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Air Pollution Control in India: Getting the Prices Right

Maureen Cropper, Shama Gamkhar, Kabir Malik, Alex Limonov, and Ian Partridge*

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Authors affiliations: Cropper, University of Maryland and Resources for the Future; Gamkhar, University of Texas, Austin; Malik, University of Maryland, Limonov, Resources for the Future; Partridge, University of Texas, Austin

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I. Introduction

Throughout the world thermal power plants, in addition to emitting greenhouse gases, are a major source of local pollution and health damages. This is especially true of coal-fired power plants, which generate 41% of the world's electricity (IEA 2008). In the United States, after three decades of regulation, coal-fired power plants were estimated to cause between 10,000 (NRC 2010) and 30,000 (Levy et al. 2009) deaths annually, due to emissions of sulfur dioxide (SO2), nitrogen oxides (NOx) and directly emitted particulate matter (PM).[1] In the US, the benefits of further reducing emissions from coal-fired power plants have been thoroughly studied (Banzhaf et al. 2004; Levy et al. 2007; Muller and Mendelsohn 2009; USEPA 2005). The purpose of this paper is to shed light on the health benefits of reducing emissions from coal-fired power plants in India, a country where 70% of electricity is generated from coal.

The regulation of power plant emissions raises several policy questions: The first is which pollutants should be targeted and how stringently they should be regulated. In the US, regulation has focused on sulfur dioxide (SO2) to control fine particles and on nitrogen oxides (NOx) to control fine particles and reduce ground-level ozone. In India, environmental regulations limit particulate emissions, and two states have begun to establish markets to control directly-emitted particulate matter.[2] But, there are no direct limitations on emissions of SO2 or NOx from coal-fired power plants. An important question is whether more emphasis should be placed on controlling SO2 and NOx.

The answer to this question depends on the benefits of reducing emissions from these pollutants relative to the costs. To help answer this question we estimate the health damages associated with SO2, NOx and directly emitted fine particles (PM2.5) from individual power plants in India. Our analysis suggests that most deaths attributable to power plants in India are associated with SO2, followed by NOx and directly emitted PM. The average number of deaths

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[1] The NAS figure is based on emissions in 2005. Levy et al. (2009) is based on emissions data from 1999. According to NRC (2010) If 2005 emissions data were used by Levy et al. the death figure would be approximately 30,000.

[2] "India to Unveil Emissions Trading Scheme February 1," The Economic Times, January 27, 2011.

per plant associated with each pollutant in 2008 was approximately 500 for SO2, 120 for NOx and 30 for PM2.5. Whether this implies that more emphasis should be placed on control of SO2 and NOx depends, of course, on the cost of measures to control these pollutants and upon how effective various measures would be in reducing emissions. Although we do not examine pollution control costs in detail, we provide illustrative calculations that suggest that scrubbers to reduce SO2 emissions are likely to pass the benefit-cost test at some plants.

A second policy question is what instruments should be used to regulate pollution: should India rely on a cap-and-trade program, as in the US, or an emissions tax? If a pollution permit program is used, should permits trade one-for-one, or should they trade at ratios that reflect differences in marginal damages across plants? The answer to this question depends on how much the damages per ton of SO2, NOx and PM2.5 vary across plants. In the US, Muller and Mendelsohn (2009) argue that the efficiency of SO2 reduction could be increased significantly by taking differences in marginal damages into account. Our analysis suggests that this is not the case for India. In India the mean number of deaths per thousand tons of SO2 is 10, the 5th and 95th percentile are 7 and 12 deaths per thousand tons. (The standard deviation is 2 deaths.)[3] The reason for the small variation in damages per ton in India is that health damages depend heavily on population density: there is much more variation in population density across power plants in the US than in India.

To estimate the health damages associated with coal-fired power plants we have assembled a database of coal characteristics and usage, electricity generation and emissions for 92 coal-fired power plants for the years 2000-2008. We estimate the health impacts of directly emitted fine particles, sulfates and nitrates based on emissions for the year 2008. To calculate the impact of emissions on ambient air quality we estimate intake fractions for each category of emissions. An intake fraction measures the change in population-weighted ambient concentrations of a pollutant (e.g., PM2.5) per unit of primary pollutant emitted from a pollution source. We estimate intake fractions using equations generated by Zhou et al. (2006) that relate the intake fraction of each pollutant to the population surrounding each power plant and

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[3] The range of damages per ton of SO2 across coal-fired power plants in the US is much greater, with the standard deviation of damages per ton equal to approximately half the mean (NRC 2010).

meteorological conditions. Concentration-response functions for fine particles from Pope et al. (2002) are used to estimate premature deaths associated with air emissions.

After characterizing the distribution of premature mortality across plants we calculate the reduction in mortality and cost-effectiveness of two options to reduce power plant emissions—washing coal to reduce ash content and installing a flue-gas desulfurization unit (scrubber). According to some calculations (Zamuda and Sharpe 2007) coal washing actually pays for itself. We calculate the health benefits and cost-per-life saved of reducing the ash content of coal at the Rihand power plant in Uttar Pradesh. Similar calculations are made for the flue-gas desulfurization unit installed at the Dahanu power plant in Maharashtra.

The paper is organized as follows: The next section presents an overview of the Indian power sector, including a discussion of Indian coal production and the environmental regulations facing power plants. Section 3 describes our database and presents summary statistics on the thermal efficiency of power plants, characteristics of coal consumed, pollutant emissions and emissions intensity. The impacts of emissions on premature mortality are described in section 4. Section 5 summarizes the policy implications of our findings and section 6 concludes.

II. Overview of the Indian Power Sector.

In 2010 India had approximately 179 gigawatts (GW) of installed electric capacity.[4] Table 1 shows the breakdown of installed capacity by fuel type and region. Coal-fired power plants accounted for 53% and natural gas plants for 11% of installed capacity; however, thermal power plants accounted for 83% of electricity generated (CEA 2010). Figure 1 maps the location of coal-fired capacity by state.

Most generating capacity in India is government-owned. The 1948 Electricity Supply Act created State Electricity Boards (SEBs) and gave them responsibility for the generation, transmission, and distribution of power, as well as the authority to set tariffs. SEBs operated on soft budgets, with revenue shortfalls made up by state governments. Electricity tariffs set by SEBs failed to cover costs, generating capacity expanded slowly in the 1960s and 1970s, and blackouts were common. To increase generating capacity, the Government of India in 1975 established the National Hydroelectric Power Corporation and the National Thermal Power

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[4] This represents capacity connected to the grid, including 19,509 MW of captive generation.

Corporation, which built generating capacity and transmission lines that fed into the SEB systems. In 1990, 63 percent of installed capacity in the electricity sector in India was owned by SEBs, 33 percent by the central government, and 4 percent by private companies (Tongia 2003).

