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Impact of current policies on future air quality and health outcomes in Delhi, India

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HIGHLIGHTS

- We model impact of current policies on future air quality for Delhi.
- Comparison with alternate stringent air pollution and climate policy scenarios.
- $PM_{2.5}$ concentrations will not meet national air quality standards by 2030.
- Stringent air pollution and climate policies together needed to achieve NAAQs.

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ABSTRACT

A key policy challenge in Indian megacities is to curb high concentrations of $PM_{2.5}$ and mitigate associated adverse health impacts. Using the Greenhouse Gases and Air Pollution Interactions and Synergies (GAINS) model we carry out an integrated analysis of the air quality regulations across different sectors for the city of Delhi. Our findings show that $PM_{2.5}$ concentrations for Delhi will not reach the recommended national ambient air quality standards (NAAQS) even by 2030 under the current policies scenario. Adopting advanced control technologies reduces $PM_{2.5}$ concentrations by about 60% and all-cause mortality by half in 2030. Climate change mitigation policies significantly reduce greenhouse gases, but have a modest impact on reducing $PM_{2.5}$ concentrations. Stringent policies to control the net flow of air pollution from trans-boundary sources will play a crucial role in reducing pollution levels in Delhi city. Achieving NAAQS requires a stringent policy portfolio that combines advanced control technologies with a switch to cleaner fuels and the control of trans-boundary pollution.

1. Introduction

It is well known that mitigating outdoor air pollution remains a major challenge in most developing countries. Annually, outdoor air pollution contributed to 3.2 million deaths and 76 million life years lost worldwide in 2010, two-thirds of which occurred in Asian countries (Lim et al., 2012). Most Indian cities face an acute problem of outdoor air pollution, with concentration levels often exceeding the recommended guidelines set in the National Ambient Air Quality Standards (NAAQS) (CPCB, 2010). Rapid urbanization, boom in construction activity, increase in number of vehicles, traffic congestion, population growth leave millions of people in urban areas vulnerable to adverse effects of air pollution (Patankar and Trivedi, 2011).

Reducing outdoor air pollution remains a major policy challenge in Indian megacities, like Delhi, despite the implementation of several policies such as shifting of public transport to Compressed Natural Gas (CNG) (Bell et al., 2004) converting coal power plants to natural gas (CPCB, 2010). Policy measures to mitigate air pollution in Delhi are important as it is among the largest megacities of the world with a population of about 16 million people (Census of India, 2011). Whereas this is not the only megacity in India with high amounts of outdoor air pollution, it is representative of larger Indian cities and the insights provided hold for other cities in India (Kandlikar and Ramachandran, 2000).

Previous research in Indian cities has analyzed air quality trends (Kandlikar, 2007), looked at source apportionment (CPCB, 2010; Srivastava and Jain, 2008; Srivastava et al., 2005) and emission

Abbreviations: GAINS, greenhouse gases and air pollution interactions and synergies; $PM_{2.5}$, particulate matter less than 2.5 microns in size; NAAQ, national ambient air quality standards; TM5, transport model, version 5; CIESIN, Centre for International Earth Science Information Network; PAF, population Attributable Fraction.

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inventories (Guttikunda and Calori, 2013; Guttikunda and Jawahar, 2012; Sahu et al., 2011) to identify areas for policy intervention. Studies linking air quality and health have looked at short term effects of air pollutants on all-cause mortality (Rajarathnam et al., 2011; Cropper et al., 1997), lung function in children and adults (Foster and Kumar, 2011) and estimation of health risks due to multi-pollutant exposure (Pandey et al., 2005). The few studies that have sought to evaluate the impact of policies regulations on air quality in Indian cities (Narain and Krupnick, 2007; Kathuria, 2004; Goyal and Sidhartha, 2003; Bose and Srinivasachary, 1997) have done so for a single policy or a single sector. For instance Narain and Krupnick (2007) found that benefits, on air quality, accrued from switching buses from diesel to compressed natural gas (CNG) were negated by increase in vehicle population over time, ultimately leading to an increase in particulate matter concentrations in Delhi.

However, it remains unclear as to what impact current policies will have on future air quality and health in Delhi. There remain many unsettled questions such as – Are the current policy measures adequate to reduce air pollution to NAAQ standards in the future? What are the future health implications of these policy measures for Indian cities? What impact will alternate development pathways (using advanced control technologies or climate change mitigation strategies) have on city level air pollution in India? The present work addresses the aforementioned questions by building on the analysis of policy actions to curb outdoor air pollution in Delhi. We use an integrated assessment modeling framework, to analyze future air quality related to current policy legislations at the city level and also present health impacts related to the same.

