Atmospheric emissions and pollution from the coal-fired thermal power plants in India

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HIGHLIGHTS

• Review of emission factors and emissions analysis for coal-fired power plants.
• Review of environmental regulations for air pollution from coal-fired power plants.
• Particulate pollution analysis via CAMx dispersion model.
• Health impacts of particulate pollution from coal-fired power plants.

ABSTRACT

In India, of the 210 GW electricity generation capacity, 66% is derived from coal, with planned additions of 76 GW and 93 GW during the 12th and the 13th five year plans, respectively. Atmospheric emissions from the coal-fired power plants are responsible for a large burden on human health. In 2010–11, 111 plants with an installed capacity of 121 GW, consumed 503 million tons of coal, and generated an estimated 580 ktons of particulates with diameter less than 2.5 μm (PM2.5), 2100 ktons of sulfur dioxides, 2000 ktons of nitrogen oxides, 1100 ktons of carbon monoxide, 100 ktons of volatile organic compounds, and 665 million tons of carbon dioxide. These emissions resulted in an estimated 80,000 to 115,000 premature deaths and 20.0 million asthma cases from exposure to PM2.5 pollution, which cost the public and the government an estimated INR 16,000 to 23,000 crores (USD 3.2 to 4.6 billion). The emissions were estimated for the individual plants and the atmospheric modeling was conducted using CAMx chemical transport model, coupled with plume rise functions and hourly meteorology. The analysis shows that aggressive pollution control regulations such as mandating flue gas desulfurization, introduction and tightening of emission standards for all criteria pollutants, and updating procedures for environmental impact assessments, are imperative for regional clean air and to reduce health impacts. For example, a mandate for installation of flue gas desulfurization systems for the operational 111 plants could reduce the PM2.5 concentrations by 30–40% by eliminating the formation of the secondary sulfates and nitrates.

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1. Introduction

India, at 210 GW, has the 5th largest electricity generation sector in the world (with captive power plants generating 31 GW more), with targets of additional 76 GW in the 12th five year plan (2012–2017) and another 93 GW in the 13th five year plan (Prayas, 2011, 2013). Thermal power plants account for 66% of generation, hydro for 19% and others (including nuclear energy) for 15%. In India, coal is the primary fuel of choice and accounts for 50–55% of the power generation and will only get larger in the coming years (Chikkatur et al., 2011; WISE, 2012; Prayas, 2013).

In India, the supply of electricity lags behind the demand. According to the Central Electricity Authority (CEA), in 2010–11, of the 122 GW peak demand, only 110 GW was supplied — which amounted to a shortfall of 10% (CEA, 2012). A third of the population that lives in rural India does not have access to electricity. Even those with access in urban India have to endure frequent power
cuts and load shedding, which results in use of in-situ diesel generator sets (Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013).

Coal-fired power generation comes with significant costs to environment and human health. The water runoff from coal washeries carries pollution loads of heavy metals that contaminate ground water, rivers, and lakes — thus affecting aquatic flora and fauna (Finkelman, 2007). Fly-ash residue and pollutants contaminate soil and are especially harmful to agricultural activities. Most importantly for human health, combustion of coal releases emissions of sulfur dioxide (SO₂), nitrogen oxides (NOₓ), particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOCs), and various trace metals like mercury, into the air through stacks that can disperse this pollution over large areas. The 2010 global burden of disease (GBD) study listed the outdoor air pollution (PM and ozone pollution) among the top 10 health risks in India, with as estimated 695,000 annual premature deaths from respiratory illnesses, compromised immune systems, and cardiovascular conditions (IHME, 2013). The known sources of outdoor air pollution in India include emissions from power plants, manufacturing industries, vehicle exhaust, cooking and heating in the households, generator sets, nature dust, on-road dust resuspension, garbage burning, and seasonal agricultural burning.

Previously, the studies on power plants in India focused on coal usage trends, resource management, greenhouse gas emissions, and innovation in use of renewable energy (Chikkatur and Sagar, 2009; Chikkatur et al., 2011; Prayas, 2011; Chaudhary et al., 2012; Ghose, 2012; WISE, 2012; Prayas, 2013) and total emissions inventories for base year 2005 or older (Streets et al., 2003; Reddy et al., 2005; Ohara et al., 2007; GAINS, 2012). Of the estimated annual anthropogenic emissions in India, the thermal power plants account for ~15% for PM₂.₅, ~30% for NOₓ, and ~50% of SO₂ (GAINS, 2012). Studies based on satellite measurements (Lu and Streets, 2012; Prasad et al., 2012) looked at the influence of power plant emissions on the column NOₓ concentrations, including the influences of other sources, but there is limited bottom-up analysis on dispersion of emissions from the coal-fired power plants.

Given the plans to greatly expand the contribution of coal to the Indian power sector (Chikkatur et al., 2011; WISE, 2012; Prayas, 2013), it is vital that decision makers understand the hidden costs of air pollution from power plants. In this paper, we present an updated list of operational coal-fired power plants in India, their generation capacities, coal consumption rates, and evaluation of the health impacts of their pollution via dispersion modeling. We also discuss the current environmental regulations for power plants in India or their lack of.

2. Data and methods

2.1. Coal-fired power plants in India

The installed power generation capacity in India grew at an average annual rate of 8% in the 1970s and at 10% since the 1980s (WISE, 2012; Prayas, 2013). The characteristics of operational coal-fired power plants in India are presented in Table 1 and the location of these plants is presented in Fig. 1. The database of plants documented by CEA was further updated with information from websites and annual reports of the state electricity boards and private electricity generation companies (CEA, 2011; CEA, 2012). The database includes geographical location in latitude and longitude, number of boiler units and size of all known power plants operated by both public and private entities.