In 1991 legislation was passed to encourage independent power producers (IPPs) to enter the electricity market, in accordance with the government's broader macroeconomic liberalization and privatization agenda. The Electricity Acts of 1998 and 2003 led to the creation of a Central Electricity Regulatory Commission—the CERC, and similar regulatory bodies at the state level—the SERCs. The Acts also paved the way for the unbundling of generation, transmission and distribution functions, the privatization of distribution companies and the restructuring of the electricity tariff structure. Currently private companies (including IPPs) own 14% of generation capacity in India; however, they own a smaller share (9%) coal-fired generation capacity. Thirty-eight percent of coal-fired capacity is owned by the central government and 53% is state owned (CEA 2010).

Plant Thermal Efficiency and Coal Quality

Coal-fired power plants in India are, in general, less efficient than their counterparts in the US. Thermal efficiency is typically measured by the net output of an electricity generating unit expressed as percent of the heat input used (net thermal efficiency), or by operating heat rate—the heat input (in kcal) required to produce a kWh of electricity. The average net efficiency of coal-fired power plants in India is currently below 28% (see Table 5). In 2008, the U.S. coal-fired power plant fleet had a generation-weighted average efficiency of 32.5% while the top ten percent of the fleet had an efficiency of 37.6%, five percentage points higher (DOE 2010). The average operating heat rate of the coal-fired power plants in our database in 2008 (see Table 5), 2856 kcal/kWh, is 20% higher than the average operating heat rate of subcritical plants in the US during the period 1960-1980 (Joskow and Schmalensee 1987).

The higher average operating heat rates of Indian plants are due in part to the poor quality of Indian coal, but also to inefficiencies in management. The design heat rate of generating units that use coal with high moisture and/or high ash content is higher than for units with low moisture and ash content (MIT 2007). The ash content of Indian coal is between 30 and 50%. This implies that Indian plants will require more energy to produce a kWh of electricity than comparable plants in the US. The operating heat rate of the plant—the actual number of kcal of thermal energy required to produce a kWh—may be higher than the design heat rate if the plant is poorly maintained or experiences frequent outages.[5] For the 50 coal-fired power plants for which we have data in 2008, operating heat rates are, on average, 18% higher than design heat rates. Privately owned plants have, on average, lower operating heat rates and smaller deviations of operating from design heat rates than state-owned plants.

Indian coal also has much lower heating value than coal mined in the US or China. One consequence of the low heating value of Indian coal is that, *ceteris paribus*, more coal is used to produce a kWh of electricity in India than in other countries. The coal consumption per kWh of electricity (in kg/kWh) equals, by definition, a plant's operating heat rate (kcal/kWh) divided by the heating value of its coal (kcal/kg). Ninety percent of the coal used to generate electricity in India is domestic coal with a heating value between 2,700 and 4,400 kcal/kg.[6] The heating value of coal mined in the eastern US is between 6,000 and 7,300 kcal/kg (MIT 2007). It is lower in the western US (4,600-4,700 kcal/kg) and slightly higher in China (4,600-6,000 kcal/kg) (MIT, 2007). The end result of higher operating heat rates and the use of coal with lower heating value is that approximately 770 grams of coal are burned to produce a kWh of electricity in India, in contrast to values half as large in the US and China.[7]

The pollution intensity of Indian power plants (i.e., grams of pollutant per kWh) also depends on the ash and sulfur content of the coal burned. Indian coal has high ash content, between 35 and 50% by weight, and lower sulfur content: about 0.5% by weight. Based on data from the late 1990s Garg et al. (2002) report a consumption-weighted ash content of 45%; Reddy and Venkataraman (2002) report a consumption-weighted ash content of 39%. The corresponding figures for sulfur are 0.51% (Garg et al. 2002) and 0.59% (Reddy and Venkataraman 2002). Information on the distribution of ash and sulfur across individual plants is more difficult to obtain. A chemical analysis of coal at five Indian plants in 1998 by researchers at Ohio State University (Ohio Supercomputer Center) revealed a range of ash

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[5] Whenever a plant is started up after an outage, more coal is burned than during the normal operation of the plant.

[6] This is the range of values reported in our database for 2008. *The Future of Coal* (MIT 2007) reports a range of 3,000-5,000 kcal/kg for Indian coal.

[7] A study by Ohio State University reports 360 g/kWh for Ohio coal, with a heating value of 6,378 kcal/kg. A study quoted by the World Resources Institute (WRI) reports 345 g/kWh in China.

contents from 26% to 47% (average = 39%) and sulfur contents from 0.33% to 0.8% (average = 0.48%). To put these numbers in perspective, the ash content of eastern US coal in the same year ranged from 7.5% to 20% and the sulfur content from 1.0% to 2.5%.[8]

The high ash content of Indian coal may lead to high PM emissions. Although all coal plants in India have electrostatic precipitators (ESPs), the high ash content of coal and its chemical composition reduce their removal efficiency (CPCB 2007). There is also the problem of fly ash disposal. Approximately 100 million tons of fly ash is generated annually. The ash is stored in ponds and poses a hazard to surface water sources from runoff and to ground water from percolation. Our analysis does not quantify the health costs associated with fly ash disposal.

Environmental Regulations Affecting Air Emissions

In India, the primary responsibility for issuing and enforcing environmental regulations lies with the State and Central Pollution Control Boards, which fall under the State and Central Ministries of Environment and Forests (MoEF) (Chikkatur 2008). The current federal ambient air quality standards for particulates, SO2 and NOx are listed in Table 2. Ambient standards vary by location (they are less stringent for industrial areas). As of this writing, there are standards for Suspended Particulate Matter (SPM), PM10, SO2, NOx, CO, ammonia and lead, but not for fine particles (PM2.5) or ozone. The State and Central Pollution Control Boards are responsible for achieving ambient standards, but implementation plans similar to those in the US are required only for 24 "critically polluted" areas and 17 cities (Narain 2008).

The CPCB issues emissions regulations for highly polluting industries, including power plants.[9] Particulate emissions are affected indirectly by coal washing requirements and directly by emission limits (see Table 3). Beginning in 2002 the use of coal with ash content exceeding 34% was prohibited in any thermal power plant located more than 1000 km from the pithead, or in urban or sensitive or critically polluted areas. At the time the regulation was issued, it was

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[8] Reliance on coal from the Appalachian and Illinois basins in the US has declined over time. Currently 30% of coal comes from the Powder River Basin. PRB coal has sulfur content below 0.5% and a lower ash (and heat) content than coal mined in the eastern US (MIT 2007).

