# Supplementary Information

Managing future air quality in megacities: Emission inventory and scenario analysis for the Kolkata Metropolitan City, India\*

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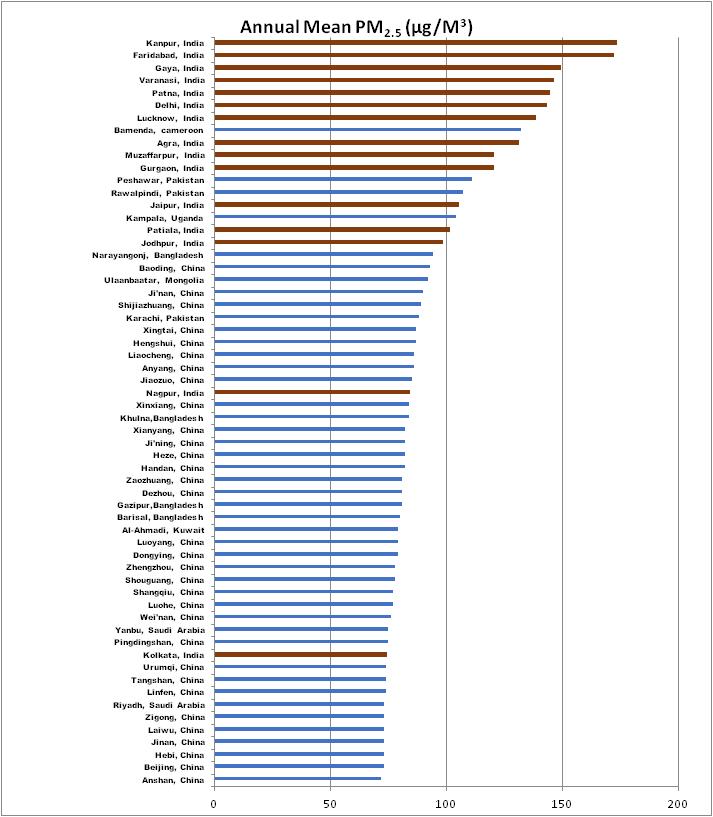
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# **Air pollution in Indian cities**

Air quality is a major cause for concern in India, particularly in cities. Air pollutants, including particulate matter (PM), sulfur dioxide (SO2), nitrogen oxides (NOx), carbon monoxide (CO), and ozone (O3) often exceed India’s National Ambient Air Quality Standards (NAAQS). According to the World Health Organization (WHO) urban air quality database, 9 of the 10 most polluted cities in the world are in India (Figure S.1) and the cities of Kanpur, Faridabad, Gaya, Varanasi, Patna, Delhi, Lucknow, Agra, and Muzaffarpur are listed in the top 10 (WHO, 2018). More than 100 cities under the NAAQS monitoring program exceed the WHO guideline for PM10. In India, the NAAQS for CO exceeds the WHO guidelines, while the NOx, SO2, and O3 standards are on a par with the WHO guidelines. However, the standards for PM10 (aerodynamic diameter <10 μm) and PM2.5 (aerodynamic diameter <2.5 μm) are lagging (Figure S.2). Kolkata ranks 53rd in the list, with an annual average PM2.5 level of 74 µg/m3 (WHO, 2018).



**Figure S1: Indian cities among the 60 most polluted cities in the World**

Source: WHO (2018)



**Figure S2: PM2.5 concentrations in selected Indian cities**

Source: WHO (2018)

# **Revised National Ambient Air Quality Standard (NAAQS)**

The current Indian National Ambient Air Quality Standard (NAAQS) was published on 18th November 2009.

**Table S.1: National Ambient Air Quality Standards**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **S. No.** | **Pollutants** | **Time**  **weighted**  **average** | **Concentration in ambient air** | | **Methods of measurement** |
| 1. | Sulfur dioxide  (SO2), μg/m3 | Annual\* | 50 | 20 | 1. Improved West and Gaeke  2. Ultraviolet Fluorescence |
| 24 Hours\*\* | 80 | 80 |
| 2. | Nitrogen dioxide  (NO2), μg/m3 | Annual\* | 40 | 30 | 1. Modified Jacob & Hochheiser (Na-Arsenite)  2. Chemiluminescence |
| 24 Hours\*\* | 80 | 80 |
| 3. | Particulate Matter  (Size <10μm) or  PM10, μg/m3 | Annual\* | 60 | 60 | 1. Gravimetric  2. TEOM  3. Beta attenuation |
| 24 Hours\*\* | 100 | 100 |
| 4. | Particulate Matter  (Size <2.5μm) or  PM2.5, μg/m3 | Annual\* | 40 | 40 | 1. Gravimetric  2. TEOM  3. Beta attenuation |
| 24 Hours\*\* | 60 | 60 |
| 5. | Ozone (O3), μg/m3 | 8 Annual\*\* | 100 | 100 | 1. UV photometric  2. Chemiluminescence  3. Chemical Method |
| 1 Hours\*\* | 180 | 180 |
| 6. | Lead (Pb), μg/m3 | Annual \* | 0.50 | 0.50 | 1. AAS/ICP Method after sampling using EPM 2000 or equivalent filter paper  2. ED-XRF using Teflon filter |
| 24 Hour\*\* | 1 | 1 |
| 7. | Carbon monoxide (CO), mg/m3 | 8 Annual\*\* | 2 | 2 | Non dispersive Infra-Red (NDIR) Spectroscopy |
| 1 Hours\*\* | 4 | 4 |
| 8. | Ammonia (NH3), μg/m3 | Annual\* | 100 | 100 | 1. Chemiluminescence  2. Indophernol blue method |
|  | 24 Hours\*\* | 400 | 400 |  |
| 9. | Benzene (C6H6), μg/m3 | Annual \* | 5 | 5 | 1. Gas chromatography-  based continuous analyzer  2. Adsorption and Desorption  followed by GC analysis |
| 10. | Benzo(a)Pyrene (BaP)-  particulate phase only, ng/m3 | Annual\* | 1 | 1 | Solvent extraction followed by  HPLC/GC analysis |
| 11. | Arsenic (As), ng/m3 | Annual\* | 06 | 06 | AAS/ICP method after sampling on EPM 2000 or equivalent filter paper |
| 12. | Nickel (Ni), ng/m3 | Annual\* | 20 | 20 | AAS/ICP method after sampling on EPM 2000 or equivalent filter paper |

\*Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform interval.

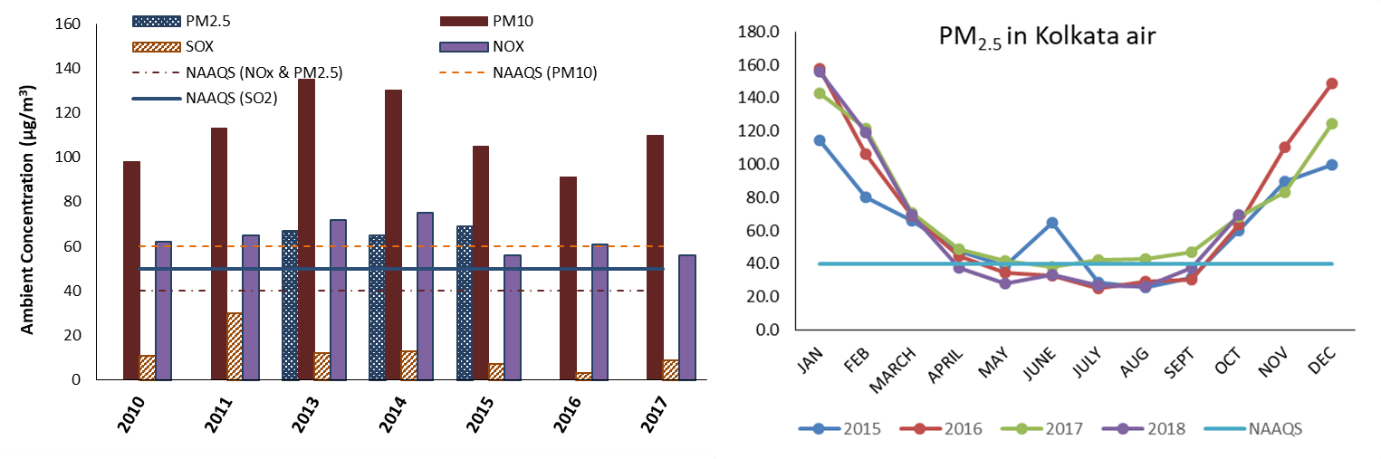
\*\* 24 hourly or 8 hourly or 01 hourly monitored values, as applicable shall be complied with 98% of the time in a year. 2% of the time, they may exceed the limits but not on two consecutive days of monitoring.