2. Materials and methods

2.1. Modeling paradigm

Emissions and future concentrations of fine particulate matter ($PM_{2.5}$) were estimated using the Greenhouse gases and Air pollution Interactions and Synergies (GAINS) model developed at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria (Amann et al., 2011). The GAINS model is currently implemented globally on regional, national or provincial levels for 45 countries in Europe (Amann et al., 2011), for the Annex-I countries of the Kyoto Protocol (Wagner et al., 2012), for fast growing economies of China (Amann et al., 2008) and India (Purohit et al., 2010), as well as for remaining countries in East and South Asia, Africa, Middle East and South America. It covers the time horizon up to 2050 in 5-years steps. IIASA along with The Energy and Resources Institute (TERI, India) adapted the GAINS modeling framework for India (Wagner et al., 2008). The GAINS model allows for comprehensive analysis of air pollution and greenhouse gas mitigation strategies in an integrated assessment framework as well as identification of emission control technologies, estimation of impacts and mitigation costs under different policy scenarios (Wagner et al., 2008). The detailed workings of the model have been published elsewhere (Amann et al., 2011).

Like all models, GAINS attempts to develop a holistic understanding of a complex reality through a variety of reductionist steps. This simplification process is burdened with many uncertainties related to methodological issues, lack of understanding and insufficient data. Thus, there exist considerable uncertainties in almost all parts of the GAINS model, e.g., in the emission inventories, the estimates of emission control potentials, the atmospheric dispersion calculations and the impact assessment (Amann et al., 2011). In addition, uncertainties are pertinent in all other components of the integrated assessment framework that feed information into GAINS (e.g., models of energy and agricultural activities, atmospheric dispersion and environmental impacts).

A full quantitative assessment of the role of individual model and data uncertainties in an integrated assessment model framework such as GAINS is a complex task. A methodology has been developed by Schoepp et al. (2005) to quantify how statistical errors (i.e., quantified uncertainties) in input parameters propagate through the GAINS model calculations to policy-relevant output, e.g., from projections of economic activity to the protection of ecosystems. In practice, however, it was found difficult to reliably quantify the input uncertainties on a solid basis, so that a robust quantification of the uncertainties themselves was considered the most uncertain element in the analysis. Furthermore, a solid quantification of correlations between input parameters (or, in several cases, even their signs) turned out to be an almost impossible task, although they could have overwhelming influence on the conclusions of an uncertainty assessment (Amann et al., 2011).

For Europe, Schoepp et al. (2005) found a typical range of uncertainties for modeled national emissions of sulfur dioxide, nitrogen oxides and ammonia was between 10% and 30%, which is consistent with the Streets et al. (2003) for developed countries. For India, Streets et al. (2003) estimated uncertainties for modeled national emissions of sulfur dioxide, nitrogen oxides and ammonia at 26%, 48% and 101%, respectively. Neither study analyzed uncertainties related to $PM_{2.5}$ which is likely to be much higher given perturbation effects, distributional impacts and the contribution of dust.

The GAINS-Asia module has India as a region, which is further subdivided into 23 regions corresponding to the major Indian states (Purohit et al., 2010). Delhi is a separate region in the GAINS. Air quality, for all Indian regions, is estimated in 1° by 1° spatial resolution (Dentener, 2008) based on source-receptor relationships derived from Transport Model, Version 5 (TM5) atmospheric chemistry and transport model (Krol et al., 2005). In addition the model adjusts for an "urban increment" for major urban agglomerations by using detailed population data from the Centre for International Earth Science Information Network (CIESIN) $2'5 \times 2'5$ population database (Purohit et al., 2010). Furthermore, for health-impact assessment a routine has been developed to capture variations in emissions at the sub-grid level as a function of local emission densities and spatial extensions of urban areas within a grid cell (Amann et al., 2011).

We use the grid cell 29° North and 77° East in the model for analysis of Delhi city and its surrounding regions of Uttar Pradesh and Haryana and assume that sector specific emissions are distributed over this resolution. While the spatial resolution is sufficient to allow us to look into our primary objective of analyzing future air quality and health impacts for the region as a whole, we do not take into account sub-grid differences related to industrial and traffic hotspots.