[9] We focus in this section on regulations that affect air emissions. Thermal power plants are also subject to Environmental Impact Assessments before they are built, and must meet standards for the discharge of water used for cooling and for disposal of fly ash (http://www.cpcb.nic.in/divisionsofheadoffice/pci2/ThermalpowerPlants.pdf).

estimated to affect approximately 24 GW of installed capacity.[10] In practice the standard is achieved by blending washed and unwashed coal (or imported coal) to reduce average ash content to 34%. Zamuda and Sharpe (2007) estimate that in 2005-06 only 5% of domestic coal used in power plants was washed. They also note that benefication plants were operating at only 44% of capacity.

The emission limits for total suspended particulates listed in Table 3 are concentration limits. Historically, they have been violated by a significant fraction of plants: In 2000-01, 63% of plants did not comply with these standards; in 2006-07, 28% of plants failed to comply (Chikkatur and Sagar 2007).

There are no emission limits for sulfur dioxide or for nitrogen oxides for coal-fired power plants.[11] SO2 concentrations are affected primarily by minimum stack height requirements and the requirement that electricity generating units of 500 MW or more leave space for a Flue Gas Desulfurization (FGD) unit (see Table 4). Generating units between 210 and 500 MW must have stacks of at least 220 meters; units greater than 500 MW must have stacks at least 275 meters in height. Currently only one plant (Dahanu) has installed a flue gas desulfurization unit.

III. Emissions and Emissions Intensity of Existing Plants

To examine the air pollution impacts of coal-fired power plants we have constructed a dataset on the operating characteristics of all coal-fired plants that report to the Central Electricity Authority of India (CEA).[12] The result is an unbalanced panel of 92 thermal power plants, located in 17 states, for the years 2000-2008.[13] Our analysis focuses on the year 2008.[14] In that year we have 57 state-owned, 22 central-government-owned and 13 privately-owned plants,

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[10] See http://www.cpcb.nic.in/divisionsofheadoffice/pci2/ThermalpowerPlants.pdf.

[11] Officials at the Central Electricity Authority report that most plants have low-NOx burners, although this is not required by law (CEA personal communication).

[12] The CEA annually publishes the Thermal Power Review which describes the operating characteristics of all state-operated thermal power plants in India, and provides some data on central-government-owned and privately-owned plants.

[13] All years in our dataset are Indian fiscal years. Thus 2000 refers to the time period April 1, 2000 through March 30, 2001. Our data on emissions begin in 2000. Data on plant characteristics are available beginning in 1994 (see Cropper et al. (2011)).

[14] All information in Tables 5-8 is based on the year 2008. Calculations based on averages for the period 2006-2008 produced very similar results.

which constituted 88% per cent of the total installed coal-fired generation capacity in the country.

Table 5 presents summary statistics on operating characteristics of plants, for all plants and for plants by type of ownership.[15] The table underscores the points made above regarding the thermal efficiency of coal-fired power plants and Indian coal: net thermal efficiency, averaged across all plants is 27.7%. The average heating value of coal is approximately 3625 kcal/kg and, on average, 770 grams of coal are burned to produce a kWh of electricity. A comparison of operating heat rates and heating value of coal by ownership status is difficult, as data are often missing for privately owned plants and for plants operated by the National Thermal Power Corporation (NTPC). The table does, however, suggest that state-owned plants consume significantly more coal per kWh than private and central plants.

The CEA reports total suspended particulate (SPM) concentrations, measured in mg per normal cubic meter of flue gases (mg/Nm^3) in its annual thermal power sector reports. Concentrations for each plant are reported as a range. Table 6 reports summary statistics for the upper and lower ends of this range, as well as the midpoint of the range, for 2008. The midpoint of the emissions range is below the 150 mg/Nm^3 standard for three-quarters of the 74 plants for which data are available. Data are not randomly missing: they are missing for 62% of private plants, 23% of state plants and 14% of central-government-owned plants. Subject to these caveats, it is clear that emission concentrations are, on average, lowest at privately-owned plants, and lower at central-government owned plants than at state-owned plants. The difference in concentration rates between state- and centrally-owned plants disappears, however, once the vintage of generating equipment and the heating value of coal are held constant.

A simple regression of the logarithm of the midpoint of SPM concentrations on the average age of generating equipment, average age squared, heating value of coal and ownership dummies explains 51% of the variation in concentration rates: concentration rates are lower the higher the heating value of coal and increase (at a decreasing rate) with the vintage of generating equipment. Evaluated at mean plant age a one year increase in the age of EGUs raises particulate concentrations by about 3.5 percent. An increase in the heating value of coal by 1000

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[15] Central plants are plants operated by the central government, including National Thermal Power Corporation (NTPC) plants.

kcal/kg is associated with 0.25 percent reduction in SPM concentrations. Concentrations are significantly lower at private plants than at state plants, but there is no statistically significant difference between state- and centrally-owned plants when age and heating value are held constant.

Table 6 also presents summary statistics on annual tons of particulate matter, SO2 and NOx emitted, as well as on the emissions intensity (kg of pollutant per MWh) of these pollutants.[16] To convert SPM concentration rates into tons of SPM emitted per year requires data on annual coal usage, as well as assumptions about the volume of flue gases per ton of coal burned. (Our calculations are described in detail in the Appendix.) Results are presented for emissions of PM2.5, assuming a ratio of PM2.5/SPM of 0.29. Calculating sulfur emissions requires data on the sulfur content of coal as well as coal consumption. Since this is not available at the plant level we calculate emissions based on the default value of 0.5% sulfur by weight for all plants. Our calculation of NOx emissions are based on information provided by the CEA that NOx concentrations in flue gases are about 400 ppm with a limited range of variation between plants.

Annual tons of pollutant emitted reflects the total electricity generated by the plant, as well as kg of coal per kWH and emissions per ton of coal burned. Pollution intensity reflects kg of coal per kWH and emissions per ton of coal burned. For all three pollutants, pollution intensity is lower at private than at state or central plants. The pollution intensity of SO2 emissions is, on average, higher at Indian than at US coal-fired power plants, in spite of the low sulfur content of Indian coal. (The median SO2 pollution intensity at US plants in 2005 was 8.9 pounds per MWh; the mean 12.3 pounds per MWh (NRC 2010).) In Table 6 median SO2 is 15.3 pounds per MWh; the mean is 15.7 pounds per MWh. This reflects the smaller amount of coal burned per MWh in the US and the fact that over one-quarter of US coal-fired plants have scrubbers. The average pollution intensity of NOx emissions is also higher at the plants in our database than at plants in the US. It was, on average, 4.10 pounds of NOx per MWh at US plants in 2005 compared with 4.6 pounds per MWh in Table 6.

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[16] SO2 and NOx emissions data are missing for plants for which coal consumption data are missing. PM2.5 emissions data are missing if either coal consumption data or SPM data are missing.