**NOTE:** Whenever and wherever monitoring results on two consecutive days of monitoring exceed the limits specified above for the respective category, it shall be considered adequate reason to institute regular or continuous monitoring and further investigation.

Source: CPCB (2012)

# **Air Quality in Kolkata**

The level of air pollution in Kolkata city is severe, and the status has been alarming for the past two decades (Ghose et al., 2005; Das et al., 2006; Chatterjee et al., 2013; Lelieveld et al., 2015). Especially with respect to NOx and respirable suspended particulate matter i.e., RSPM (~PM10) the annual average was consistently non-compliant with the national standard during the 1999–2011 period (CPCB, 2015a, 2015b). The dominant sources were identified as coal combustion, soil dust, road dust, and solid wastes (Gupta et al., 2007). The Kolkata urban air shed is considered to be NOx-sensitive based on the VOC/NOx ratio (CPCB, 2010). However, SO2 levels in Kolkata have been well below the NAAQS during last two decades. In recent years, however, the annual average PM10 and NOx level has been found to consistently exceed the NAAQS, while the PM2.5 level far exceeds the standard in the winter months (Figure 1). NOx concentrations exceeded the NAAQS on several occasions at all the monitoring sites, while PM10 and PM2.5 exceeded more than 60% and ~40% of days, respectively, in Kolkata during 2013–2015 (CPCB, 2014; CPCB, 2015b; CPCB, 2016; WBPCB, 2016). Kolkata shows typical seasonal variation with respect to key air pollutants, with a very high level during the winter months (September to February) due to meteorological factors (CPCB, 2015a).



(a) (b)

**Figure S3: (a) Ambient air quality (annual average) of Kolkata; (b) monthly variation in ambient PM2.5 level of Kolkata**

Sources: CPCB (2014, 2015b, 2016); WBPCB (2016); AQIS (2019)

# **The GAINS model**

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, developed by the International Institute for Applied Systems Analysis (IIASA), is an extension of the RAINS (Regional Air Pollution Information and Simulation) model which deals with the synergistic relationship between multiple key air pollutants and major greenhouse gases. The GAINs model has been extensively used at a regional scale in Europe to evaluate the impacts of air pollutants and greenhouse gas (GHG) emissions and to formulate a suitable policy framework to define appropriate mitigation measures (Amann et al., 2011).

The GAINS model accepts activity data for various sectors and segments that may affect the emission of key air pollutants, both particulate (PM10, PM2.5) and gaseous (SO2, NOx, NH3, CO, and VOCs). It also accepts projected future economic data and activity for future years. The model considers city-level activity data, along with associated control strategies and relevant emission factors; it generates a detailed sector-wise emissions inventory for present and future years. A number of alternate scenarios can be generated in the model related to various alternative policy scenarios along with their cost implications and mitigation potential for key air pollutants and major GHGs (CO2, CH4, N2O, HFC, PFC, and SF6) considered in the Kyoto Protocol. The GAINS model also considers measures for emissions of precursors of secondary pollutants such as secondary aerosols or ozone that have a detrimental effect on human health and cause damage to ecosystems. Accordingly, the GAINS model tool can be applied to derive a comprehensive and integrated analysis of air pollution and climate change mitigation strategies, which reveals important synergies and co-benefits between these policy areas (Amann et al., 2008).

For each of the pollutants mentioned above, GAINS estimate current and future emissions as per Eq. (1):

(1)

where *i, k, m, p*, respectively, represent the country, activity type, abatement measure, and pollutant, *Ei,p* the emissions of pollutant p in country *i, Ai,k* is the activity level of type *k* (e.g., coal consumption in power plants) in country *i*, *efi,k,m,p* is the emission factor of pollutant *p* for activity *k* in country *i* after application of control measure *m*, and *Xi,k,m,p* is the share of total activity of type *k* in country *i* to which a control measure *m* for pollutant *p* is applied.

# **Major city-specific policies in place for Kolkata**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sector** | **Policy** | | **Reference** |
| Power plants | * Electrostatic precipitators (ESPs) for coal-based thermal power plants * Flue gas desulfurization (FGD) for control of SO2 for coal-based thermal power plants | | MoEFCC (2015) |
| Waste | Ban on open burning of wastes. | | MoEFCC (2016) |
| Automobile Pollution | India 2000  (EURO-I equivalent) | For all new vehicles from 1April 2000 | APR (2015); MoRTH (2016) |
| Bharat Stage II  (EURO-II equivalent) | For all new passenger cars from 31December 2000 |
| Benzene content in petrol <3% | June 2000 |
| Low sulfur fuel (<0.05% or <50 ppm) | For both gasoline and diesel from 1January 2001 |
| Loose 2-T oil \* | Ban on use, sale, and distribution from 1st October 2001 |
| Bharat Stage III  (EURO III equivalent) | April 2003 |
| Bharat Stage IV  (EURO IV equivalent) | April 2010 |
| Bharat Stage VI  (EURO VI equivalent) | April 2020 (proposed) |
| Benzene content in petrol <1% | 2016 |
| Phasing out of 15-year-old vehicles | From 2009 | DoE (2008); DoE (2010) |
| Industry | Air polluting industries are not permitted within municipal areas of KMC | | WBPCB (2016) |

\*Loose 2-T oil used to be sold on the open market as fuel for 2-stroke petrol vehicles; mainly used in 3-wheelers and 2-stroke vehicles locally known as “katatel, 2-T was often blended locally with a cheap adulterant and had a high air-pollution potential.

# **Multi-pollutant emissions inventory for Kolkata Metropolitan City (KMC)**

The emissions inventory for 2010 and 2015 presented for Kolkata Metropolitan City (KMC) also reffred to as Kolkata Metropolitan Area (KMA) is based on activity data and emission factors for different sectors including the transport, power/industry, residential/commercial, and agriculture sectors. Key assumptions and data sources are briefly discussed in the following subsections:

## Industrial Sector

The number of operational industries within the KMA was about 1,160, which includes metallurgy, tanneries, textiles, chemicals, engineering, paper and pulp, bakery, and many others. Most of these industries fall into medium-, small-, and micro-scale and belong to the Orange category (moderately polluting) (EMIS, 2015). According to the Industrial Siting (locational) policy for West Bengal (WBPCB, 2011), industries of Special Red and Ordinary Red categories were not permitted after 2010 in municipal areas falling under the KMA (i.e., KMC). Industries could be set up beyond the municipal areas if they had an adequate pollution abatement system, subject to site clearance by local bodies. Industries in the Orange category were permitted in all municipal areas except Kolkata Municipal Corporation and Howrah Municipal Corporation areas (except in industrial estates), as long as adequate pollution control measures in place and subject to the site receiving clearance from the municipal authorities for setting up new units. Industries in the Green category are permitted in any area in the state if they have adequate pollution control measures subject to site clearance by the local body.