<table>
<thead>
<tr>
<th>State</th>
<th>Number of plants</th>
<th>MW</th>
<th>Coal consumption (kg coal/kWh)</th>
<th>% Installed units &lt;210 MW</th>
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<td>56.0</td>
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<td>West Bengal</td>
<td>12</td>
<td>10,695</td>
<td>36.1</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>111</strong></td>
<td><strong>120,727</strong></td>
<td><strong>503</strong></td>
<td><strong>0.73 ± 0.10</strong></td>
</tr>
</tbody>
</table>

Table 1 Summary of annual coal consumption at the power plants in India in 2010–11.

Chhattisgarh, West Bengal, Bihar, Jharkhand, and Orissa. Some large power plants are located on the coast, for the availability of cooling water from the sea and ease of importing coal. While the coastal winds are beneficial in some cases, the impacts are still at large for cities in the vicinity. For example, Chennai (Tamilnadu) and Ahmedabad (Gujarat), each host two coal-fired power plants of more than 1000 MW electricity generation and located closer to the city premises. Chennai, being a coastal city, records a smaller fraction of the power plant emissions in their ambient measurements, compared to Ahmedabad, which is in-land (Guttikunda and Jawahar, 2012). In Delhi, up to 8% of the ambient PM pollution can be attributed to the coal-fired power plants of 2000 MW, operated within 60 km from the city center (Guttikunda and Goel, 2013). Similar shares are expected for the cities of Mumbai, Ahmedabad, Kolkata, and some medium to smaller size cities like Nagpur, Raipur, Ranchi, Kota, Bhathinda, Raichur, with power plants in the vicinity of 100 km.

2.2. Coal characteristics

Indian coal (Gondwana coal) has high ash content (35—45%) and low calorific value (averaging 3820 kcal/kg in 2003–04 and 3603 kcal/kg in 2010–11). The sulfur content in Indian coals is less than those observed in the United States (1.0—1.8%) and Chinese coals (0.5—1.0%). The sulfur content in the Indian coal has a consumption-weighted average of 0.6% (Reddy and Venkataraman, 2002).

The high ash content and low calorific value affects the thermal power plant’s operational efficiency and increases emissions per kWh generated. As a comparison, power plants in India use about 0.72 ± 0.10 kg of coal to generate 1 kWh, while a power plant in the USA of the same technology would consume 0.45 kg of coal per kWh (Chikkatur, 2008). The estimated annual coal consumption rates by state are listed in Table 1. The average thermal efficiency of the coal-fired power plants in India between 2004 and 2011 remained 32—33% (CEA, 2012) while this is peaking above 35% for the power plants in China (Seligsohn et al., 2009).

The high silica and alumina content in Indian coal ash is another problem, as it increases ash resistivity and reduces the collection efficiency at the electrostatic precipitators (ESPs). To address this issue, the government has mandated the use of coal whose ash content has been reduced to at least 34% in power plants in urban, ecologically sensitive, and other critically polluted areas. The
compliance with this mandate has been uncertain due to lack of access to the continuous monitoring data from the stacks.

Coal obtained from opencast mines has greater ash content — much of India’s coal is mined using open-cast methods and is likely to continue as such. In 2005, about 110 MT of coal ash was generated in India from more than 70 thermal power plants. Estimates for 2012 put this at 170 MT per annum (Bhangare et al., 2011).

2.3. Chemical transport dispersion model

Atmospheric dispersion modeling was conducted to study the impact of the emissions from the coal-fired power plants on the ambient PM concentrations and their health impacts. The modeling schematics are presented in the Supplementary Material. We utilized the ENVIRON—Comprehensive Air Quality Model with Extensions (CAMx), an Eulerian photochemical dispersion model, suitable for integrated assessments of gaseous and particulate air pollution over many scales ranging from sub-urban to continental. The model formulation, advection and scavenging schematics, chemical solvers, and gas-to-aerosol conversion mechanisms, are detailed in the model manual (http://www.camx.com). The model utilizes full gas phase SAPRC chemical mechanism (Carter et al., 2000) (217 reactions and 114 species) with two mode coarse/fine PM fractions including gas to aerosol conversions, for SO$_2$ to sulfates, NO$_x$ to nitrates, and VOCs to secondary organic aerosols (SOA). The removal processes include dry deposition schemes using an updated approach with 26 landuse patterns and wet deposition due to predominant meteorological conditions. The most important advantage of CAMx is the use of 3D meteorology and independently controlled plume rise and emission release point for each power plant, according to the stability profile at the plants location (Turner et al., 1986).

There are other atmospheric dispersion models, equally capable of carrying out this modeling exercise. The CAMx model was selected for its modular nature in characterizing and treating the plumes from point sources. Recent CAMx applications for similar modeling exercises include Huang et al. (2010) — an urban scale study to quantify the contributions of various sources to PM$_{10}$ pollution in Beijing, China; Sun et al. (2012) — a regional study to simulate the changes in ozone concentrations due to new NO$_x$ emission regulations in the power plants in Eastern USA; Emery et al. (2012) — a study on sources of background ozone concentrations over the USA and its policy implications; Wu et al. (2013) — a regional study evaluating the control policies for the sources of PM$_{2.5}$ in the Pearl River Delta region.