Validation checks by comparing GAINS estimates with full model estimates for an emission scenario other than that used in deriving transfer coefficients as well as comparison with measurements have been carried out for Delhi and overall agreement levels are reasonable (Amann et al., 2011).

We adopted the reference energy scenario developed by the International Energy Agency (IEA) for the World Energy Outlook (WEO) 2011 as the base case. IEA/WEO (2011) estimates that real GDP growth rate for India will be 6.4% between the years 2008 and 2035. While economic growth in the Delhi region is likely to be higher, we do not correct for this. Economic development in conjunction with population growth (from 1.1 billion in 2005 to 1.5 billion in 2030) will enhance the demand for energy supply. The total primary energy demand is expected to increase by a factor of 2.75, from 2005 to 2035 (Purohit et al., 2010), indicating decoupling between energy consumption and economic growth brought about by technological improvements and structural transformations of the Indian economy (Shukla, 2006).

In this scenario coal remains the key source of primary energy in India, constituting about 50% of the energy mix in 2030 (IEA, 2011;

Garg and Shukla, 2009). Increased demand for transportation will see oil demand increase by a factor of 3.2 in 2030 as compared to 2005. The share of renewable, hydro and nuclear energy is expected to contribute about 1%, 1.5% and 2.3%, respectively, to the energy mix in 2030 (IEA, 2011) This is consistent with other studies that have analyzed the scenario in the Indian context (e.g. Shukla and Chaturvedi, 2011). Despite economic growth it is estimated that 53% of the population in India will lack access to clean cooking fuels to meet their energy requirements (IEA, 2011).

2.2. City specific policies

City level policy makers are struggling with air pollution as it is a multifaceted problem and no single policy can tackle all sectors. Thus, we present an approach that analyzes city specific policies in Delhi across sectors – transport, industry, power and waste - and additionally look at alternative policies including those related to climate change. Table 1 lists the policies implemented in the model across the different scenarios and these are further described in detail below.

2.2.1. Transport sector

India's auto fuel policy report (MoPNG, 2003) laid down the standards for controlling pollution from both new and in-use vehicles. For 20 cities (including Delhi) it mandates the introduction of Euro IV equivalent emission norms for all private vehicles, city public vehicles and light commercial vehicles from April 1, 2010. In addition, for two and three wheelers, it mandates Bharat Stage III norms from April 1, 2010.

Using the data of vehicle numbers in Delhi (from 2000 to 2008) the average growth rate (2000–2008) was calculated (CMIE, 2012). It was assumed that this growth rate reflected the new vehicles being added to the current stock and would remain unchanged in the long term. The growth rates were 9%, 7% and 5% for two wheelers, 4 wheelers and heavy duty buses and trucks, respectively. The appropriate control strategies (as mandated in the Auto fuel policy report) were applied to this new stock starting 2010. It was assumed that new vehicles were added each year; the same proportion of older vehicles (with older emission norms) would cease from operating. Thus, by 2025, 100% of vehicles would adhere to Euro IV standards as legislated.

Following a Supreme Court order, in the early 2000s more than 100,000 vehicles in Delhi were switched to CNG which also included the retrofitting of about 3000 diesel buses (Kathuria, 2004; Chelani and Devotta, 2005; Bell et al., 2004). We assumed that 10% of the buses were operating for inter-state travel while the rest were public transport buses within the National Capital Territory (NCT) of Delhi. The activity data corresponding to vehicle kilometers, vehicle numbers and energy were adjusted in GAINS accordingly to reflect this policy.

2.2.2. Relocation of polluting industries and brick kilns

Accepting the order of the Supreme Court, the Central Pollution Control Board (CPCB) categorized various industries as green, orange or red based upon varying levels of air pollution potential from low to high, respectively (MoEF, 1989). Highly polluting industries (categorized red) and brick kilns were not permitted to operate within the jurisdiction of the NCT of Delhi (Narain and Bell, 2006; SoE Delhi, 2010). These included industries such as cellulose products, cement manufacturing, fertilizer and inorganic chemical industries, paper, rubber and wood industries.

For the region of Delhi, this policy was implemented in detail by eliminating sectors corresponding to these industries (cement, lime, paper, etc.) and brick kilns in the GAINS model. These sectors were relocated to the neighboring states of Uttar Pradesh and Haryana, and we thus include their long range trans-boundary effects on Delhi region.