## Power sector

The power supply authorities in KMC are Calcutta Electric Supply Corporation (CESC) and West Bengal State Electricity Distribution Company Limited (WBSEDCL). There are five major power plants located within the boundary of KMC. Among them are four plants at Budge Budge (750 MW), Titagarh (240 MW), Garden Reach (535 MW), Cossipore (100 MW) operated by CESC and a fifth, Bandel power plant (135 MW) operated by West Bengal Power Development Corporation Limited (WBPDCL). All five power plants operating in the study area are coal-based thermal power plants. Coal consumption data were collected from individual power plants. The PLF (plant load factor) and plant operation time percentage for the individual power plants were obtained from CESC (2016) and WBSEDCL (2011); and WBSEDCL (2016). The overall capacity of the plants except the one at Cossipore is 1660 MW as the Cossipore plant has been closed since 2014.

* + 1. Electricity distribution

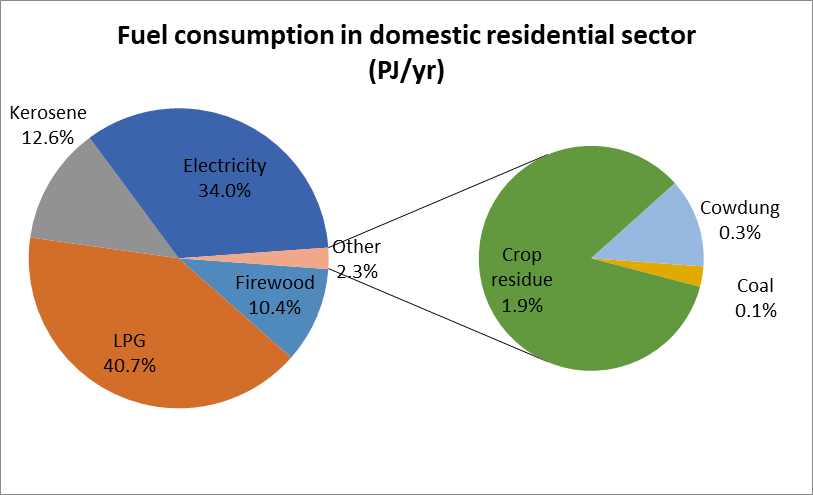
The share of total electricity generated in the KMC is distributed among different sectors for different purposes. The percentage share of power generation by CESC was obtained from CESC (2016). To obtain the estimated share of distribution for the WBPDCL supply, the distribution districts under KMC and the percentage of the population share of individual districts supplied by WBPDCL in each district were obtained (WBSEDCL, 2011, 2016).

* + 1. Generator sets

Diesel Generator (DG) sets are used mainly for industrial purposes; information on DG sets and their fuel usage was obtained for the industrial sector from EMIS (2015). The status of residential electricity is satisfactory in the KMC area and instances of power outages are rare. Therefore, the residential DG-set usage was not taken into consideration.

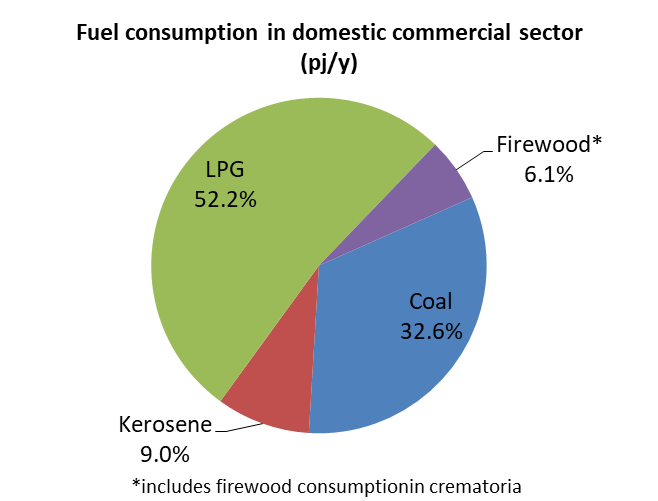
## Domestic sector

* + 1. Domestic residential sector

Activity data on fuel used for cooking and lighting in households in residential areas (including slum areas) have been comprised. Information on the type and quantity of fuel used, and the hours when they were used for cooking, was estimated from the primary household survey conducted as part of this study. Information on population and district-wise fuel usage details for domestic purposes was collected from the 2011 census (GoI, 2011). Electricity usage for the domestic sector was also obtained from CESC (2016) and WBSEDCL (2016). The population of the KMC is assumed to be distributed among 2.8 million households with an average of five people per household. Figure S3 presents the share of different fuel use in the KMC for household cooking, lighting, household appliences and other purposes.

**Figure S3: Energy consumption (in %) in domestic residential sector in 2015**

* + 1. Domestic commercial sources

Information on registered hotels, restaurants, and bakeries was collected from the West Bengal Pollution Control Board (EMIS, 2015). The fuel type and monthly fuel use trend data were obtained from a primary survey conducted as part of this study in representative hotels and restaurants to allow total fuel usage in this sector to be calculated. Packed LPG data used for the industrial sector were obtained from sales data and considered under the domestic commercial sector for this study. There are a considerable number of unregistered hotels and roadside eateries in operation in Kolkata. They serve good quality food at a cheap price to a huge number of the city dwellers. They are part of the reason why Kolkata is known as one of the cheapest metropolitan cities in India. A question-based in-house primary survey was undertaken in 2017 as part of the present study to assess the number of such establishments and their fuel use, etc. For the purposes of the survey, the KMC area was divided into a 2 km x 2 km grid. Eight representative grids were chosen for the survey. All the temporary unregistered establishments in those grids were counted. Ten percent of the establishments were interviewed for the questioner survey to see if there was a trend in the type and amount of fuel used. The survey result was extrapolated to the entire KMC area to project the total number of unregistered hotels, restaurants, and mobile food vendors using different fuel types. For the purposes of this study, the 2017 survey data were used for 2015 and backcasted for 2010 based on total KMC population. Figure S4 presents the estimated share of energy consumption from various fuels in the domestic commercial sector indicating the contribution from the registered and unregistered hotels, restaurants, and mobile food vendors.

**Figure S4: Energy consumption (in %) in domestic commercial sector including contribution of registered hotels and unregistered eateries**

In 2010, a few bakeries operating within the KMC areas were using firewood (EMIS 2015). The production units with a capacity of more than 1 ton per year were considered under industrial sources. The West Bengal Pollution Control Board (WBPCB) imposed control on individual bakeries within the KMC (WBPCB 2019). Use of firewood in small registered units was considered under the registered hotel category.

## Waste sector

* + 1. Municipal solid waste (MSW) disposal

The major sources of MSW in the KMC area are residential areas, commercial or market places, and some floating waste from the riverside areas. The details of waste generated in the KMC area were estimated from the 2011 census (GoI, 2011) and Das et al. (2011).

It is assumed that the 1% of total MSW generated within the KMC area is subjected to open burning. Although open burning within the Kolkata city area is banned by the WBPCB, the ban has not yet been strictly implemented and open burning, especially during the winter, is a common sight.

* + 1. Hazardous waste management and waste incinerators

The state of West Bengal has one Common Hazardous Waste Treatment, Storage and Disposal Facility (CHWTSDF) at Haldia (outside KMC) developed by the West Bengal Waste Management Ltd (WBWML). This activity is not considered in this study. The facility has been catering to the hazardous waste–generating units of the entire state, including those from the KMC, for almost 12 years. The facility deals with biomedical waste as well as municipal solid wastes for adjacent municipal areas and other Indian states. In 2010–2011, a total of 26,409 Million Ton of waste were sent directly to landfill and 3060 MT were incinerated (WBPCB, 2011).