IV. Health Damages from Coal-Fired Power Plants

Measuring the health effects of air pollution emissions requires estimating the impact of emissions on ambient air quality and using dose-response functions to relate population-weighted changes in concentrations to health endpoints. We estimate intake fractions—the change in population-weighted ambient concentrations of a pollutant—for directly emitted particles, sulfates and nitrates using relationships established by Zhou et al. (2006) for China. The resulting changes in population-weighted ambient concentrations are translated into premature deaths using Pope et al. (2002).

The Intake Fraction Approach to Estimating Health Damages

An intake fraction measures the change in population-weighted ambient concentrations of a pollutant (e.g., PM2.5) per unit of primary pollutant emitted from a pollution source. For example, if Q = emissions of PM2.5 from a power plant in grams per second, ΔC_i is the change in ambient PM2.5 in grid cell i resulting from Q, P_i is the population of the grid cell and BR is the average breathing rate, then the intake fraction is defined as,

$$(1) \qquad IF = [\sum_i P_i \Delta C_i BR] / Q ,$$

where the sum in (1) is taken over all grid cells for which $\Delta C_i > 0$.[17] If the average annual intake fraction for PM2.5 for a power plant were 1×10^{-5}, this would mean that for every metric ton of PM2.5 emitted by the plant, 10 grams are inhaled by the exposed population.

The IF corresponding to an air pollution source depends on the distribution of population around the source, on meteorological conditions, and on characteristics of the source that affect $\{\Delta C_i/Q\}$. For power plants, source characteristics include stack height, stack diameter and exit velocity. Meteorological conditions include wind speed and direction, temperature, and the concentration of ammonia in the atmosphere.

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[17] In Zhou et al. (2006) BR = 20 m^3 per day.

Rather than modeling intake fractions by running an atmospheric dispersion model for each power plant we estimate intake fractions using the results of Zhou et al. (2006). Zhou et al. (2006) use a Lagrangian plume model (CALPUFF) to estimate the impact of an 800 MW coal-fired power plant with fixed design characteristics on air quality (i.e., $\{\Delta C_i\}$) in 29 locations in China. IFs are calculated for PM_1, PM_3, PM_7, PM_{13}, SO_2, ammonium sulfate and ammonium nitrate. For each pollutant, the authors regress the annual average intake fraction on the population in concentric annuli around each plant and on annual precipitation at the plant (in mm/year). The R^2s range from 0.96 (for PM_1) to 0.89 (for PM_{13}). (See Table A2 of the Appendix). We use these equations to predict intake fractions for Indian power plants. (Details of this transfer are described in the Appendix.)

The validity of these transfers depends on the similarity between the characteristics of the plant in Zhou et al. (2006) and Indian power plants.[18] Zhou et al. (2006) use a plant with two stacks of 4 and 7 meters in diameter and 210 meters in height. Because damages per ton of pollutant generally decrease with stack height (Muller and Mendelsohn 2007) this will tend to overstate the impacts of power plants with taller stacks and underestimate the impacts of power plants with shorter stacks. Zhou et al. (2006) estimate the impact of the plant on ambient air quality using a modeling domain for 3360 km by 3360 km. We examine the impact of each power plant in our database on area that includes India, Pakistan, Bangladesh and Sri Lanka.

Once the intake fraction has been estimated for a particular source and pollutant, it can be used to calculate health impacts. Rearranging equation (1), the population-weighted average change in ambient concentrations, $\sum_i P_i \Delta C_i$, is given by

$$(2) \qquad IF * Q / BR = \sum_i P_i \Delta C_i \ .$$

Thus, once IF has been calculated and annual emissions (Q) are known, $\sum_i P_i \Delta C_i$ can be calculated. In most epidemiological studies of the health effects of air pollution, the relative risk (RR) of death or illness associated with a change in pollutant concentration is given by

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[18] It also depends on similarity in meteorological conditions such as wind speed and direction, which are more difficult to compare.

(3) $$RR = \exp(\beta \sum_i P_i \Delta C_i),$$

where β is estimated from an epidemiological study. The number of cases (E) of premature mortality or illness associated with $\sum_i P_i \Delta C_i$ is given by

(4) $$E = ((RR - 1)/RR) * BaseCases.$$

Implying that *(RR-1)/RR* is the fraction of existing cases attributable to the source.

Application of the Intake Fraction Approach to Indian Power Plants

We calculate premature mortality associated with the emissions from each power plant, compared to no emissions, using all-cause mortality coefficients from Pope et al. (2002). Because Pope et al. (2002) relate premature mortality to PM2.5, we convert estimates of SPM to PM2.5 assuming a ratio of PM2.5 to SPM of 0.29 (USEPA AP-42). We use SO2 and NOx emissions for each power plant to estimate the contribution of the plant to sulfates and nitrates, which we add to directly emitted PM2.5.

Choice of Concentration-Response Function

The effects of air pollution on human health include the chronic effects of long-term exposure and the acute effects of short-term exposure. In the past two decades, a large number of studies—especially short-term, time-series studies—have reported concentration-response relationships between air pollution exposure and premature mortality. Long-term cohort studies provide the best method of evaluating the chronic effects of air pollution on human health, whereas time-series studies are appropriate for revealing the acute effects of short-term fluctuations in pollution levels. Concentration-response coefficients from cohort studies of premature mortality are typically several times higher than coefficients reported in time-series studies. It is assumed that the short-term effects found in time-series studies are embedded in the long-term effects on mortality rates derived from cohort studies.

As of this writing there are only a few time-series studies relating air pollution to mortality that have been conducted in India (Cropper et al. 1997; Health Effects Institute 2011). The most recent studies—in Ludhiana, Delhi and Chennai—are part of the Health Effects Institute's Public Health and Air Pollution in Asia (PAPA) program. These studies find similar impacts of PM10 on daily mortality as time series studies conducted in the US (NMMAPS) and Europe (APHEA) (HEI 2011). There are, however, no studies that capture the effects of long-term exposure to particulate matter on mortality in India. Thus we must rely on concentration-response transfer.

The prospective cohort study by Pope et al. (2002) added measurements of air pollution levels (fine particles in 50 cities and sulfates in 151 cities) to data on approximately 500,000 individuals in a prospective cohort assembled by the American Cancer Society. The study, which followed adults aged 30 and over, relates all-cause, cardiopulmonary and lung cancer mortality to annual average PM2.5 using a Cox proportional hazard model. Separate coefficients are reported for exposures in 1979-83 and 1999-2000.