2.2.3. Conversion of coal based power plants

In Delhi, there was a conversion of existing coal based thermal power plants to gas based plants; in addition to a directive that mandates all future power plants to be based on gas (SoE Delhi, 2010; CPCB, 2010). Appropriate changes were made for the region of Delhi in GAINS to reflect this policy. No changes were made for the activity data corresponding to coal based power plants adjacent to Delhi as there is no policy in place requiring them to switch to cleaner fuels. This implies that given trans-boundary impacts in GAINS, these plants will still play an important role in contributing to overall air quality in Delhi.

2.2.4. Waste management

In accordance with the policy on municipal solid waste management rules promulgated in 2000, the open burning of wastes is prohibited in Indian cities (MoEF, 2010). Therefore, control strategies were changed to reflect a ban on the burning of waste in the residential sector for Delhi.

The set of city specific policies have been compared to two alternate scenarios, wherein it is assumed that advanced control technologies (representative of policies in cities in industrialized countries) or climate change mitigation policies (consistent with 450 scenario) were put into place for Delhi.

Table 1
Advanced control technologies and city specific policies comparison.

Sector	City specific policies	Advanced control technologies[a]	450 Scenario[a]	References
Transport	Stage II control measures in buses and trucks Stage II control measures in two and three wheelers Introduction of Euro IV standards in Indian megacities from 2010	Stage III controls in buses and trucks Stage III controls Introduction of Euro V and Euro VI standards from 2015	Higher reliance on clean fuels bringing down $PM_{2.5}$ emissions by 20% in 2030	MoPNG (2003)
Fuel shifts	Shifting of public transport buses from diesel to CNG in Delhi	Same as city specific policies		Bell et al. (2004)
Power plants	Shift of all power plants from coal to natural gas Use of high efficiency ESP[b] technology in large coal based power plants (where applicable)	Same as city specific policies Use of high efficiency de-dusters in coal based power plants where applicable	High reliance on gas based power plants and renewables bringing down $PM_{2.5}$ emissions by 60% in 2030	CPCB (2010); SoE Delhi (2010)
Industry	Closing down/moving highly polluting industries outside city limits	Same as city specific policies	No significant change in industrial $PM_{2.5}$ emissions	CPCB (2010)
Waste	Ban on open residential burning of garbage and plastics	Same as city specific policies	No significant change in waste sector $PM_{2.5}$ emissions	MoEF (2010)

[a] Advanced control technologies and 450 Scenario are two hypothetical scenarios against which current city specific policies are compared.
[b] ESP: Electrostatic precipitator.

2.3. Health impacts

From a human health standpoint, the amount of particulate matter breathed in (personal exposure) determines health impacts. However, at a population level, such measurements are difficult to perform, expensive and lacking in developing countries (Kandlikar and Ramachandran, 2000). Therefore we estimated all-cause mortality using the population attributable fraction (PAF) approach that estimates the gradient of risk between observed exposure and a theoretical minimum level of air pollution (WHO, 2002). This has been the methodology of choice for Global Burden of Disease Assessments by the World Health Organization. This methodology involves determining population exposure to $PM_{2.5}$; applying appropriate concentration response functions; estimating baseline mortality and finally estimating number of deaths that can be attributed to air pollution (Rao et al., 2012). The model can be expressed as

$$\text{PAF} = [P^*(\text{RR}-1)]/[P^*(\text{RR}-1)+1]$$

where P is the exposure expressed as $PM_{2.5}$ concentrations and RR is the relative risk for non-exposed and exposed populations. The disease burden attributed to air pollution is a product of total mortality and the attributable risk. We use risk rates based on Pope et al. (2002). A number of uncertainties are inherent in using this approach. These include uncertainties in model estimates, monitoring of particulate matter, dosage response functions, calculations of personal exposure and data associated with health end-points.

The application of risk rates from developed countries to developing countries, as we do here, implicitly assumes that particle composition, demographic structure, population exposure, particulate matter concentrations are similar. However, developing countries such as India have significantly higher particulate matter concentrations, a younger population and a higher population density in urban areas as compared to developed countries such as the United States (Kandlikar and Ramachandran, 2000). The recent GBD (Lim et al., 2012) study also presents non-linear concentration response functions for $PM_{2.5}$ thus implying that significant particulate matter reduction may have only modest health benefits in highly polluted cities. Thus while highly uncertain, the estimation of health impacts should be viewed as indicative of policy efficacy in mitigating air pollution.