* + 1. Crematoria

There are seven crematoria operating inside Kolkata City, namely, Keoratala, Nimtala, Birjunala, Kashi Mitra Lane, Siriti, Garia. There are another seven operating in the KMC, as reported in the Kolkata Metropolitan Development Authority report (KMDA, 2005). Crematoria were mainly operated using an electric cremation system but the option of a wood cremation has remained. During the primary survey conducted as part of this study at local crematoria, it was reported that an average of 350 kg wood is used for a single cremation . Wood burning in crematoria is incorporated into the domestic commercial sector.

## Construction sector

Construction activity data for West Bengal were gathered from DoEA (2015). The type of constructions in the transport sector was mainly roads and bridges. In the KMC region, there was a total of 70 construction activities in the energy, transport, water, sanitation, social, and commercial infrastructure sectors, of which 37 came under the transport sector. Other than transport, there were 26 ongoing construction projects on water sanitation and sewage treatment in various parts of the KMC. Details of sanctioned residential projects were obtained from the Kolkata Municipal Corporation authority through personal communications, and these were projected for the KMC considering 50% residential construction in KMC regions outside the Kolkata Municipal Corporation (old city boundary) in 2010.

Kolkata Municipal Corporation data indicate a yearly 3.3% decrease in residential construction from 2010 to 2015 (KMC 2018). This figure was adopted for projecting construction activity till 2030 within the original city under Kolkata Municipal Corporation area. It was assumed that housing needs will be met by residential construction outside the Kolkata Municipal Corporation area but within the KMC region: hence, given the increasing population, it was assumed that the rate of construction (per square km) in the KMC outside the Kolkata Municipal Corporation area will increase by 5% yearly; a projection for construction outside the Kolkata Municipal Corporation was made, based on this, up to 2030. The total residential construction of the KMC region is thus estimated and projected as the sum of construction activity inside and outside the KMC area. For infrastructural projects, an overall 5% yearly increase was assumed for the KMC area.

## Agriculture sector

Crop cultivation, furtilizer use, land use and animal husbendary/dairy activities have been considered under Agriculture sector (SAWB 2015, DLLR 2005). Rice is a major crop in west Bengal as well as in periurban areas of KMC. District wise rice cultivation area is adopted from SAWB (2015) and projected for KMC. Ghosh et al. (2017) reported ~2% annual decrease of cultivable land within old Kolkata city during past forty years (1987-2017). We assumed slower annual decrease rate (@1% per year) for rice cultivable land in KMC area till 2030. District wise livestock statistics were adopted from DSH (2011) and projected for KMC based on population. Livestock in future year is projected based on KMC population. The fartilizer use data was downscaled from state level data (DoF 2013) based on KMC area and the consumption is normalised for urban area. A limited survey was undertaken in the fartiliser shops in peri urban area of KMC in 2014 as part of this study to understand the trend in sale of fartilizer type. An annual 1.4% decrease in fartiliser use is assumed till 2030.

## Non-road mobile sector

* + 1. Railway locomotives and maritime

The eastern and southeastern railway operates diesel locomotives within the KMC area. Inland waterways are also in operation with small vessels running up and down the River Ganga. The total fuel consumption in these sectors was obtained from IOCL (2015).

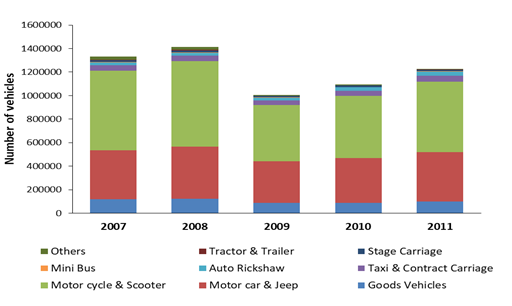
* + 1. Aviation sector

There is only one airport within the KMC area, namely, Nataji Subhas Chandra Bose International Airport. Information regarding the number of flights and share of domestic and international flight at Kolkata International airport was obtained from AERAI (2012) and information on aviation fuel consumption from IOCL (2015).

## On-road vehicle exhaust

Information on registered vehicles was obtained from the District Statistical Handbooks of individual districts falling under the KMA as well as from individual Regional Transport Offices of the KMC. The registered vehicles were divided into 6 categories: 2-wheelers, 3-wheelers, 4-wheelers, buses, trucks, agricultural, and others. In July 2008, the Department of Environment of the Government of West Bengal issued an order to phase out all vehicles that were 15 years and older (DoE, 2008). The impact of the order is reflected in the following graph which shows yearly vehicle registration in the KMC.

The total fuel consumption in the transport sector (on-road vehicles) was cross-referenced with supply data (IOCL, 2015). It was reported that in 2010 that the entire amount of gasoline sold in the KMC was used in the transport sector. Eighty percent of the total diesel sold through retail outlets is used in the transport sector, not counting the railway, marine, and aviation sector usage. Auto LPG is wholly used for 3-wheelers (auto-rickshaws).



**Figure S5: Registered vehicles, according to type, in the KMC**

Source: (DSH, 2011; RTO, 2015)

On-road vehicle data were taken from WBPCB (2015) and ADB (2008). Moreover, traffic video recordings, provided by the traffic department of Kolkata were also used to collect primary data related to on-road traffic movement and fleet composition. The years 2005, 2010, and 2015 were considered for calculating the average hourly on-road vehicle and fleet distribution. ADB (2008) showed the average numbers of vehicles per 24 hours using different roads like the national highways, arterial roads, and other residential commercial roads. These calculations were used to obtain the average number of vehicles on all roads on a one-hour and 24-hour basis.

Traffic video footage for the year 2010 (KTP, 2010) was thoroughly studied to estimate on-road vehicles on the major roads and crossings of Kolkata on the basis of a 12-hour survey. The on-road vehicle numbers thus obtained were used to calculate the hourly average number of different vehicles and to estimate fleet distribution. The average trend of on-road vehicle numbers throughout 2005–2015 is shown below.

**Table S2: Fleet composition in KMC road**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Year** | **2W**  **(bike+scooter)** | **3W**  **(auto)** | **4W**  **(car+taxi)** | **Bus**  **(large+ small)** | **Truck**  **(large + small)** |
| 2005a | 16% | 7% | 56% | 9% | 11% |
| 2010b | 18% | 7% | 61% | 8% | 5% |
| 2015c | 12% | 9% | 50% | 22% | 6% |

Source: (aADB, 2008; bKTP, 2010; cWBPCB, 2015)

A decrease in 2-wheelers and 4-wheelers and an increase in bus use may indicate a shift toward the public transport system. There is also an increasing trend for 3-wheelers. However, unlike in other Indian cities, 3-wheelers in Kolkata ply on fixed routes and are also used on a sharing basis, making it a type of public transport system.

# **Emission factors**

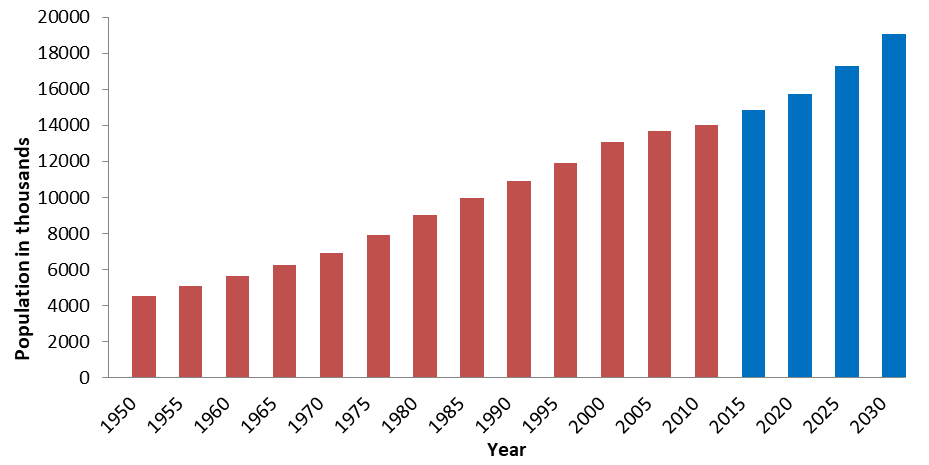
The emission factors for different fuel types used to estimate emissions from the power, industrial, residential, and commercial sectors are taken from different sources, tailored to the Indian conditions. These are based on the number of reports and experiments conducted by government certification agencies and also by government-authorized non-governmental, and autonomous agencies under various projects (UNEP, 1999; US EPA, 2000, 2006; Reddy and Venkataraman, 2002a, 2002b; NEERI, 2008; CPCB, 2011) . We used the GAINS emission factors in cases where emission factors were not available. To calculate PM and SO2 emissions, the most relevant ash and sulfur content for fuels used in India was used (CPCB, 2011), as these emission factors are based on ash and sulfur content in fuel (Shah and Nagpal, 1997; IPCC, 2006; UNEP, 2006; NEERI, 2008; CEA, 2014; IOC, 2015) .