Transferring all-cause mortality coefficients from Pope et al. (2002) to India may be inappropriate for two reasons: the levels of PM2.5 in India are higher than in United States, and the distribution of deaths by cause in the US differs from the distribution in India. One way to deal with the former problem is to use the Pope et al. (2002) coefficients based on air pollution readings in the US in the 1979-83 period, when average air pollution levels were higher than in the years 1999-2000. Our analysis is based on the former coefficients. The similarity of results in time-series studies across cities with very different pollution readings is also comforting. The second problem is handled by transferring impacts from Pope et al. (2002) by cause of death. The primary impact of air pollution on mortality occurs through cardiopulmonary mortality (ICD9 codes 401-440 and 460-519). In the US in 2007 42.5% of all deaths over the age of 30 were due to cardiopulmonary causes (CDC 2011); the comparable figure for India in 2004 was 41.7% (Indiastat). We proceed with dose-response transfer, based on the cardiopulmonary dose-response coefficient from Pope et al. (2002).[19]

In interpreting our results, several points should be kept in mind: The Pope et al. (2002) study applies only to adults 30 years of age and older. Our estimates therefore do not capture the impact of air pollution on child deaths.[20] We also ignore the impact of air pollution on morbidity. In this sense, our estimates represent lower bounds to health effects. At the same time, we

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[19] Pope et al. (2002) also find a significant impact of PM2.5 on lung cancer deaths. Lung cancer accounts for less than one percent of deaths over age 30 in India (Indiastat), hence we ignore this endpoint.

[20] Deaths occurring under the age of 30 constitute 28.8% of deaths in India.

calculate the impact of air pollution on premature mortality in India, Pakistan, Bangladesh and Sri Lanka. Approximately 16% of the deaths reported below occur outside of India.

Estimated Deaths Due to Air Pollution from Coal-Fired Power Plants

Table 7 presents summary statistics for the distribution of deaths attributable to directly emitted PM2.5, SO2 and NOx from the power plants for which emissions data are available. The average number of deaths associated with current emissions levels, compared to zero emissions, is approximately 650 per plant per year: approximately 500 deaths are associated with SO2, 120 with NOx and 30 with PM2.5. The table also presents information on the damages per ton of pollutant, which can be calculated for all plants. Damages per ton are, on average, greater for directly emitted PM2.5 than for SO2 or NOx. There are, on average, 23 deaths per 1,000 tons of PM2.5, 10 deaths per 1,000 tons of SO2 and 9 deaths per 1,000 tons of NOx.

Two results from Table 7 deserve emphasis: the first is that more deaths are attributable to SO2 emissions than to either directly emitted particulates or NOx. Although SO2 is associated with fewer deaths per ton than PM2.5, plants emit many more tons of SO2 than PM2.5. (Recall that all plants use electrostatic precipitators.) NOx is also associated with more deaths than PM2.5 for the same reason. This suggests that more emphasis be placed on policies to control SO2. The second is that the variation in deaths per ton of pollutant across plants is small: deaths per 1,000 tons of PM2.5 range from 24 (5th percentile) to 47 (95th percentile). For SO2 they range from 11 (5th percentile) to 19 (95th percentile). This variation is due solely to differences in plant location and to variation in the size of the population surrounding each plant. Because we count populations 1,000 (and more) km from a plant—whether people live in India or elsewhere—differences in exposed populations across plants are not as great as in the US.

Table 8 shows deaths associated with air pollution broken down by plant ownership. While there are few differences in mean deaths per ton of pollution among state, center and private plants, there are significant differences in deaths per GWh. These reflect differences in pollution intensity across plants: private plants use, on average, less coal to produce a kWh of electricity. And, in the case of particulate emissions, emit less pollution (on average) per ton of coal burned than do state- or center-owned plants.

V. Policy Implications of Our Results

Our analysis of health damages associated with power plants can be used to evaluate the benefits of specific pollution control options. To illustrate how it can be used, we calculate the benefits of two pollution abatement strategies that are not currently in widespread use in India: coal washing and installation of a flue gas desulfurization unit (FGD). Although thermal power plants located more than 1,000 km from the pithead or in urban or sensitive or critically polluted areas are required to use coal containing no more than 34% ash content (CEA 2010), only 5% of non-coking coal is washed (Zamuda and Sharpe 2007). We analyze the costs and benefits of using washed coal at the Rihand plant in Uttar Pradesh. We also calculate the benefits of installing a flue-gas desulfurization unit at the Dahanu power plant in Maharashtra (the only plant to have installed a scrubber) and calculate the cost per premature death avoided.

Health Benefits and Costs of Using Washed Coal

Coal washing reduces the ash content of coal, improves its heating value and also removes small amounts of other substances, such as sulfur and hazardous air pollutants. The benefits of using washed coal are its greater combustion efficiency (less coal needs to be burned to produce electricity), reductions in particulate and sulfur emissions, reductions in flyash disposal costs and reductions in the cost of transporting coal, per unit of heat input. Use of washed coal may also reduce plant maintenance costs and increase plant availability (Zamuda and Sharpe 2007).

We examine the costs and benefits of using washed coal at the Rihand plant, which is located in a coal-mining area and is thus not currently required to use beneficiated coal. Rihand is a 2000 MW plant that in 2008 produced 17,000 GWh of electricity, using coal with a sulfur content of 0.39% and an ash content of 43%. We assume that using washed coal would reduce the ash content of coal burned to 35%, the sulfur content to 0.34% and would raise the heating value of coal by 17%. Based on information provided by the CEA we calculate the levelized cost of electricity generation (lcoe) at Rihand using unwashed coal to be 1.206 Rs/kWh. We estimate that using washed coal increases the lcoe by 16.5%, to 1.405 Rs/kWh (see Appendix).

Our cost analysis focuses only on the yield and direct operating costs of washing. Other researchers have found that the use of washed coal leads to significant gains in generation plant availability and plant load factor, and reductions in repair costs (see, for example, Zamuda and Sharpe (2007)). Our estimates take no account of these economic benefits, nor of likely rail freight savings.

The health benefits of coal washing (see Table 9) come from reductions in the ash content of coal, which reduces PM2.5 emissions, and reductions in sulfur emissions. Tons of PM2.5 and SO2 emitted are also reduced by the fact that less coal need be burned to generate electricity. Although coal washing is usually regarded as a measure aimed at reducing SPM emissions, our analysis indicates that benefits due to the reduction in SO_2 far outweigh those of lower PM2.5 emissions. This is particularly significant because the coal used at Rihand has a sulfur content of 0.39%, which is lower than the average for Indian coal. Our estimates assume that NOx emissions are essentially proportional to the energy throughput of the boiler. The assumption of unchanged electricity generation thus implies unchanged emissions of NOx.