For the modeling domain, the meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) is derived from the National Center for Environmental Prediction (NCEP) (NCEP, 2012) global reanalysis database for the base year 2010–11 and processed through WRF 3.5 meteorological model at 1 h temporal resolution. An example animation for the wind speeds and wind directions at the surface level, mixing layer height, and precipitation fields, for one month are presented in the Supplementary Material. The initial conditions for the dispersion model were extracted from the MOZART global chemical transport model, for which an interface is available with the CAMx model. To further localize the initial conditions, the model was looped over each month for 10 days before starting the model calculations for the study analysis. The boundary conditions are also extracted from the MOZART global chemical transport model. After initializing the
model, the emissions from only the power plants were utilized in order to isolate the impacts of these emissions on the ambient concentrations. The study domain extends from 7° N to 39° N in latitudes and 37° E to 99° E in longitudes at 0.25° grid resolution (Fig. 1). The vertical resolution of the model extends to 12 km stretched over 23 layers, with the lowest layer designated at 50 m and six layers within 1 km to advance vertical advection closer to the ground level.

2.4. Health impacts

In India, the morbidity and mortality burden of outdoor air pollution, is particularly costly in terms of work days lost, lost productivity, and loss in terms of gross domestic product, approximately USD 23.4 billion and 1.7% of national GDP in 2009 (World-Bank, 2012). Since, most of the pollution related deaths occur within a year or two of exposure, reducing PM pollution from sources like transport and power plants has immediate benefits for health and national economy. The direct link between outdoor air pollution and human health has been extensively documented under the 2010 GBD study (IHME, 2013). Epidemiological studies conducted in India have consistently demonstrated higher rates of respiratory and cardiovascular diseases in populations exposed to PM, NOx, and ozone pollution (Chhabra et al., 2001; Pande et al., 2002; Gupta et al., 2007; Wong et al., 2008; CBHI, 2010; Siddique et al., 2010; Balakrishnan et al., 2013).

The total health risk for mortality is quantified using the following risk functions for various endpoints defined as

\[
\delta E = \sum_{i=1}^{\text{#grids}} \frac{(RR_i - 1)}{(RR_i)} \delta \text{POP}_i \times \text{IR}
\]  

(1)

\[RR_i = \exp(\beta \cdot \delta C_i)\]

(2)

The total health risk for morbidity is quantified using the following equation for various endpoints

\[
\delta E = \sum_{i=1}^{\text{#grids}} \beta \delta C_i \times \delta \text{POP}_i
\]  

(3)

where

- \(\delta E\) = number of estimated health effects (various end points for morbidity and mortality).
- \(\text{IR}\) = incidence rate of the mortality and morbidity endpoints. A total death incidence rate for India is set at 7.1 per 1000 inhabitants.
- \(\delta \text{POP}\) = the population exposed to the incremental concentration \(\delta C\) in grid \(i\); defined as the vulnerable population in each grid. The gridded population is estimated using GRUMP (2010) for the model resolution of 0.25°. The total population of 1.2 billion is adjusted to Census-India (2012) by state totals, with the urban centers accounting for 30% of the total.
- \(RR\) = relative risk for mortality and morbidity endpoints.
- \(\beta\) = the concentration–response function; which is defined as the change in number cases per unit change in concentrations per capita. For all-cause mortality in this study, the function is defined as 3.5% change in the mortality rate per 4 \(\mu\)g/m\(^3\) change in the PM\(_{2.5}\) concentrations (Hart et al., 2011). The uncertainties involved in the risk assessments are detailed in IHME (2013) for long term integrated exposures. The morbidity effects are calculated as cases of asthma attacks, chronic bronchitis, hospital admissions, and work days lost, for which the concentration–response functions are extracted from Abbey et al. (1995) and World-Bank (2012).

\[\delta C = \text{change in concentrations from the ambient standards in grid } i, \text{ an output from the CAMx dispersion model as the annual average PM}_{2.5}\text{ concentration due to the coal-fired power plant emissions.}\]

This methodology of relative risk and concentration–response function was applied for similar studies — IHME (2013) and Ostro (2004) for GBD assessments for 2010 and 2000 respectively; Bell et al. (2006) for health impacts of urban air pollution in the cities of Santiago, Mexico city, and Sao Paulo; GAINS (2012) for Asia and Europe regional studies evaluating the impacts in terms of life years lost due to baseline air pollution or benefits in life years saved due to future controls; Yim and Barrett (2012) for premature deaths in the United Kingdom caused by long-range transport of combustion emissions from the European Union; Cropper et al. (2012) for benefits of better environmental regulations in controlling pollution from coal fired power plants in India; Guttikunda and Jawahar (2012) for health impacts of urban air pollution in 2 large, 2 medium, and 2 small cities in India; Guttikunda and Goel (2013) for a megacity Delhi and its surrounding satellite cities.

3. Results and discussion

3.1. Atmospheric emissions

For 2010–11, the total estimated annual emissions are 580 ktons for PM\(_{2.5}\), 1200 ktons for PM\(_{10}\), 2100 ktons of SO\(_2\), 2000 ktons of NO\(_x\), 1100 ktons of CO, 100 ktons of VOCs and 665 million tons of carbon dioxide (CO\(_2\)). The total estimated emissions by state are presented in Table 2. The total emission rates are calculated based on the boiler size, coal consumption rates, and control equipment efficiencies, which is collected from thermal power plant performance reports (CEA, 2011; CEA, 2012). For the emissions input to the dispersion model, the annual emissions were further segregated by month, based on the coal-consumption data by month from the power plants. The diurnal cycle of the emissions was kept constant by month.