To calculate GHG emissions from fuel combustion, India-specific emission factors were used, wherever available, or otherwise taken from the GAINS model for South Asia (Purohit et al., 2010). GAINS emission factors were also used in this study for CO2 emissions. To estimate CH4 and N2O emissions, and emission factors for waste and agricultural activities, the IPCC Guidelines for National Greenhouse Gas Inventories, published in 2006 (IPCC, 2006), were used with India-specific values for each activity.

Vehicular pollution sources are not homogenous, as there is a mix of fuel (gasoline, diesel, natural gas), engine type (2-stroke, 4-stroke) and controls (Bharat Stage (BS-I), BS-II, BS-III or BS-IV etc.). Emission factors developed by the Automotive Research Association of India (ARAI) are used in this study; these include the Indian driving cycle, the age of vehicles, and current engine technology (ARAI, 2007; NEERI, 2008; CPCB, 2011). Emission factors for new control technologies (BS-IV, BS-VI) are taken from the GAINS model. Emission factors from the GAINS model are also used to estimate emissions from tyre wear, break wear, and abrasion—the resuspension of dust on roads was estimated using the USEPA AP-42 methodology (US EPA, 2006) based on silt content (NEERI, 2008; CPCB, 2011), modified in consultation with IIASA, and then added to abrasion emissions.

# **Drivers of future projections for Kolkata**

The growth of population in KMC from 1950 to 2015 and projected to 2030 is adopted from the 2011 census (GoI 2011) and Banerjee (2018).

**Figure S4: Population growth for KMC from 1950 to 2010 and projected population till 2030**

The gross domestic product (GDP) of Kolkata city is obtained from the GoWB Report (2015) at 2004–2005 constant prices. The estimate of city-specific per capita GDP is then used to derive the GDP of KMC. The GDP of KMC for 2010–2011 is estimated to be €14.9 billion (at an average INR to euro exchange rate of 2010, i.e., 60.59, and at 2004–2005 constant prices). Various published documents were referred to, including government project planning, development strategies, and long-term objectives of national and city-specific policies in place for KMC.

Projections of future activity for business as usual (BAU) scenario was carried out for different sectors. There has been appreciable population growth in the KMC area in the past few decades: this has increased i) infrastructure and urban development; ii) demand in the service sector; and, in turn, iii) energy demand. In making future projections, various national and state-level planning and projection documents, as well as sector-specific policy documents, were considered.

The following assumptions were made to estimate emissions under the business-as-usual (BAU) scenario up to 2030 in intervals of 5 years:

## General assumptions:

* The normal growth rate in population would result in a proportionate increase in different sectors, and also in fuel consumption.
* The average annual growth rate for West Bengal during 2005–2006 to 2012–2013 is reported to be 6.59% (GoWB, 2015). This rate is used to project the GDP of Kolkata to 2030.
* The share of various economic sectors in the city’s GDP is obtained from GoWB (2015). To project the future GDP in different sectors of the economy, the annual average growth rates (for 2005–2013) of the GDP of the state of West Bengal by industry of origin at constant (2004–2005) prices used were taken from GoWB (2015). Moreover, for sectoral growth projection it is assumed that the construction and transport sector within the KMC area will have 25% more growth than the rest of West Bengal. In the industrial sector (manufacturing) owing to the decision of the authority not to permit any more industry to open within the KMC area, a nominal 1% annual growth is assumed compared to 5.59% projected growth for rest of West Bengal.

## Area sources

* For the year 2010 to 2030 the total fuel requirement for domestic cooking and heating purposes is projected based on the projected population.
* It has been assumed that in the business-as-usual scenario there will be a shift toward LPG use for domestic cooking (yearly increase of 2%, based on primary survey undertaken as a part of this study) which leads to LPG having a projected share of 89% in domestic fuel by 2030. This was assumed in view of the increased GDP as well as the national programs such as Pradhan Mantry Ujjwala Yojana (PMUY) to distribute 80 million LPG connections to women of families living below the poverty line (BPL) and subsidies in the LPG price for BLP users. The shift is projected to be away from firewood and kerosene (yearly decrease of 1% in use of each fuel type) with a contribution of 2.3% and 3.2%, respectively, toward total fuel by 2030. The burning of coal and cow-dung for domestic cooking is also projected to be replaced by cleaner fuel within the KMC. The electricity demands in residential sector were projected based on India’s domestic growth in consumption published by the World Bank (2008).
* As, so far, there has been no drive toward biogas generation and use, the use of biogas is not expected in the BAU scenario.
* The activity projection in BAU scenario for the domestic commercial sector was carried out based on the projected population.
* For the projection of waste generation it was assumed that per capita waste generation will increase by 1% annually. It is also assumed that 1% of total municipal solid waste will continue to be subject to open burning.

## Point sources

* The West Bengal Pollution Control Board (WBPCB) has decreed that no new industry will be permitted within the KMC area (WBPCB, 2016) and that no expansion of the present industrial units there will be considered. Hence, in the BAU scenario, industrial fuel consumption is projected to be maintained at the status quo during 2015–2030.
* The electricity demands of the city were projected based on India’s domestic growth in consumption published by the World Bank (2008).
* As no new power plants are proposed or allowed within the KMC area, only increased plant load factor (PLF) (up to 95% of present PLF range of 69–92%) have been considered for the existing units when projecting power generation. The deficit between power generation and power requirement will have to be met by importing power from outside the jurisdiction of KMC.

## Line source

* The total active fleet was estimated from the observed number of on-road vehicles per hour, considering an average vehicular speed of 17 km/hr, which gives the vehicular density per km of road length.
* This vehicular density was projected based on the total length of roads in the KMC to derive the total active fleet of the city. For future projection of the active fleet of the city under the BAU scenario, the vehicular density was projected using the 2005–2015 trend.
* It was assumed that the road length will increase at a rate of 1% per year with ~1% decrease in average vehicular speed due to increasing population and fleet volume (from 17k/hr in 2015 to 14km/hr in 2030).
* It was assumed that the fleet distribution will remain unchanged in the BAU scenario.
* The 2-stroke to 4-stroke engine ratio for 2-wheelers for the year 2010 was assumed as 1:4 based on a parking lot survey carried out in 2015 as part of this study. The same survey, while repeated in 2017, showed that the ratio had shifted considerably toward 4-stroke engines. It was assumed that all 2-stroke engines will be replaced by 4-stroke engines by 2025.
* With a proposed shift from diesel to CNG, it was assumed that 50% of diesel use for buses will be shifted to compressed natural gas (CNG) by the end of 2030, starting from 10% in the year 2020.
* As per BS-IV norms, sulfur content in diesel is restricted to 50 ppm from 2010.
* All new CNG buses in use from 2020 are assumed to be BS-VI–compliant.
* The ratio of domestic and international flight at Kolkata airport were projected based on AERAI 2012.