Total population exposures to $PM_{2.5}$ were estimated using projected population data from the GAINS database for Delhi. The theoretical minimum value for $PM_{2.5}$ exposure was set at 10 $\mu g/m^3$ which are the air quality standards recommended by the World Health Organization (WHO, 2006) and Delhi specific death rates from census data were applied to estimate baseline mortality (Census of India, 2011).

It must be pointed out that there are multiple relevant health end-points related to particulate matter exposure, nevertheless, we choose to focus on mortality as it is the most important health impact in terms of disability adjusted life years (de Hollander et al., 1999) and economic impacts (Kunzli et al., 2000). Furthermore in the Indian context, the lack of consistent baseline data makes it difficult to apply concentration response functions to estimate morbidity related health impacts.

3. Results

3.1. Emissions inventory

For the purpose of ensuring consistency, the GAINS estimates of $PM_{2.5}$ for the base year (i.e. 2010) are compared with actual monitoring data in the study by the Central Pollution Control Board (CPCB, 2010). We found good agreement for concentrations between GAINS model (89.4 $\mu g/m^3$ for 2005) and CPCB measurements of 125.2 $\mu g/m^3$for 2007. Since the GAINS reports results in 5 year increments, exact corresponding years between measured and estimated concentrations were not available. The CPCB measured pollutant concentrations at ten monitoring stations but did not carry out any monitoring for three months corresponding to the monsoon season (CPCB, 2010).

Fig. 1 presents estimates of changes in anthropogenic particulate matter emissions by sector and fuel type across different policy

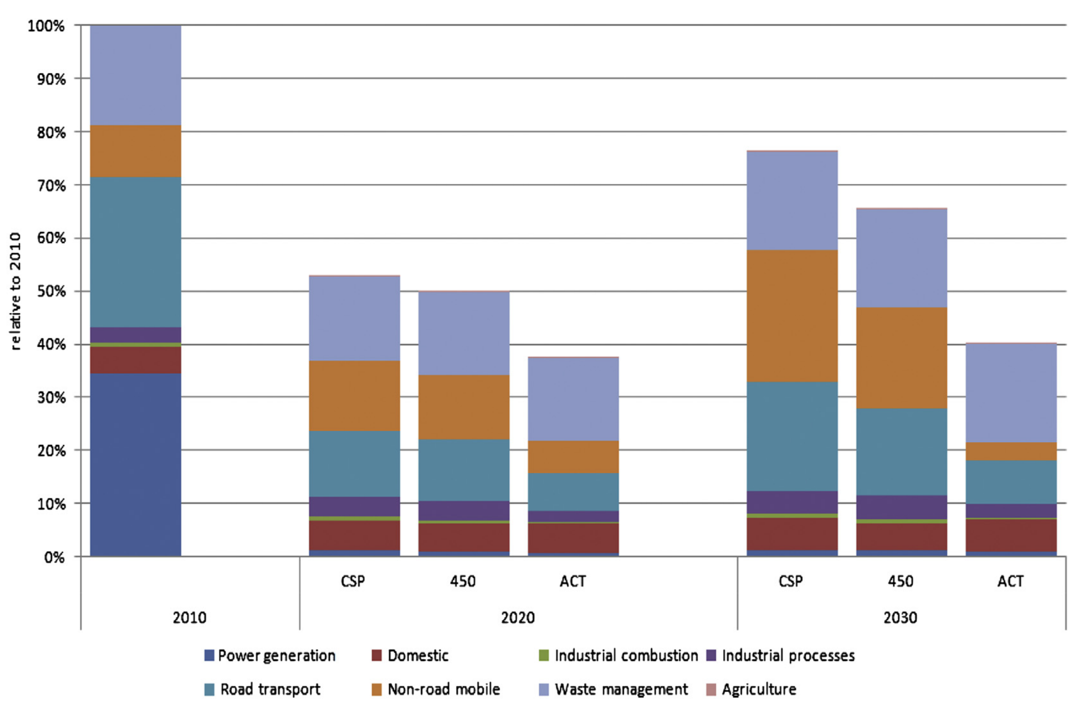

Fig. 1. $PM_{2.5}$ emissions aggregated by CORINAIR SNAP1 sector for Delhi under alternate scenarios.

scenarios. The absolute emissions of particulate matter are reduced when advanced controls or climate mitigation policies are adopted as compared to the city specific policies scenario. The shift from coal to natural gas in power plants is estimated to reduce emissions from the power sector significantly. Road transport related emissions decline by approximately 55% in 2020 and then increase by in 2030 under the city specific policies scenario. One explanation for this is that benefits accrued from implementation of control technologies are likely to be outweighed by the increase in future vehicle population. Road and non-road mobile transport emissions decrease steadily over time with implementation of advanced control technologies.