3.1.1. Emission factors

We summarized the regional emission factors for the coal based power plants in Table 3 in both tons/PJ and tons/h. The latter is for comparisons with any data available from the online monitoring. Previously published studies are regional estimates either for all of India and for all the power plants in Asia, and most are estimated for the base year 2000–05 and prior. A serious lack of monitoring data availability from the stacks, results in uncertainty estimates of emission factors. The overall uncertainty in the total emission estimates is ±20%, stemming from the variations in the information at the plant level on in-use coal characteristics, coal consumption rates, efficiencies in control operations, and emission factors.

3.1.2. Emission regulations

Comparative emission rates as gm/kWh for NO\(_2\), SO\(_2\), and PM\(_{2.5}\) is presented in IEA (2012) for France, Germany, Italy, United Kingdom, China, India, Russia, the United States, Canada, Japan, South Africa, and Australia (Supplementary Material). Under the current emission regulations, the emissions rates are the highest in Russia and India. China, the United States, the European Union (EU) and Australia have stronger regulations (Table 4). Even with 55% of the installed coal-based generation capacity, there is a conspicuous lack of regulations for SO\(_2\), NO\(_x\), and Mercury emissions. There is also no continuous and open emission monitoring data available at...
the plant level, which makes enforcement of what standards do exist, nearly non-existent.

3.1.3. Particulate emissions

The total PM emissions from the power plant stacks are regulated as concentrations and vary with boiler size. For example, for the plants with generation capacity more than 210 MW, the PM concentration limit is 150 mg/Nm³ and for the plants with generation capacity less than 210 MW, the limit is 350 mg/Nm³. These limits are much weaker compared to those practiced limits in Australia, China, USA, and EU. The limit for the smaller plants is 150 mg/Nm³, if they are located in an urban, ecologically sensitive, and other critically polluted areas.

Differential emission regulations also tend to result in use of control equipment with low efficiency and higher emissions. For example, the Kolghat power plant in West Bengal state has 6 units of 210 MW and the Raichur power plant in Karnataka state has 7 units of 210 MW, each with a total generation capacity of more than 1000 MW, are allowed to adhere to the lower emission standard, only because the individual boiler size is less than or equal to 210 MW.

PM is the only pollutant for which any pollution controls are widely applied. A schematic of a coal-fired power plant is presented in Fig. 2 that shows flue gas from the boilers at high temperature and velocity passing through heat exchangers to recycle the residual energy. This then enters the particulate control equipment (ESPs and cyclone bag filters) for removal of entrained ash. ESPs are installed in all coal-fired power plants in India. As removal efficiencies at ESPs are higher for coarse particles, most of the PM dispersing from the top of the stack is in the size range of respirable PM (10 μm or less). Lu et al. (2010) measured fractions of 50–60% PM2.5, and 50–95% PM10 in the total filterable PM in the flue gas at a 660 MW power plant. The PM in the flue gas also contains high concentrations of heavy metals such as arsenic, lead, cadmium, mercury, copper, and zinc, which not only contributes to potential health hazard than the bottom ash (Finkelman, 2007), but also increases the resistivity and reduces the ESPs collection efficiency to as low as 98%. Reddy et al. (2005) measured the chemical composition of the bottom ash, fly ash, and flue gas from a coal-fired power plant in the western India and estimated 1–7% of zinc, 2–7% of copper, 5–8% of manganese, 7–10% of cobalt, 12–18% of

Table 2
Total annual emissions (rounded) from coal based power plants in India in 2010–11.

<table>
<thead>
<tr>
<th>State</th>
<th>PM0.5 tons</th>
<th>PM10 tons</th>
<th>SO2 tons</th>
<th>NOx tons</th>
<th>CO tons</th>
<th>VOC tons</th>
<th>CO2 million tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andhra Pradesh</td>
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<td>2500</td>
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<td>7500</td>
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<td>2,100,000</td>
<td>2,000,000</td>
<td>1,100,000</td>
<td>100,000</td>
<td>665.4</td>
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Table 3
Regional emission factors database.

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<th>PM10</th>
<th>SO2</th>
<th>NOx</th>
<th>CO</th>
<th>VOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study*</td>
<td>2010–11</td>
<td>49–68</td>
<td>90–138</td>
<td>174–192</td>
<td>177–189</td>
<td>100</td>
<td>9</td>
</tr>
<tr>
<td>Streets et al. (2003)**</td>
<td>2000</td>
<td></td>
<td></td>
<td>400–762</td>
<td>219–562</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ohara et al. (2007)*****</td>
<td>2000</td>
<td>504</td>
<td>367</td>
<td>205</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garg et al. (2006)*****</td>
<td>2000</td>
<td>251</td>
<td>367</td>
<td>205</td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lu and Streets (2007)*****</td>
<td>1996–2006</td>
<td></td>
<td></td>
<td>177–410</td>
<td>0.5–2.0</td>
<td>0.05–0.2</td>
<td></td>
</tr>
<tr>
<td>This study*</td>
<td>2010–11</td>
<td>0.3–1.4</td>
<td>0.6–2.8</td>
<td>1.0–4.0</td>
<td>0.9–3.7</td>
<td>0.5–2.0</td>
<td>0.05–0.2</td>
</tr>
<tr>
<td>Kansal et al. (2009)*****</td>
<td>2004–05</td>
<td>0.7–1.1</td>
<td>4.0–5.0</td>
<td>1.2–1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Units: tons/PJ.
** Units: tons/h.
*** The range corresponds to the averages over the states.
**** Base line factors for various technologies without or limited controls, global program.
***** Base line factors with best available control technology for each pollutant, global program.
****** The emission factor segregation was for China, Japan, and Others in Asia.
******* Calculated as ratios of total emissions and coal consumption corresponding to the power sector, PM factor is for total suspended particulates.
******** The range corresponds to coal fired boilers with and without low NOx burner technology, by boiler size.
********* Range corresponds to the estimated average emission rate per plant in each state.
********** PM factor is for total suspended particulates, based on measurements at one station in Delhi per stack.
cadmium, 60–70% of selenium, 70–80% of mercury, and traces of arsenic, iron, lead, and chromium contained in the coal was emitted in the flue gas. Similar levels of entrainment were reported in an estimate of total trace metal emissions from coal-fired power plants in China (Chen et al., 2013).