## Existing control strategies and future projection

* ESP efficiency in power plants were reported to be 99.4– 99.9% with an average of 99.6% as per official communication with individual power plants. It is assumed that all power plants were under ESP-II control in 2010–2030.
* It is proposed that existing power plants should be fitted with flue gas desulphurization (FGD) units within next few years owing to stricter emission norms for control of SO2 emission. As no FGDs have yet been fitted, no control of SO2 is assumed until 2015. It is assumed that 50% of emissions will be subject to FGD unit control by 2020 and 100% by 2025.
* WBPCB has proposed a control on the use of firewood in bakeries within the KMC. This was also taken into account in the projections for the domestic commercial sector from 2020 onward.
* In the industrial sector, proper documentation on control strategies could not be obtained. It has thus been assumed that
  + 10% of PM emissions are controlled by bag filter in each industrial sector
  + 10% of SO2 emission are controlled by wet scrubber
* There is no specific notification regarding any drive for implementation of control strategies in the industrial sector in addition to present regulations. Therefore, the same control is projected from 2010–2030.
* In the KMC, of the electric crematorium constructed in 22 municipalities, 13 have in built air pollution control devices (WBPCB press release). The remaining nine municipalities with electric crematoria have no air pollution control device. Accordingly, control was considered for fuel use under this sector for 2010–2030.
* The phasing out is reflected in the total number of registered vehicles. However, the primary survey done in 2013–2014 under this project indicated that older vehicles (registered before 1998) were still on the road.
* The control technology effective in line source was estimated based on primary survey in 2013-14 undertaken in parking lot and petrol pumps.
* In accordance with government regulations, both gasoline and diesel fuel used in the road transport sector should emit <10 ppm sulfur from 2020. We assumed 60% implementation of the regulations by 2020 and 100% by 2025.

# **Policy consideration under different alternate scenarios.**

**Table S3. Policy consideration toward control air pollutants and GHG emissions in all policy scenarios for Kolkata City**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sector** | **City specific policies (CSPs) in BAU scenario** | **Alternative Scenarios** | | |
| **ACT scenario** | **LCI scenario** | **CAS scenario** |
| Power plants | Particulate emission control with high- efficiency technology (ESP) in coal-based thermal power plants (as applicable) | Particulate emission control with high-efficiency technology (ESP) in coal-based thermal power plants (as applicable) | Fuel switching for all thermal power plant (from coal-based to gas-based) by 2030 | Same as ACT |
| SO2 emission control (with Flue Gas Desulfurization technology) in power plants initiated from 2020, fully implemented by 2030 | SO2 emission control (with Flue Gas Desulfurization technology) in power plants within 2020 (as applicable) | Not applicable | Same as ACT |
| No specific policies regarding NOx control technology at power plants | Combustion modification and selective catalytic reduction on existing coal-based thermal power plants for NOx control (as applicable) | Appropriate control technology for NOx | Same as ACT |
| Industries | No new air-polluting industries allowed. Closing of highly polluting industries within city limits but continuing with fewer polluting industries | Same as CSPs. Use of control equipment as applicable | Switching fuel in industrial sector from LDO/diesel/ fuel wood to Natural Gas, Use of control equipment same as CSPs | Same as LCI |
| Allowing non-polluting industries | Same as CSPs | Same as CSPs | Same as CSPs |
| Transport | For heavy vehicles BS-VI measures, from 2020 cancellation of registration of vehicle more than 15 years old\* | Same as CSPs | Same as CSPs | BAN on vehicles less than BS-IV from 2020 over and above CSPs |
| Introduction of BS-III measures in 2-W and 3-W from 2010; registration cancellation for vehicle more than 15 years old\*; BS-VI measures from 2020 for new registrations | Same as CSPs | Same as CSPs |
| Introduction of BS-IV measures from 2010; registration cancellation for vehicle more than 15 years old\*; BS-VI from 2020 for four wheelers | Same as CSPs | Same as CSPs |
| No restriction in number of vehicles in active fleet | No restriction | No restriction | Restriction for 2-W and 4-W car in active fleet (up to 50% by 2030 of CSP scenario) with shift toward public transport (BS-VI compliant buses) |
| Fuel switch and Fuel quality in transport sector | Use of low sulfur diesel and shifting from diesel to CNG of public transport buses in Kolkata (50% by 2030) | Same as CSPs with use of ultra-low sulfur fuel for both diesel and petrol (<10ppm) from 2020 | Same as CSP | Same as ACT |
| Residential/ Commercial | Switch toward LPG from biomass fuel via national policy i.e., Pradhan Mantri Ujjwala Yojna (PMUY). No city-specific policy | Switch over from traditional to advanced cookstoves | Faster switch from solid fuels /kerosene to clean fuels (LPG, NG, or electricity) over and above CSP | Faster switch from solid fuels/kerosene to clean fuels (LPG, NG, or electricity) by 2030; ban on firewood from 2020. 10% coal combustion remains for tandoor activity with advanced cookstove in residential/ commercial sector |
| Crematorium | No specific policy | No specific policy | Complete switch from wood to electricity | Complete switch from  wood to electricity |
| Waste | Ban on open burning of household waste | Same as CSPs but with strict compliance | Same as CSPs but with strict compliance | Same as CSPs but with strict compliance |
| Road dust | No specific policy | No specific policy | No specific policy | Road paving, water sprinkling/ cleaning of roads |
| Construction | No specific policy | Use of spray in 50–80% activity between 2020 to 2030 | Same as CSP | Use of water spray in 100% activity by 2030 |
| Other/fugitive | No specific policy | Implementation of best management practices where applicable | Same as CSP | Same as ACT |
| \*It is assumed that a fraction of active vehicular fleet are older than 15 years and are registered outside the city. | | | | |

# **Comparison of 2015 emissions inventory**

Few studies on air quality have been conducted in Kolkata city during the past two decades. Very few reported studies deal with emission inventories for air pollutants for the KMC. Table S4 presents a comparison of our results regarding pollutant emissions from different sectors with previously reported studies. Sharma et al. (2002) report 0.55 kt of “particulate” emissions for the year 1990 using a rather simplistic approach, based on per capita pollutant emissions in the transport sector only. The total PM10 reported in ADB (2005) for the city is 76 kt for 2003 which is 32% higher than estimated in this study for 2015. ADB (2005) indicated road dust as a major contributing source (60%) followed by the transport sector (22%) and industrial emissions (9%) for the year 2003. The projected PM10 emission of the city from all sources for 2014 was ~55 kt after implementation of controls proposed at that time. Interestingly, our study estimates of PM10 for 2015 came very close to the projected level, although the percentage source contribution for various sources varies considerably. Gurjar et al. (2010) estimated 11 kt and 9 kt of total suspended particulate matter in the year 2000 and 2010 from vehicular exhaust emissions only. The reduction is attributed to the phasing-out of older vehicles. Vehicular emissions are identified as the dominant source of PM2.5 (derived from the PM10 inventory) with a 49% contribution, followed by industrial emissions (17%) (ADB, 2005). Particulate emissions from the transport sector have been estimated at 4.6 ton/day (1.7 kt /year) for Kolkata city (187 km2) for the year 2011 by CPCB (2015b) somewhat comparable with our estimated 2.5 kt emission from the KMC (1887 km2).