The net impact of coal washing on mortality associated with air emissions from the Rihand plant is to save 251 lives. The increased cost of coal washing is Rs. 3.39 billion, implying a cost per life saved of approximately Rs. 13.5 million. This figure falls within estimates of the Value of a Statistical Life (VSL) for India which, conservatively estimated, range from Rs. 1 million to Rs. 15 million.[21]

Health Benefits and Costs of a Flue Gas Desulfurization Unit

Only one Indian power plant—Dahanu, in Maharashtra—is currently fitted with a FGD (scrubber), although the MOEF stipulates that space be set aside in power plants with 500 MW and greater capacity to facilitate retrofitting of a FGD (see Table 4). The Dahanu plant is a 500 MW plant located in an environmentally sensitive area. Its SPM emissions are among the lowest in our database (32.5 mg/Nm^3 in 2008). In 2000, the Indian Supreme Court ordered that an FGD be installed at the plant.

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[21] Bhattacharya et al. (2007) report a preferred VSL estimate of Rs. 1.3 million (2006 rupees) based on a stated preference study of Delhi residents. Madheswaran’s (2007) estimate of the VSL based on a compensating wage study of workers in Calcutta and Mumbai is approximately Rs. 15 million. Shanmugam (2001) reports a much higher value (Rs. 56 million) using data from 1990.

Various scrubber technologies exist: in the U.S. wet scrubbing is the most common. The The U.S. EPA's AP42 database indicates that a wet scrubber can achieve up to 95% SO_2 removal; equipment suppliers claim SO_2 removal efficiencies of up to 99% with additives in the flue gas stream. The Dahanu FGD is a seawater scrubber: this type is particularly cheap to operate but has a maximum removal efficiency of about 80%.[22]

Capital costs of wet scrubbers range from \$100 to \$200/KW and the auxiliary power for operation ranges from 1.0%-3.0% depending on coal sulfur level and removal level (MIT 2007). Operating costs of FGD units in the U.S. average 0.16 cents/KWh,[23] ranging up to 0.30 cents/KWh depending on sulfur level, removal efficiency and the costs (or potentially revenues) from disposal of sludge (MIT 2007). Our analysis of generation costs shows that the retrofitted FGD at Dahanu adds about 9% to the lcoe.[24] The Dahanu FGD has very low operating costs as it employs seawater as the reactant to absorb SO_2 rather than purchased chemicals—a design that obviously can be employed only for a plant at a coastal location. If the additional O&M cost for a FGD is instead taken as the average figure for the U.S. the effect is to increase the lcoe by a further 6% (see Appendix for details).

Assuming a removal rate of 80%, and a sulfur content of coal of 0.5%, the FGD at Dahanu saves 123 lives per year, at a cost of Rs. 3.55 million per life saved. An important question is how applicable these results are to other power plants. The costs of scrubbing will be higher at plants employing conventional wet scrubbers—in the neighborhood of 15% of the levelized cost of electricity (see Appendix). Obviously benefits will be lower at plants burning coal with lower sulfur content than 0.5%. The benefits of installing a scrubber with an 80% removal rate will, however, be substantial, given the results in Tables 7-9: at the Rihand plant approximately 990 statistical lives would be saved. We also note that estimated deaths per ton of SO2 at the Dahanu plant are among the lowest of all plants in our database.

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[22] A useful source is an evaluation of control technologies considered for a power station in Hong Kong (see http://www.epd.gov.hk/eia/register/report/eiareport/eia_1232006/HTML/Main/Section2.htm)

[23] See http://www.eia.gov/cneaf/electricity/epa/epa_sum.html (the EIA Electric Power Annual 2009).

[24] Cost data taken from the report of a regulatory hearing before the Maharashtra Electricity Regulatory Commission dated September 8, 2010.

VI. Conclusions and Caveats

The goal of this paper is to provide bottom-up estimates of the health damages associated with coal-fired power plants in India and the benefits of reducing emissions of particulate matter, SO2 and NOx at individual plants. Our analysis of the health effects of air emissions from coal-fired power plants is a preliminary one, using intake fraction equations derived from power plants in China to estimate the impact of power plant emissions on population exposures. We also rely on concentration-response transfer from the United States to estimate impacts on premature mortality. Because we estimate impacts only for persons aged 30 and older and only for cardiopulmonary mortality, our estimates are lower-bound estimates of health effects. As is the case for most estimates of the health effects of air pollution, the weakest part of our analysis is the atmospheric chemistry linking changes in emissions to changes in population-weighted exposures. We believe, however, that some conclusions are possible from our study.

Policies to control air pollution from Indian power plants have traditionally focused on reducing particulate emissions, due to the high ash content of Indian coal. The low sulfur content of Indian coal has, perhaps, been responsible for failure to directly control SO2 emissions (Chikkatur and Sagar 2007). This paper suggests that more emphasis should be placed on SO2 control. The current approach—relying on tall stacks—mirrors the approach taken in the US in the 1980s to achieve local air quality standards. Tall stacks cause pollution to be dispersed, but do not eliminate exposure, especially in a densely populated country. Although Indian coal has lower sulfur content than coal mined in the eastern US, more coal is used to produce a kWh hour of electricity in India due to the low heating value of Indian coal. This, combined with the magnitude of SO2 emissions from coal-fired power plants, makes SO2 the main pollutant of concern from a health standpoint.

Whether the use of FGDs to reduce SO2 emissions passes the benefit-cost test depends on the cost of scrubbers and on plant location. We note that the scrubber installed at the Dahanu plant in Maharashtra does pass this test (i.e., it has a cost-per-life-saved below estimates of the VSL for India), in spite of the fact that the deaths per ton of SO2 associated with this plant are among the lowest of the 89 plants in our database. Coal washing, which may pay for itself based on improved combustion efficiency and reduced transportation costs, also has health benefits. Most health benefits result from the need to burn less coal, as well as from small reductions in the sulfur content of coal burned. The percentage reduction in SO2 emissions at the Rihand plant (see Table 9) is 25%. Due to the importance of sulfates v. directly emitted PM, the reduction in deaths from reduced SO2 emissions conveys more health benefits than the 30% reduction in directly emitted PM2.5.

Our estimates can also be used to calculate (a lower bound to) monetary damages per ton of PM2.5, SO2 and NOx. This, however, requires estimate of the Value of a Statistical Life for India. Estimates of the VSL in the United States have been controversial, but are used in policy analyses. There are fewer estimates of the VSL for India, and the estimates vary widely. It is, our title states, important to get pollution prices right. But doing so will require better evidence on the value of health benefits in India.