Besides flue gas PM emissions, fugitive dust from coal-handling plants and ash ponds (after the disposal from the plants) is a problem. According to CEA, after the combustion and application of control equipment, ash collection at the power plants ranged 70–80% of the total ash in the coal (CEA, 2011; CEA, 2012). It is assumed that the remaining ash is dispersed from the stacks. In 2003, an amendment notification from MoEF mandated 25% of bottom ash in all brick kilns within 100 km radius of any coal based thermal power plant and all building construction within 100 km for any coal-fired thermal power plant to use 100% ash based bricks, blocks, and tiles. To date, percentage of ash utilized in the construction industry is low – approximately 13% used for brick manufacturing and other construction activities.

### 3.1.4. Gaseous emissions

There are no legally mandated emission standards for SO$_2$. Only a handful of coal-fired power plants operate flue gas desulfurization (FGD) units and among those to be commissioned through 2020, only 7 power plants are listed to have FGD (Prayas, 2011). The FGD systems could range from in furnace control via limestone injection, wet scrubbing of flue gas, to capturing SO$_2$ in the flue gas through industrial processes (Fig. 2). Presence of a FGD system further improves removal of PM.

In India, for SO$_2$, only the stack heights are mandated assuming that the emissions will be dispersed to farther distances and thus diluting the ambient concentrations. For example, MoEF requires all power plants with generation capacity more than 500 MW to

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### Table 4

Summary of emission standards for coal-fired power plants.

<table>
<thead>
<tr>
<th>Country</th>
<th>PM</th>
<th>SO$_2$</th>
<th>NO$_2$</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>India$^a$</td>
<td>350 mg/Nm$^3$ for &lt;210 MW</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>China$^b$</td>
<td>100 mg/Nm$^3$ for new</td>
<td>100 mg/Nm$^3$ for old</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Australia$^c$</td>
<td>None</td>
<td>800 mg/Nm$^3$ for 1997–2005</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>European Union$^d$</td>
<td>Pre-2003</td>
<td>Pre-2003</td>
<td>Pre-2003</td>
<td>In discussion based on USA standards</td>
</tr>
<tr>
<td>USA$^{ed}$</td>
<td>245 mg/Nm$^3$ for old</td>
<td>42 mg/Nm$^3$ for new</td>
<td>0.08 gm/MWh for lignite</td>
<td></td>
</tr>
<tr>
<td>USA$^{ef}$</td>
<td>640 gm/MWh</td>
<td>720 gm/MWh for old</td>
<td>0.01 gm/MWh for IGCC</td>
<td></td>
</tr>
</tbody>
</table>

---

$^a$ From Central Pollution Control Board (India) (http://cpcb.nic.in/Industry_Specific_Standards.php). Last accessed Feb 17th, 2013. Besides PM, only national ambient standards exist.


$^d$ Emission rates are translated to mg/Nm$^3$ based on assumed plant efficiency.

$^e$ In official units; for mercury this is based on 12 month rolling average.

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![Fig. 2. Simplified schematics of coal-fired power plant operations.](image-url)
build a stack of 275 m; those between 210 MW and 500 MW to build a stack of 220 m; and those with less than 210 MW to build a stack based on the estimated SO\textsubscript{2} emissions using a thumb rule of height = 14\(^\circ\)Q\(^{0.3}\) where Q is the estimated SO\textsubscript{2} emissions rate in kg/h. The stack heights for old power plants ranged between 150 m and 220 m.

Despite an estimated 30% of the total NO\textsubscript{x} emissions in India originating from power generation (Garg et al., 2006; GAINS, 2012), there are no regulations to control these emissions. Some of the new installations and extensions are equipped with low-NO\textsubscript{x} burners, with little details on their operational performance (Chikkatur et al., 2011).

### 3.1.5. Previous estimates

Few studies have reported emission rates and total emissions from the power plants in India. One national emissions inventory for the coal and gas based power plants is maintained by the GAINS program at the International Institute for Applied Systems Analysis (IIASA, Austria), which for the base year 2005, estimated total emissions of 490 ktons for PM\textsubscript{2.5}, 1900 ktons for SO\textsubscript{2}, 1300 ktons for NO\textsubscript{x}, 43 ktons of VOCs. A major difference between GAINS and this study is in the database of plants, which is updated for the new installations and extensions for the existing plants, and assumed control efficiencies. A database of coal characteristics, control efficiencies, and emission rates is available online (GAINS, 2012). Another global emissions inventory by specific sectors is EDGAR with estimates for base year 2008 (http://edgar.jrc.ec.europa.eu). Average emission factors for PM, SO\textsubscript{2}, NO\textsubscript{x}, CO, and BC for all combustion sectors for base year 2000 are presented in Streets et al. (2003).