3.2. Future $PM_{2.5}$ concentrations

Based on the emissions inventory discussed in Fig. 1, the GAINS model estimates the concentrations of $PM_{2.5}$. There is a decrease in concentrations under all the three scenarios (Fig. 2) in the future (2030) as compared to 2010 values. The maximum reductions of about 60% are observed when advanced control technologies are adopted. However even this reduction is not enough to meet the NAAQ standards (40 $\mu g/m^3$ of $PM_{2.5}$). Climate mitigation policies have a modest impact contributing to about 20% reduction in future $PM_{2.5}$ concentrations.

Under the city specific policies scenario, there is a 20% increase in concentrations from 2020 to 2030. This increase can be explained in part by the increased emissions from the road and non-road mobile transport sectors. Population growth, increasing incomes due to economic growth are likely to positively impact the demand for private transportation (Graham and Glaister, 2005) thereby contributing to higher emissions. A key implication of this is that the city level policies currently in place are unlikely to reduce $PM_{2.5}$ concentrations in Delhi to the NAAQ standards in future.

One of the contributing factors to air pollution in Delhi may be trans-boundary air pollution a phenomenon that has been recognized in literature (Chelani and Devotta, 2005). Each region in GAINS is attributed as one 'station' location at the point of maximum emission. This allows for the calculation of contribution of PM concentrations to one receptor region from other source regions i.e. trans-boundary effects. A preliminary analysis suggests that the trans-boundary fraction may not be insignificant. However, we acknowledge that more detailed spatial modeling that simulates more information on multiple stations, meteorological detail and locational distribution could help improve the estimate of the trans-boundary fraction, we stress here that our goal is mainly to draw attention to the fact that this fraction is likely to be significant for urban areas in developing countries and that it is necessary to take this into account while calculating overall air quality.

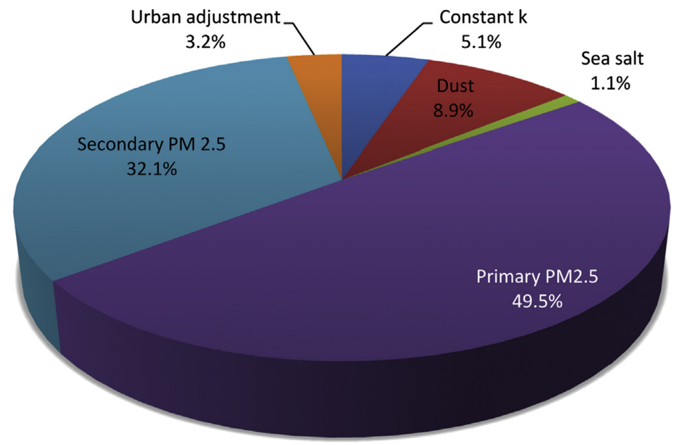

Fig. 3. Component wise break-up of $PM_{2.5}$ concentrations in Delhi for the base year ($\mu g/m^3$).

Fig. 3 presents contributions to $PM_{2.5}$ at Delhi receptor grid from each of the source regions considered in GAINS and this contribution is split into the primary and secondary components. The constant term represents contributions from outside the GAINS India area. The GAINS estimate represented here also includes urban increment as well as fine fraction of the natural dust concentration and sea salt. It may be noted that the constant term "k" and corrections for natural dust and sea salt are independent of the emissions scenario in GAINS.

One implication of these findings is that pollution control measures in Delhi alone may not be effective in reducing air pollution.