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APPENDIX: Calculation Methodologies and Sources of Data

Calculation of Emissions Estimates – Base Case

The CEA Annual Report provides SPM emissions data for most Indian power plants in mg/Nm^3, shown as a range (the highest and lowest actual readings during the year). For each plant the midpoint of the range was converted into grams per second using the F-factors method given in the U.S. Code of Federal Regulations (see 40 CFR Part 60, Appendix A Method 19). The F-factors calculation is based on the ultimate analysis of the coal used: in the absence of plant by plant data on coal quality an analysis of a coal sample from the Dadri power station (made by the U.S. National Energy Technology Laboratory) was used for all locations – this grade is typical of Indian thermal coals. The Dadri analysis was taken from a study entitled *Anthropogenic Emissions from Energy Activities in India* made by the OSU Supercomputer Center1.[25] The F-factor calculation requires a value for the oxygen content of flue gas – this was taken as 4% (personal communication from CEA). The resulting emissions rate for SPM was converted to PM2.5 using data on particle size distribution from the US EPA's AP42 methodology.

Emissions of SO_2 were estimated assuming that 7.5% of sulfur in the coal is retained in ash with all the rest emitted as SO_2 (i.e., emissions of other oxides of sulfur taken as zero). The 7.5% retention figure is the mean of several values found in the literature.

Emissions of NO_x were estimated by taking a representative figure of 400 ppm in flue gas, measured as NO_2 (CEA personal communication).

Emissions and Economics – Coal Washing and FGD Cases

We examined the effects on emissions and generation costs of (a) using washed coal; and (b) retrofitting flue gas desulfurization equipment. In both cases the effect on the levelized cost of electricity (lcoe) was estimated using a model of a representative new 500MW subcritical generation unit in India.[26] Key assumptions are described below:

a. Prior studies of the use of washed coal in India focus on economic impact—typical economic assumptions were provided by the CEA (private communication). An ultimate analysis of Dadri washed coal made for a USAID project[27] was modified to be

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[25] See http://www.osc.edu/research/archive/pcrm/emissions/coal.shtml.

[26] Described in *"What can an analysis of CDM projects tell us about the problem of cutting greenhouse gas emissions in India?"* (http://www.webmeets.com/aere/2011/prog/viewpaper.asp?pid=421); by Partridge and Gamkhar; (presented at the conference of the Association of Environmental and Resource Economists, June 2011.

[27] See http://www.indiapower.org/igcc/standon.pdf

compatible with the yield/ash reduction data provided by the CEA. We found that washing Dadri coal to reduce its ash content by 8% increased the lcoe by 17% (c.f. advice received from the CEA that washing increases generation cost by 15%-20%).

Our cost analysis (and the CEA's) focus only on the yield and direct operating costs of washing. Other researchers have found that the use of washed coal leads to significant gains in generation plant availability and PLF, and reductions in repair costs—see, for example, (Zamuda and Sharpe 2007). Our estimates take no account of these economic benefits, nor of likely rail freight savings.

The impact of washing on PM2.5 emissions was estimated for an 8% reduction in coal ash content assuming that 80% of coal ash goes to fly ash, of which 99.84% is removed by the ESP. These percentages are in line with CEA advice and, averaged over a sample of modern plants, are in line with actual emissions as reported by the CEA. The impacts on SO_2 and NO_X emissions were estimated as described above.

b. The only flue gas desulfurization unit currently operating in India is located at the Dahanu plant, in Maharashtra. Information on its capital and operating costs and additional auxiliary power requirement is given in a regulatory case before the Maharashtra Electricity Regulatory Commission dated September 8, 2010. Based on these data, retrofitted FGD adds about 9% to the lcoe. The Dahanu FGD has very low operating costs as it employs seawater as the reactant to absorb SO_2 rather than purchased chemicals—a design that obviously can be employed only for a plant at a coastal location. If the additional O&M cost for a FGD is instead taken as the average figure for the U.S.[28] the effect is to increase the lcoe by a further 6%.

Table A1: Levelized Cost of Electricity in Various Plant Configurations (2010 Rs/kWh)

500MW plant with no FGD	1.134
500MW plant with FGD: O&M cost from Dahanu regulatory hearing	1.233
500MW plant with FGD: O&M cost from EIA data for U.S.	1.296
500MW plant with no FGD: coal washed to 30% ash content	1.327

Note: Cost of electricity is calculated for a plant at a pithead location (i.e. no rail freight). The assumed coal price is the average CIL price for thermal coal in 2010, including royalty and similar charges but excluding VAT.

Estimation of Health Damages using Intake Fractions

Zhou et al. (2006) used CALPUFF, a Gaussian dispersion model recommended by the US EPA for long range pollution transport studies[29] to estimate the ambient concentrations of pollutants (primary particulates with equivalent diameters of 1,3,7 and 13 µm, SO_2, secondary sulfates and secondary nitrates) across a wide area due to emissions from a point source.

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[28] See http://www.eia.gov/cneaf/electricity/epa/epa_sum.html (the EIA Electric Power Annual 2009).

[29] See http://www.src.com/calpuff/FR_2003Apr15.pdf.

Separate CALPUFF runs were made for hypothetical identical generation plants at 29 locations in China. By combining the resulting matrices of concentration data with a gridded population data set, Zhou et al. estimated the population weighted average human exposure to each pollutant within a domain measuring 3,360 by 3,360 km, (almost the whole of China) due to emissions from each source. The exposure estimates were converted into intake fractions (defined as "the fraction of material or its precursor released from a source that is eventually inhaled or ingested by a population" (Zhou et al. 2006)) for each pollutant at each of the 29 locations. Zhou et al. then estimated regression models for each pollutant, with intake fraction as the dependent variable (see Table A2). The independent variables used in the final models were the annual rainfall at the plant and population living within concentric annuli centered on the plant (at 100km, 500km and 1,000km from the plant, and beyond 1,000km but within the overall domain). R^2s for these models ranged between .89 and .96.

Zhou et al. did not use plant characteristics as independent variables as they assumed an identical plant at each location. However they made a number of sensitivity analyses using alternative values for such variables as stack height. These alternative values made little difference to the results of the analysis, at least within the range (e.g., of stack heights) likely to be encountered at modern power stations.[30] Sensitivities using different assumed emission rates for pollutants showed that estimated intake fractions remained reasonably constant (Zhou et al. 2006; Zhou et al. 2003).

We used the Zhou et al. regression models to estimate intake fractions for primary $PM_{2.5}$ and secondary sulfates and nitrates for actual plant locations in India. Population estimates (i.e., population living within 100km, 500km and 1,000km of each plant location) were made using the Landscan gridded population data set for 2008 maintained by the Oak Ridge National Laboratory (ORNL).[31] The overall domain (used to estimate population beyond 1,000km) was taken as the whole of India, Pakistan, Bangladesh and Sri Lanka. Estimates of annual rainfall are primarily from Indian data sources, but as these relate mainly to major cities and large towns, in several cases values had to be interpolated between locations reasonably close to a plant.

The methodology and assumptions used for analysis of health impacts based on these estimated intake fractions are described in the text of the paper.