The CEA also reports, as part of the power plants performance evaluation, the emissions for total suspended PM in mg/Nm\(^3\) (CEA, 2012). Since, these are not continuous measurements and mostly observed at select times during the year, it was difficult to either confirm or reject the estimates based on them. Kansal et al. (2009) studied the emissions from six coal and gas fired power plants in and around Delhi, based on the reported measurements, which tend to underestimate the contribution of power plant emissions to the region (Guttikunda and Goel, 2013). Similarly, based on intermittent measurements Cropper et al. (2012) estimated average emissions of 110 ktons/year for PM\textsubscript{2.5} from 92 coal fired power plants.

For NO\textsubscript{x}, Prasad et al. (2012) studied the influence of thermal power plants on tropospheric NO\textsubscript{2} column measurements from the ozone monitoring instrument (OMI) onboard aura satellite (http://aura.gsfc.nasa.gov) and also studied the algorithm to deduce ground level concentrations, which could reflect the power plant emissions. This study particularly highlights the cluster regions over the states of Delhi, Haryana, Indo-Gangetic plains, and most of central India with the highest concentrations possibly originating from the power plants. Lu and Streets (2012) also studied the satellite data and further estimated the emissions based on boiler size and coal consumed for the period between 1996 and 2010, which overlays the changes in satellite observations to the newer installations and extensions commissioned during this period. They estimated a 70% increase in the column NO\textsubscript{x} concentrations during this period, with the power plants contributing a total estimated 2300 ktons NO\textsubscript{x} emissions for 2010.

### 3.2. Atmospheric dispersion

#### 3.2.1. Ambient pollution

The atmospheric dispersion simulation was carried out for 11 days per month from 10th to 21st of each month and averaged to obtain monthly, seasonal, and annual concentrations. The modeled annual average PM\textsubscript{2.5} concentrations due to emissions from coal based power plants only are presented in Fig. 3.

![Fig. 3. Modeled annual average ambient PM\textsubscript{2.5} concentrations due to the emissions from coal-fired thermal power plants in India.](image-url)
daily average concentrations are presented in the Supplementary Material. The largest impact is felt over most of the central-east India including states of Maharashtra, Madhya Pradesh, Chhattisgarh, and Orissa, with the largest coal-fired power plants. Similar observations are reported based on satellite measurements of column NO2 concentrations (Lu and Streets, 2012; Prasad et al., 2012).

For PM2.5 concentrations in Fig. 3 includes fine PM, sulfur, and nitrate concentrations (from chemical conversion of SO2 and NOx emissions, using the predefined chemical mechanisms in CAMx). The concentrations are an incremental pollution from the coal-fired power plants only, which is considered in addition to the pollution from transport, domestic, and other industrial activities, on an annual basis. The population weighted concentration due to the coal-fired power plant emissions only is 3.6 μg/m3. The national ambient annual average standard for PM2.5 is 40 μg/m3 and the WHO guideline is 10 μg/m3.

The PM pollution in Central India, covering the states of Madhya Pradesh, Jharkhand, Orissa, and Chhattisgarh, is the highest due to the density of the power plants in the region and high installed generation capacity, due their proximity to the coal mines. The Delhi-Haryana region with the highest population density with more than 21.5 million inhabitants in Delhi and its satellite cities is exposed to higher PM pollution from coal-fired power plants. The range of modeled PM pollution in 7 sub-regions is presented in Table 5. The coastal regions experience the least of the PM pollution due to strong land-sea breezes, with much of the pollution dispersed over the seas. To date the inland power plants are still the majority in the country and a serious threat to human health and other environmental concerns.

- The Korba cluster (State: Chhattisgarh (CH)) has a combined generation capacity of 4380 MW between four power plants located within a 10 km radius. Major cities in the Korba region are Ranchi, Jamshedpur, Rourkela, Jabalpur, Nagpur, and Raipur (capital of Chhattisgarh).
- The Mundra cluster (State: Gujarat (GJ)) has a combined generation capacity of 9620 MW between two private sector power plants located within 5 km radius. Major cities in the Mundra region are Jamnagar (major industrial port), Rajkot, and Ahmedabad (300 km away, with two local power plants of 1000 MW).
- The Mumbai cluster (State: Maharashtra (MH)) has one coal based power plant in Trombay and multiple gas powered plants.

While the impact of the emissions is felt within 200 km of the power plants, under windy conditions the influence can be tracked to distances as far as 400 km from the source region. The animated forward trajectories over one day for the coal-fired power plants in Korba, Jhajjar, Mumbai, and Mundra clusters, for three months (April, July, and October), is presented in the Supplementary Material. The forward trajectories illustrate that the emissions from these high stacks affects the regions and people far away from the source region and this should be accounted for in the environmental impact assessments of the coal-fired power plants, which under the current regulations is limited to only 50 km radius, from the power plant stacks (MoEF, 2010).

