and 6 will eliminate black and organic carbon particles from open fires and reduce ozone formation by cutting methane, VOCs, and CO emissions.

Industrial and Power Sectors

7. *Adopt cleaner and efficient production technologies*

- Technological intervention in industries can improve energy efficiency, reduce emissions, and result in financial savings. Cleaner (gaseous/liquid) fuels, wherever possible, should be supplied in the industries near highly populated and polluted cities. Industries need to shift to cleaner fuels as mandated or through the use of economic instruments. India's power generation industry is already moving towards super-critical technologies which ensure lower coal consumption and hence, lower emissions of both GHG and air pollutants. We recommend the use of low NO_x burners to ensure lower NO_x emissions. Advanced brick manufacturing technologies like vertical shaft kilns, hoffman kilns, and tunnel kilns, should be promoted with the use of fiscal instruments to ensure lower black carbon emissions from the brick industry. We also recommend improvements in air conditioning technology to improve energy efficiency of room air conditioners for urban households. Improving AC energy efficiency in urban households can reduce air pollution equivalent to 60 to 140 medium-sized peak power plants by 2030 (Shah et al, 2015a), while also reducing pollution from diesel generators used during blackouts.

8. *Deploy national Emission Trading Schemes (ETS) with cap-and-trade for power generation and other large polluting industries.*

- These schemes should be developed on the lines of the carbon trading schemes and should be enforced in large industries. A cap on emissions should be assigned for a region and allocations should be made for each of the contributing large industries within that region. Stacks should be monitored on a continuous basis and the industries should be allowed to trade emission credits. India is trying the ETS schemes in three industrial clusters in Gujarat, Tamil Nadu, and Maharashtra. The scheme needs to be scaled up to other important industrial clusters with targets established for PM and SO_2 emission control.

9. *Implement stringent emission standards to control gaseous pollutants (NO_x, SO_2) and fine particulate (black carbon and fly ash) emissions from both power plants and big industries.*

- In addition to market-based instruments such as ETS, 'command and control' emissions standards should be set to limit emissions of gaseous pollutants (NO_x, SO_2) and fine particulate emissions from both coal- and gas-based power plants, and other big industries. This will lead to introduction of control technologies (such as wet flue gas desulphurization [FGDs] units) in all big industries that rely on sulphur-based fuels. Strict monitoring and maintenance of electrostatic precipitators (ESPs) and other control equipments for efficient tail pipe controls should be ensured.

Solutions 7, 8, and 9 will both reduce PM levels by reducing emissions of sulphates, nitrates, fly ash, black carbon, and mitigate ozone formation through reduction in NO_x. Additionally, there is a need to randomise the vigilance and enforcement process to reduce possibilities of manipulations and corruption. Institutes of highest reputation and capacity should be involved in carrying out third-party audits of industries. All major industries should be directed to carry out continuous monitoring and reporting of their emissions.

Dust and Waste

10. *Wall-to-wall paving of streets and vacuum cleaning of roads; enforce ban on open burning of solid waste; management of waste and recovery of methane from landfills.*

- Dust and waste burning is a major source of PM in cities. Solution 10 will drastically cut contribution of dust to PM levels in cities. Proper construction, maintenance, and cleaning of roads should be ensured with random tests and checks and IT-based monitoring systems. Wall-to-wall paving (with provision of rainwater percolation) should be carried out to the extent possible to reduce kerbside dust. Maintenance of roads should be ensured with the use of mobile applications to spot and inform irregularities. Delhi is already trying the vacuum cleaning devices for road cleaning; these devices should be pilot tested in few other cities before scaling them up widely in all major dust prone cities in India. Unpaved roads in the entire NCR should be paved, and, if not possible, they should be covered with gravel and maintained that way.

- Scientific management of municipal solid waste is required to control refuse burning and also to avoid methane emissions from landfills. A complete ban should be enforced on refuse burning with strict penalties. There is also a need for proper scientific treatment of biodegradable municipal waste and promotion of reusing and recycling materials. These programmes can be built under the 'Swachh Bharat Abhiyan'. Second-hand markets need to be developed and formalized for goods which can be reused for incentivizing people participation.
- Methane is a key precursor for ozone formation and also a potent greenhouse gas (GHG). It is essential to control emissions by capturing methane from municipal waste landfills, and sewage treatment facilities. TERI has demonstrated a pilot-scale methane recovery plant at the Okhla landfill site in Delhi. The recovered methane can be used as an energy source. All possible landfill sites in Delhi should be tapped for methane recovery. Livestock is another important source of methane in India and should be controlled through farm-scale anaerobic digestion of manure from cattle and pigs.

Finally, we would like to point out the nexus and synergy between air pollution mitigation measures and climate mitigation measures. For instance, India's ambitious target of 100GW power generation through solar by 2022 can drastically reduce its emissions of $PM_{2.5}$, NO_x, and SO_2 from the power sector. Similarly, improving the energy efficiency of room air conditioning units can sufficiently reduce energy demand to avoid the need for 60–140 medium sized peak power plants in India by 2030 (Shah et al., 2015a). Lastly, reducing fugitive methane emissions from landfills, farm manure, and gas pipe leaks will reduce the ozone levels since methane is an ozone precursor. As both methane and ozone are potent greenhouse gases, reductions in fugitive methane emissions would also mitigate climate change.

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