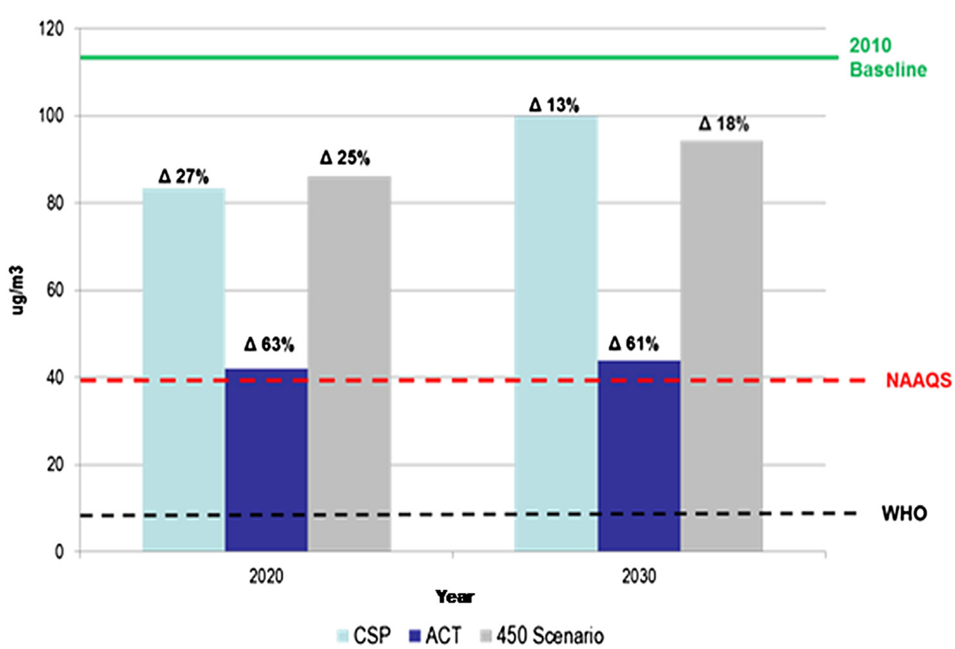

Fig. 2. Annual mean concentrations of $PM_{2.5}$ calculated for Delhi across policy scenarios. *Delta values show change in $PM_{2.5}$ concentrations compared to 2010 baseline.

Table 2
Estimates of all – cause mortality in population >30 years in 2030 attributable to outdoor air pollution in Delhi (number of deaths).

	Central estimate (RR = 1.06)
City specific policies	22,000 (10,000–32,000)
Advanced controls	11,000 (4000–18,000)
450 Scenario	21,000 (9000–31,000)

Numbers in brackets indicate the 95% confidence intervals with the lower estimate of relative risk being 1.02 and a higher estimate of relative risk being 1.11 as described in Pope et al. (2002).

The net flow of pollutants should be reduced by implementing stringent policies to control industries in Uttar Pradesh and Haryana.

3.3. Health impacts

Table 2 shows that the central estimate for number of excess deaths attributable to outdoor air pollution in Delhi in 2030 is 22,000 if current city specific policies continue. These deaths can be reduced by half if advanced control technologies are adopted. Health gains as a result of adopting climate mitigation policies are relatively small given the modest impact on air quality. This analysis makes it apparent that air pollution is likely to have a large impact on health outcomes in Indian cities if further stringent control actions are not taken.

4. Discussion

Although modeling exercises have been carried out at the country level for India (Purohit et al., 2010), there are few studies that look at future air quality and health impacts at the city level. Guttikunda and Calori (2013) develop a detailed GIS based spatial inventory for Delhi for multiple pollutants by using data from seven monitoring stations. However, their study does not undertake an evaluation of current policies on future air quality and associated health impacts. Using the GAINS-Asia model, Purohit et al. (2010) looked at air quality and health impacts for 23 regions in India but did not incorporate specific city level policies into the modeling framework. Given the heterogeneity of air pollution levels within a city, we believe it is more responsive to local policies as compared to regional/national initiatives. This dichotomy becomes important especially in the case of India where policies related to air pollution are first implemented in the twenty cities including Delhi and subsequently in other parts of the country (MoPNG, 2003). Thus, the current policies scenario in our study represents the most advanced policy portfolio to tackle air pollution in the country.

We find that the current policy legislation in Indian cities of Delhi will not bring particulate matter concentrations down to National Ambient Air Quality Standards by 2030, leading to significant future health impacts. Full application of advanced control technologies currently available in the market could substantially reduce air pollution impacts in Indian cities however their implementation requires substantial economic resources. This uniform across-the-board application of advanced controls may not be cost effective and careful selection of energy and technology choices may reduce future air pollution and health impacts at a much lower cost.