3.2.2. Seasonal variations

Generally, the wind speeds at 200 m or above are much faster than those observed at the ground level. The release of the emissions at the stack height plus any uplift due to the flue gas velocity and temperature, dictates the movement of the emissions and its vertical diffusion towards the ground. The forward trajectories presented in the Supplementary Material for the select clusters, further demonstrates the fast movement of the power plant plumes

### Table 5

<table>
<thead>
<tr>
<th>No.</th>
<th>Cluster (size in degrees)</th>
<th>Regional features</th>
<th>No. of plants (those more than 1000 MW)</th>
<th>Installed capacity (MW)</th>
<th>Modeled PM2.5 - median (95th percentile) μg/m³</th>
<th>Estimated premature mortality within the region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Delhi – Haryana</td>
<td>Delhi is the national capital, listed among the top 10 cities with worst air quality in the world (WHO, 2011) and Haryana is an agricultural state</td>
<td>8 (5)</td>
<td>8080</td>
<td>3.9 (7.7)</td>
<td>6400–8800</td>
</tr>
<tr>
<td>2</td>
<td>Kutch (Gujarat)</td>
<td>A coastal cluster, with two super-critical power plants in Mundra (Gujarat), both private, operated by Tata and Adani power groups</td>
<td>5 (2)</td>
<td>9900</td>
<td>1.0 (2.8)</td>
<td>100–120</td>
</tr>
<tr>
<td>3</td>
<td>Western-MH</td>
<td>Including Mumbai, the most commercial and congested city in the country</td>
<td>3 (1)</td>
<td>2780</td>
<td>0.9 (2.3)</td>
<td>1700–2400</td>
</tr>
<tr>
<td>4</td>
<td>Eastern MH and Northern AP</td>
<td>All plants are located closer to the coal belts of Chandrapur and Ghagus (Maharashtra – MH) and Singareni (Andhra Pradesh – AP)</td>
<td>10 (6)</td>
<td>14,800</td>
<td>3.2 (5.1)</td>
<td>1100–1500</td>
</tr>
<tr>
<td>5</td>
<td>MP–CH–JH–OR</td>
<td>This cluster covers four states – Madhya Pradesh (MP), Jharkhand (JH), Chhattisgarh (CH) and Orissa (OR) and home to the largest coal fields of Jharia, Dhanbad, Korba, Singrauli, Karanpura, and Mahanadi</td>
<td>21 (10)</td>
<td>29,900</td>
<td>9.1 (23.1)</td>
<td>7900–11000</td>
</tr>
<tr>
<td>6</td>
<td>WB–JH–BH</td>
<td>This cluster covers West Bengal (WB), JH, and Bihar (BH) sourcing mostly from Raniganj and Jharia coal belts</td>
<td>19 (7)</td>
<td>17,100</td>
<td>3.7 (5.6)</td>
<td>10700–14900</td>
</tr>
<tr>
<td>7</td>
<td>Eastern AP</td>
<td>A coastal cluster including the port city of Vishakhapatnam</td>
<td>2 (2)</td>
<td>3000</td>
<td>0.8 (1.8)</td>
<td>1100–1500</td>
</tr>
</tbody>
</table>

a The PM2.5 concentrations are modeled grid averages and is the concentration due to the emissions from the coal-fired power plants only, which is incremental to pollution from other sources in the region. For these sub-regional domains, the CAMx dispersion modeling was repeated @ grid resolution of 0.1°, equivalent of 10 km. Median and 95th percentile value is based on averages for all the grids in the select sub-regional domain.

b This is the estimate for the exposed population in the select geographical sub-region, but the influence of the power plant emissions reaches farther (illustrated in the forward trajectories – Supplementary Material).
Fig. 4. Dispersion modeling results by season (Dec–Jan–Feb for winter; Mar–Apr–May for spring; Jun–Jul–Aug for summer; and Sep–Oct–Nov for fall) due to the emissions from coal fired thermal power plants in India (a) average PM$_{2.5}$ concentrations (b) percentage contribution of secondary (sulfates and nitrates) aerosols to average PM$_{2.5}$ concentrations by season.
in India. The meteorological conditions have a large variation in the subcontinent between the monsoonal and non-monsoonal months. This variation also affects the dry and wet deposition and the ambient concentrations of various pollutants. In Fig. 4, we present the seasonal average concentrations — Dec—Jan—Feb for winter, Mar—Apr—May for spring, Jun—Jul—Aug for summer, and Sep—Oct—Nov for fall season. The south-west monsoons from the Arabian Sea during the months of April to August tend to push and disperse the emissions upwards and north, while the north-east monsoons from the Bay of Bengal Sea during the months of October to November tend to push and disperse the emissions inland and south resulting in a wider spread of pollution. For the spring season, beginning of the south-west monsoon, strong winds and higher mixing heights were observed (Supplementary Material), which tend to lift the pollution higher into the troposphere, resulting in lower ground concentrations. In the later months, the cloud cover is higher, reducing the mixing heights, and increasing the ground level concentrations. There is much uncertainty in the monsoons and weather patterns that could not only influence the pollution patterns, but also there is growing evidence that the pollution from transport and industrial processes can affect the monsoonal patterns (Corrigan et al., 2006; Lau et al., 2009).

3.2.3. Secondary chemical contributions

The CAMX modeling system includes full gas phase SAPRC chemical mechanism, with gas and aerosol chemical conversions to support secondary particulate pollution assessment. With no FGD systems to control SO2 emissions at most of the power plants, the secondary contributions are significant. SO2, once airborne, further interacts with the hydroxyl radicals to form aerosol sulfates. The formation of aerosol nitrates is more complicated due to the involvement of the multiple nitrogen species and numerous chemical reactions with hydroxyl radicals and volatile organic compounds.

The percentage contribution of the secondary aerosols (sulfates and nitrates) to total PM2.5 from the coal fired power plants in presented in Fig. 4. The maps are presented by season, Dec—Jan—Feb for winter, Mar—Apr—May for spring, Jun—Jul—Aug for summer, and Sep—Oct—Nov for fall season. The highest secondary contributions were estimated for the summer months. This is partly due to the higher photochemical activities and presence of oxidizing agents, which increase the oxidation of SO2 and NOx gases and their conversion rate to sulfates and nitrates.