Sharma et al. (2002) report 2.73 kt of NOx from the transport sector only in 1990. In 2003, NOx emissions from various activities in Kolkata were 130 kt, with a major contribution from motor vehicles (95 kt) and power plants (32 kt) (ADB, 2005). Our NOx emissions from power plants, 50 kt in 2010, corroborate these well, considering the increasing power demand between 2003 and 2010. The projected NOx level reported in ADB (2005) is 237.5 kt for 2014. The introduction of BS-II from 2001 for newly registered vehicles (refer to section 5 of the Supplementary information) and the policy decision of banning vehicles older than 15 years in 2009 may have reduced the actual NOx emissions from transport sector after 2009. The banning of older vehicle may have had a two-fold effect on NOx and on particulate matter emissions: first, by reducing uncontrolled NOx from older vehicles without any control system; second, by reducing the total fleet volume temporarily by the year 2010. Gurjar et al. (2010) estimated 81 kt of NOx emissions the transport sector in the year 2010 but only where they have assumed phasing out of vehicles older than 25 years during the 2000–2010 period - based on a larger fleet volume than was used for our estimation based on active fleet volume. Our estimated total NOx emission is 78 kt for 2010 in Kolkata city and 22 kt from the transport sector, which is much less than Gurjar et al. (2010). In fact, vehicles older than 15 years were banned suddenly in 2009. In practical terms, the ban may have taken some time to implement; however, the reduction of pollutant emissions especially, NOx, may have been more effective than slowly phasing them out during the last ten years (2000-2010). The transport sector within the city limits is estimated to emit NOx at the rate of 44.3 ton/day (16.1 kt/year) in 2011 (CPCB 2015b). Our study estimates 21.9 kt of NOx emissions for 2010 from transport exhaust for the KMC area, which is comparable considering the wider area considered under KMC compared to Kolkata city.

**Table S4. Air pollutants and GHG emission in Kolkata city.**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Reference** | **Air pollutants (kt)** | | | | | | | | | **GHG emissions (kt)** | | | **Year** | **Study domain (Area-km2)** | **Population (in millions)** | **Remarks** |
| **SO2** | **NOx** | **PM10/TSPα** | **PM2.5** | **BC** | **OC** | **CO** | **VOC** | **NH3** | **CO2** | **CH4** | **N2O** |
| Present study | 76.5 | 77.9 | 58.6 | 29.4 | 7.7 | 7.2 | 78.7 | 35.9 | 24.8 | 20.3 | 74.8 | 25.2 | 2015 | KMC (1887) | 14.9 |  |
| Sharma et al. (2002) | NA | 2.73 | 0.55α | - | 2.18 | - | 17.77 | - | - | - | - | - | 1995 | KMC (not mentioned) | 10.90 | The study used the per capita emissions approach. The details of estimation of per capita emissions are not mentioned. “Particulate” may be called (TSP) α |
| NA | 3.20 | 0.59α | - | 2.49 |  | 21.70 | - | - | - | - | - | 11.86 |
| Guttikunda et. al. (2003) | 64.6γ | - | - | - | - | - | - | - | - | - | - | - | 2000 | 1°x1° grid cell covering the city limitsγ | 32γ | Modeled using RAINS-Asia model |
| 200.7γ | - | - | - | - | - | - | - | - | - | - | - | 2010 |
| ADB (2005) | 12.38 | 129.7 | 75.14 | - | - | - | - | - | - | - | - | - | 2003 | KMC (1246) | 13.7 | This study considered motor vehicle, industry, road dust, area sources for PM10 and PM2.5. For NOx, power plant, industry, and mobile sources are considered, whereas for SO2 only power plants are considered. |
| Gurjar et al. (2010) | 21 | 81 | 9α | - | - | - | 111 | 74β | - | 4.51 | - | - | 2010 | Kolkata megacity (not mentioned) | Not mentioned | The study estimates air pollution emissions only from the vehicular sector. Emissions correspond to the scenario where vehicles older than 25 years have been phased out during 2000–2010 |
| Srivastava and Majumdar (2010) | - | - | - | - | - | - | - | 0.12 | - | - | - | - | 2004 | Kolkata city (187) | 4.58 | Estimation is for evaporative emissions only. |
| Sahu et al. (2008) | - | - | - | - | 3.3 – 7.2φ | - | - | - | - | - | - | - | 2001 | 1°x1° grid cell covering the city limitsγ | Not mentioned | The study presents a contour map of BC emissions for India. BC emissions normalized for the KMC area are presented. |
| CPCB (2015b) | 0.1 | 16.1 | 1.7 | - | - | - | 21.8 | - | - | 1.87 | - | - | 2011 | Kolkata city (187) | 4.5 | This study only considers road transport exhaust emission within the city boundary. |

αTSP: Total suspended particulates, βEstimated from Graph (Gurjar et al., 2010)., γCorresponding to area of 11.4x103 sq. km. δ Normalized for KMC area. φEstimated from concentration contour plot and normalized for KMC area

The SO2 emissions from power plants in 2000 were estimated at 64.6 kt by Guttikunda et. al. (2003). Although Guttikunda et. al. (2003) estimated the emissions for population of entire 32 million residing in the 1° x 1° area (approximately 11.4 x103 km2) in which the 1887 km2 Kolkata metropolitan city is situated. Guttikunda et. al. (2003) projected SO2 emissions for 2010 as 200.7 kt, which is much higher than in our estimated SO2 emissions for 2015. Guttikunda et al. (2003) considered all sources operating outside the KMC boundary but within the study domain, which is not considered in our estimates; that may have resulted in a higher estimate than in the present study. Gurjar et al. (2010) estimated 21 kt of SO2 emissions in 2010 from the transport sector which is much higher than in this study. As Gurjar et al. (2010) projected 2010 emissions based on 2000 and 2005 data, the effect of banning of old vehicles in 2009 may not been considered, resulting in a higher estimate than ours. Moreover, low sulfur fuel with <0.05 ppm (both diesel and gasoline) was made available from January 2001, far earlier than in other states (APR, 2015). For 2011, however, the SO2 emissions from transport sector are estimated to be only 0.15 ton/day (54.8 ton/year) within the city limits (CPCB, 2015b). Srivastava and Majumdar (2010) reported only evaporative emission of VOCs for Kolkata city along with other metro cities of India.

For comparison, there are very limited studies on emission inventories of air pollutants in Kolkata. Most of the studies reported estimates for a base year prior to 2005, and those studies mainly targeted vehicular emissions, power plant, and industrial emissions as major contributors. The studies also did not account for certain emission sources such as emissions from the residential, commercial, construction, and waste sector, which emerge as significant contributors as of 2015. Several regulations and policies have been adopted for the city since 2000 (see: section 5 above). It is thus difficult to compare the present estimates consistently with earlier findings.