There may be multiple approaches (Table 3) toward achieving the NAAQ standards such as switching to renewables in transport and electricity generation; leapfrogging from Euro IV to Euro VI standards or higher as well as levy of congestion charges in traffic hotspots. The National Mission on Sustainable Habitat (NMSH) focuses on initiatives such as better urban planning, enhanced energy efficiency through better lighting, heating and cooling systems that may help reduce air pollution (NAPCC, 2010). GHG mitigation strategies provide ancillary benefits in reducing local air pollution (Garg, 2011) but these effects are modest and should be done in conjunction with air pollution control measures.

The building and extension of the metro rail in Delhi may lead to modal shifts between public and private transportation. However, it is difficult to predict shifts in human behavior on an a priori basis given the positive elasticity of demand between income and private road transportation (Graham and Glaister, 2005). The way GAINS is structured does not allow for the explicit capture of land use changes at the city level. Therefore this remains a limitation of our study. Needless to say, a detailed city level model that can capture such changes is required for further research to obtain more nuanced policy insights.

For Delhi, addressing trans-boundary pollution will play a crucial role to reduce air pollution in the city. Despite policy intervention, there remain brick kilns (majority being fixed chimney bull's trench

Table 3
Policy portfolio for air pollution reduction in Delhi.

Sector	Policies	Measures	Implementation strategies	Key institutions[a]
Power sector	Efficiency improvements	Emission targets, emission standards	NCR as sub-grid in northern grid; Increasing generation capacity; load management through smart grid connections; reduced distribution losses; strict control on diesel generator sets	MoEF, CERC, EMC
	Fuel switch	Taxation mechanisms	Technology transfer; Infrastructure development for renewable energy through PPP[b]	MoEF, MNRE
Transport	Efficiency improvements	Emission standards	Leapfrog to Euro VI standards	MoPNG
	Technology push	Subsidy mechanisms	Penetration of electric and hybrid vehicles	MoEF
	Process improvements	Awareness, education	Traffic light synchronization, road dust management systems, better linkages between metro and outer areas of Delhi; creating unified transport authority	MoRTH
Industry	Process improvements and recycling	Standards, tax, awareness	Strict monitoring and correction; adoption of vertical shaft brick kilns	Regulatory bodies, industry associations
	Raw material improvements & switch	Industry standards	Industry leadership, supply chain management	
Trans-boundary effects	Efficiency and process improvements	Emission targets, emission standards, awareness	Enhancing metro connectivity, ban on open combustion and burning of crop residue	MoEF, Delhi, Haryana and Uttar Pradesh state governments

[a] MoEF – Ministry of Environment and Forests, CERC – Central Electricity Regulatory Authority, EMC – Energy Management Centre, MNRE – Ministry of New and Renewable Energy, MoPNG – Ministry of Petroleum and Natural Gas, MoRTH – Ministry of Road Transport and Highways.
[b] PPP: Public Private Partnership. Source: adapted from Garg et al. (2002).

kiln type) in Gurgaon and Ghaziabad which are not controlled well enough (Maithel et al., 2012) and may contribute significantly to air pollution. While there are uncertainties, the contribution of trans-boundary air pollution in Delhi may not be insignificant and needs stringent policy control measures in neighboring areas of Uttar Pradesh and Haryana.

A clear limitation of our study is that a detailed uncertainty analysis has not been undertaken. However, we do believe that such studies are required to inform policy, especially in situations where there remain possibilities of making choices to avoid future lock-ins. Furthermore, we do not prescribe any optimal policies or claim to do so. This study compares alternate policy portfolios against one another to examine which may be better suited to address the problem of air pollution in Indian cities.

In conclusion, this study addresses some of the research gaps by estimating the combined impact of policies across different sectors on future air pollution and health for the city of Delhi. It is clear that reaching NAAQS depends on structural transformations along with combination of advanced controls and climate centric policies. This study has taken the first steps to evaluate the current policy portfolio, but remains far from suggesting an optimal approach which should be the focus of future research. From a policy context, moving toward sustainable development pathways holds key for air pollution mitigation in Indian megacities.

5. Financial interests declaration

The authors declare no competing financial interest. Hem H. Dholakia was provided financial support for completion of this work under the Young Scientist Summer Programme (YSSP) of the International Institute of Applied Systems Analysis (Austria) by the Technology Information Forecasting and Assessment Centre (TIFAC), New Delhi. TIFAC had no involvement in planning, designing or execution of this study.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2013.04.052.

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