From the coal-fired power plants, we estimate 30—40% of the PM pollution is secondary in nature, with the most coming from chemical conversion of gaseous SO2 to aerosol sulfate. Since a majority of the power plants do not operate a dedicated FGD system, most of the SO2 from coal combustion is emitted and ends up in respirable PM fraction, resulting in more health impacts. In the environmental impact assessment studies, which is required before commissioning any power plant, a provision for a FGD is discussed, but the power plants are not required to operate a FGD. The combined benefits of a FGD in conjunction with the already operational ESPs will have a significant effect on overall health impacts. We believe that FGD technology should become mandatory for all new power plants and a provision should be introduced to implement the same for the larger and older power plants to control SO2 emissions and to reduce the overall PM2.5 concentrations by at least 30—40%.

3.3. Mortality and morbidity estimates

The health impacts are calculated by overlaying the griding population with the modeled PM2.5 pollution from the coal fired power plants. Total premature mortality using for the range of mortality risks ranged between 80,000 and 115,000 per year. The estimated mortality and morbidity cases due to these emissions are summarized in Table 6. Using a conservative value of INR 2,000,000 (approximately USD 40,000) per life lost, based on the average life insurance policy’s issued in India, the estimated premature deaths would result in a health cost of INR 16,000 to 23,000 crores (approximately USD 3.2 to 4.6 billion) annually.

In Table 5, we also present the estimated range of premature deaths for the population exposed in the sub-regions. The regions 1 (Delhi—Haryana—Uttar Pradesh) and 6 (West Bengal—Jharkhand—Bihar) are the densest, with average population density above 1000 per km², with peaks of more than 10,000 per km² in the cities of Delhi (capital of India) and Kolkata (capital of West Bengal). These regions also experience highest risk of exposure. These seven sub-regions account for 40% of the total premature deaths estimated for India.

4. Implications

Coal remains the main fossil fuel for power generation in India. In this study, we isolated the emissions from the coal-fired power plants and estimated a premature mortality rate of 80,000 to 115,000 due to their contribution to the ambient PM2.5 concentrations. This number does not include the impacts of the water run-off and soil contamination due to the release of heavy metals. Combined with a strong demand for reliable electricity and consistent shortage in supply, it is doubtful that pollution will be controlled absent strong regulation for the operational 111 coal-fired power plants. There is a vast potential for controlling emissions from these plants and the resultant health impacts. The main conclusions from this analysis are the following

- To date, the pollution standards exist only for ambient air quality and not for individual power plants, which compromises the efforts to control any pollution. Only after standards are regulated at the plant level, can we proceed to the next steps of monitoring and enforcing, and reduce the impact of emissions from coal-fired power plants
- Going forward, coal-fired power plants should be subjected to tighter emission standards, similar to those found in emerging economies (like China) and developed economies (like EU, Australia, and USA). For example, a mandate for installation of FGD systems for the existing 11 coal-fired power plants could reduce the PM2.5 concentrations by 30—40%, by eliminating the formation of secondary sulfates and nitrates, and some additional benefits to the primary particulates
- The efficiency improvement of existing older power plants, irrespective of the boiler size, should become a starting point for reducing overall coal consumption and associated atmospheric emissions
- Unlike pollution from the transport or domestic sector, pollution from stacks is a point source — meaning a finite and known

Table 6

<table>
<thead>
<tr>
<th>Effect</th>
<th>Health impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total premature mortality</td>
<td>80,000 to 115,000</td>
</tr>
<tr>
<td>Child mortality (under 5)</td>
<td>10,000</td>
</tr>
<tr>
<td>Respiratory symptoms</td>
<td>625 million</td>
</tr>
<tr>
<td>Chronic bronchitis</td>
<td>170,000</td>
</tr>
<tr>
<td>Chest discomforts</td>
<td>8.4 million</td>
</tr>
<tr>
<td>Asthma attacks</td>
<td>209 million</td>
</tr>
<tr>
<td>Emergency room visits</td>
<td>900,000</td>
</tr>
<tr>
<td>Restricted activity days</td>
<td>160 million</td>
</tr>
</tbody>
</table>
number of units releasing emissions. Moreover, with a majority of the power plants operated by the public sector, mandating technologies that reduce pollution would seem to represent a simple solution.

- The stack emissions can be monitored relatively easily as compared to non-point sources (such as vehicles, garbage burning, domestic burning, and fugitive dust). While, the larger power plants are now equipped with continuous stack monitors, this information is not open to public, either for analysis or for scrutiny of the emission loads. This adds to the uncertainty of similar studies. Besides strengthening standards, newer policies are required for dissemination of information from the coal-fired power plants

- The environmental impact assessment procedures need to be revised, in order to include the health and environment damages due to long-range transport of pollution from the stacks, as high as 275 m, and travelling the distances of more than 300 km in less than 24 h. Currently, the procedure require assessment for an area of 50 km radius from the plants

In India, the amount of power generated from coal will remain high at least through 2030 (Prayas, 2011, 2013), and unless a better way is proposed to manage pollution from the coal-fired thermal power plants, the environmental effects and human health costs will be high.

Acknowledgments

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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.2014.04.057.

References


WISE, 2012. Risks of Coal Based Electricity Generation in India. World Institute of Sustainable Energy, Pune, India.