# **Air pollutant and GHG emissions projected for Kolkata in 2030**

**Table S5: Estimated sector wise emissions under policy scenarios in 2030 (in kt)**

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Air Pollutant/ GHG | Scenarios | Power Plants | Domestic Combustion | Industrial emission | Road Transport (exhaust) | Road Transport (non-exhaust) | Waste and open burning | Construction | Agriculture | Non-road machinery | Fuel conversion | Solvent use | Fuel production & distribution | Non-energy use | Total emission |
| **PM10** | **BAU** | 12.2 | 11.8 | 3.7 | 2.4 | 40.5 | 3.9 | 7.6 | 1.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | **83.7** |
|  | **ACT** | 1.4 | 4.6 | 1.0 | 2.4 | 40.5 | 3.6 | 6.4 | 1.3 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | **61.6** |
|  | **LCI** | 0.0 | 1.6 | 3.6 | 2.4 | 40.5 | 3.9 | 7.6 | 1.3 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | **61.4** |
|  | **CAS** | 1.4 | 0.8 | 1.0 | 1.9 | 38.2 | 3.0 | 6.1 | 1.3 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | **54.1** |
| **PM2.5** | **BAU** | 6.5 | 6.9 | 1.3 | 2.3 | 6.2 | 3.9 | 0.8 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | **28.6** |
|  | **ACT** | 1.1 | 3.8 | 0.3 | 2.3 | 6.2 | 3.6 | 0.7 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | **18.7** |
|  | **LCI** | 0.0 | 1.1 | 1.3 | 2.3 | 6.2 | 3.9 | 0.8 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | **16.3** |
|  | **CAS** | 1.1 | 0.7 | 0.3 | 1.8 | 5.8 | 3.0 | 0.7 | 0.3 | 0.4 | 0.0 | 0.0 | 0.0 | 0.0 | **14.1** |
| **BC** | **BAU** | 0.0 | 1.3 | 0.0 | 0.9 | 0.9 | 0.4 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | **3.6** |
|  | **ACT** | 0.0 | 1.2 | 0.0 | 0.9 | 0.9 | 0.3 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | **3.6** |
|  | **LCI** | 0.0 | 0.2 | 0.0 | 0.9 | 0.9 | 0.4 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | **2.5** |
|  | **CAS** | 0.0 | 0.0 | 0.0 | 0.5 | 0.8 | 0.3 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | **1.8** |
| **OC** | **BAU** | 0.0 | 0.3 | 0.0 | 1.1 | 4.2 | 1.7 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **7.4** |
|  | **ACT** | 0.0 | 0.2 | 0.0 | 1.1 | 4.2 | 1.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **7.1** |
|  | **LCI** | 0.0 | 0.0 | 0.0 | 1.1 | 4.2 | 1.7 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **7.1** |
|  | **CAS** | 0.0 | 0.0 | 0.0 | 1.0 | 4.0 | 1.2 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | **6.3** |
| **SO2** | **BAU** | 9.6 | 0.9 | 3.4 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **13.9** |
|  | **ACT** | 9.7 | 0.9 | 0.7 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **11.3** |
|  | **LCI** | 0.2 | 0.1 | 1.2 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **1.6** |
|  | **CAS** | 9.7 | 0.1 | 0.3 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **10.1** |
| **NOx** | **BAU** | 60.7 | 3.2 | 0.7 | 37.2 | 0.0 | 0.0 | 0.0 | 0.0 | 4.4 | 0.4 | 0.0 | 0.0 | 0.0 | **106.7** |
|  | **ACT** | 14.1 | 2.3 | 0.3 | 37.2 | 0.0 | 0.0 | 0.0 | 0.0 | 4.4 | 0.0 | 0.0 | 0.0 | 0.0 | **58.3** |
|  | **LCI** | 4.4 | 3.2 | 0.8 | 37.2 | 0.0 | 0.0 | 0.0 | 0.0 | 4.4 | 0.4 | 0.0 | 0.0 | 0.0 | **50.4** |
|  | **CAS** | 14.1 | 2.3 | 0.3 | 27.9 | 0.0 | 0.0 | 0.0 | 0.0 | 4.4 | 0.0 | 0.0 | 0.0 | 0.0 | **49.0** |
| **CO** | **BAU** | 3.3 | 5.6 | 0.2 | 43.1 | 0.0 | 9.9 | 0.0 | 0.0 | 1.5 | 0.1 | 0.0 | 0.0 | 0.0 | **63.6** |
|  | **ACT** | 3.0 | 5.2 | 0.2 | 43.1 | 0.0 | 8.5 | 0.0 | 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | **61.6** |
|  | **LCI** | 2.3 | 2.2 | 0.1 | 43.1 | 0.0 | 9.9 | 0.0 | 0.0 | 1.5 | 0.1 | 0.0 | 0.0 | 0.0 | **59.3** |
|  | **CAS** | 3.0 | 1.9 | 0.1 | 34.9 | 0.0 | 8.5 | 0.0 | 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | **49.9** |
| **VOC** | **BAU** | 2.3 | 0.6 | 0.0 | 29.7 | 0.0 | 0.3 | 0.0 | 0.0 | 0.9 | 0.0 | 11.3 | 9.4 | 0.0 | **54.7** |
|  | **ACT** | 2.3 | 0.6 | 0.0 | 29.7 | 0.0 | 0.1 | 0.0 | 0.0 | 0.9 | 0.0 | 11.3 | 7.2 | 0.0 | **52.1** |
|  | **LCI** | 0.6 | 0.2 | 0.0 | 29.7 | 0.0 | 0.3 | 0.0 | 0.0 | 0.9 | 0.0 | 11.3 | 9.3 | 0.0 | **52.4** |
|  | **CAS** | 2.3 | 0.1 | 0.0 | 28.8 | 0.0 | 0.1 | 0.0 | 0.0 | 0.9 | 0.0 | 11.3 | 7.0 | 0.0 | **50.6** |
| **NH3** | **BAU** | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 36.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **36.5** |
|  | **ACT** | 1.2 | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 31.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **33.3** |
|  | **LCI** | 0.4 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 36.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **36.9** |
|  | **CAS** | 1.2 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 31.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | **33.3** |
| **CO2\*** | **BAU** | 18.5 | 3.1 | 0.2 | 7.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.7 | 0.0 | 0.0 | 0.3 | **31.2** |
|  | **ACT** | 18.5 | 3.1 | 0.2 | 7.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | **30.2** |
|  | **LCI** | 11.0 | 3.0 | 0.2 | 7.6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.7 | 0.0 | 0.0 | 0.3 | **23.7** |
|  | **CAS** | 18.5 | 3.0 | 0.2 | 6.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.0 | 0.0 | 0.0 | 0.0 | **28.9** |
| **CH4** | **BAU** | 0.0 | 0.2 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | 39.0 | 2.7 | 0.0 | 0.0 | 0.0 | 0.0 | **42.1** |
|  | **ACT** | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | 39.0 | 2.7 | 0.0 | 0.0 | 0.0 | 0.0 | **42.1** |
|  | **LCI** | 0.0 | 0.1 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | 39.0 | 2.7 | 0.0 | 0.0 | 0.0 | 0.0 | **42.0** |
|  | **CAS** | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.2 | 0.0 | 39.0 | 2.7 | 0.0 | 0.0 | 0.0 | 0.0 | **42.0** |
| **N2O** | **BAU** | 0.3 | 0.0 | 0.0 | 0.4 | 0.0 | 2.0 | 0.0 | 93.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | **96.3** |
|  | **ACT** | 3.3 | 0.0 | 0.0 | 0.4 | 0.0 | 2.0 | 0.0 | 93.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | **99.3** |
|  | **LCI** | 0.0 | 0.0 | 0.0 | 0.4 | 0.0 | 2.0 | 0.0 | 93.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | **96.0** |
|  | **CAS** | 3.3 | 0.0 | 0.0 | 0.3 | 0.0 | 2.0 | 0.0 | 93.5 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | **99.3** |

\* in Mt

# **Cost**

The primary goal of the cost evaluation in the GAINS model was to quantify the values to society of diverting resources to reduce emissions. There are three major points with respect to abatement-cost calculation in the GAINS model (Amann et al., 2011; Höglund-Isaksson et al., 2012). First, the process of approximating these values is achieved by estimating abatement costs at production level rather than at the consumer price level. Thus, as highlighted by Klimont et al (2002), the cost estimation processes ignore mark-ups charged on production costs by manufacturers or dealers, and any taxes added to production costs. These decisions are based on the rationale that mark-ups charged and taxes added are not representative of actual resource use costs. Second , the process does not consider issues of competitiveness or redistribution of income associated with abatement actions. Third, GAINS cost calculation works on the assumption of a free international market for abatement equipment that is accessible to all countries under the same conditions. For each of the emission control options, GAINS estimates their costs of local application considering annualized investments, fixed and variable operating costs, and how they depend on technology, country and activity type. Thus the abatement controls defined in the model are available (if not necessarily applicable) to all countries in the system. A final point to note is that all costs are generally expressed in constant € values of a given year (e.g., 2000, 2005). On a more specific level, the handling of cost combines information that is both “country-specific” and “common.” The exact manner in which cost is estimated, however, is determined to some extent by the sector and the combination of pollutants being studied. Further information is available at <https://www.iiasa.ac.at/web/home/research/researchPrograms/air/IR-98-035.pdf>

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