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[30] This is not quite true –runs using different stack heights found significant differences for large primary particles, but the impact of large particles on human health is limited.

[31] See http://www.ornl.gov/sci/landscan/.

Table A2: Matrix of Coefficients for Zhou et al. Regression Models

Pollutant	R^2	Pop 0-100km	Pop100-500km	Pop 500-1,000km	Pop >1,000km	Precipitation
SO2	0.96	9.9E-08**	1.3E-08**	3.0E-09	1.8E-09**	-6.3E-10
PM1	0.96	1.5E-07*	2.3E-08**	1.1E-08**	3.9E-09**	-1.7E-09**
PM3	0.92	1.4E-07*	1.7E-08**	6.4E-09	3.0E-09**	-2.4E-09**
PM7	0.91	9.9E-08**	8.9E-09*	3.1E-09	1.5E-09*	-1.2E-09**
PM13	0.89	6.7E-08**	4.3E-09	9.4E-10	7.3E-10	-4.6E-10*
SO4	0.95	2.4E-08	7.9E-09*	6.9E-09**	2.6E-09**	-1.2E-09**
NO3	0.93	4.3E-08	1.3E-08**	3.5E-09	2.5E-09**	-1.9E-09**

Source: (Zhou et al., 2006)

Notes: *** Estimate significant at 0.05 level*

** Estimate significant at 0.10 level*

Population variables in millions; precipitation in mm/yr.

Table 1. Distribution of Electric Generating Capacity by Fuel and Region (MW) on 3-31-10

	Thermal					Renewable		
Region	**Coal**	**Gas**	**Diesel**	**Total**	**Nuclear**	**Hydro**	**R.E.S.**	**Total**
Northern	21275	3563	13	24851	1620	13311	2407	42189
Western	28146	8144	18	36307	1840	7448	4631	50225
Southern	17823	4393	939	23155	1100	11107	7939	43301
Eastern	16895	190	17	17103	0	3882	335	21320
N. Eastern	60	766	143	969	0	1116	204	2289
Islands	0	0	70	70	0	0	5	75
All India	84198	17056	1200	102454	4560	36863	15521	159399

Note: Captive generating capacity connected to the grid = 19,509 MW

Source: Central Electricity Authority, Ministry of Power, Government of India, New Delhi, 2010. accessed online (on December 29, 2011): *www.cea.nic.in/reports/monthly/executive_rep/mar10/8.pdf*

Table 2. Ambient Air Quality Standards for PM, SO2 and NOx in India

		Concentration in Ambient Air		
Pollutants	**Time-weighted average**	**Industrial Areas**	**Residential Rural and other areas**	**Sensitive areas**
Sulphur Dioxide (SO2)	Annual Average	80 µg/m3	60 µg/m3	15 µg/m3
	24 hours	120 µg/m3	80 µg/m3	30 µg/m3
Oxides of Nitrogen as (NOx)	Annual Average	80 µg/m3	60 µg/m3	15 µg/m3
	24 hours	120 µg/m3	80 µg/m3	30 µg/m3
Suspended Particulate Matter (SPM)	Annual Average	360 µg/m3	140 µg/m3	70 µg/m3
	24 hours	500 µg/m3	200 µg/m3	100 µg/m3
Respirable Particulate Matter (RPM) (size less than 10 microns)	Annual Average	120 µg/m3	60 µg/m3	50 µg/m3
	24 hours	150 µg/m3	100 µg/m3	75 µg/m3

µg/m3 = microgram per cubic meter. Annual average: arithmetic mean of minimum 104 measurements in a year taken twice a week 24 hourly at uniform interval. 24-hour values should be met 98% of the time in a year. However, 2% of the time, these may be exceeded but not on 2 consecutive days.

Table 3. Particulate Emissions Standards for Coal Based Power Plants

Capacity	Pollutant	Emission limit
Coal based thermal plants		
Below 210 MW & plant commissioned before 1.1.82	Particulate matter(PM)	350 mg/Nm3
210 MW & above		150 mg/Nm3
Units located in protective areas irrespective of generation capacity		150 mg/Nm3

Source: Central Pollution Control Board website, access on 12/27/11.
Note: The Andhra Pradesh Pollution Control Board and Delhi Pollution Control Committees have stipulated stringent standards of 115 and 50 mg/Nm^3 respectively for control of particulate matter emissions.

Table 4. Stack Height Requirements for SO_2 Control

Power Generation Capacity	Stack Height (meters)
Less than 200/210 MW	H = 14 (Q)0.3 where Q is emission rate of SO 2 in kg/hr, H = Stack height in meters
200/210 MW or less than 500 MW	220
500 MW and above	275 (+ Space provision for FGD systems in future)

Source: Review of Performance of Thermal Power Stations, Annexure 14.2, CEA 2010

Table 5. Distribution of Plant Performance Indicators 2008

	# obs	Mean	Std Dev	5th	25th	Median	75th	95th
	All Plants , 2008			**Percentile**				
Nameplate (MW)	92	802	661	125	255	630	1121	2100
Adjusted Age (Yrs)	87	21.8	11.9	2.0	13.0	20.3	31.0	42.6
Capacity (MW)	90	806	663	125	260	630	1152	2100
Net Generation (GWh)	87	5134	4994	353	1298	3465	7273	16008
Net Efficiency (GWh/Joule)	47	0.28	0.04	0.21	0.25	0.28	0.31	0.34
Design Heat Rate (Kcal/kWh)	50	2407	171	2227	2302	2356	2438	2739
Operating Heat Rate (Kcal/kWh)	50	2856	434	2302	2563	2751	3148	3495
Specific Coal Consumption (Kg/kWh)	68	0.77	0.11	0.62	0.68	0.75	0.85	0.95
Gross Calorific Value of Coal(Kcal/Kg)	37	3625	389	2985	3314	3541	3860	4303

	State-owned				Center-owned				Private-owned			
	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev
Nameplate	57	711	640	495	22	1341	1025	860	13	289	250	151
Adjusted Age	57	22.4	22.0	11.4	22	18.6	17.7	11.6	8	27.0	24.9	15.2
Capacity	57	697	630	493	22	1339	1025	862	11	307	260	158
Net Generation	57	3996	2891	3384	22	9104	7398	6905	8	2327	2226	1641
Net Efficiency	39	0.28	0.28	0.04	6	0.25	0.26	0.03	2	0.33	0.33	0.01
Design Heat Rate	39	2405	2350	177	6	2507	2484	141	5	2301	2314	77
Operating Heat Rate	39	2866	2770	432	6	3116	3016	410	5	2460	2454	151
Specific Coal Consumption	44	0.81	0.81	0.11	19	0.71	0.71	0.07	5	0.71	0.67	0.15
Gross Calorific Value of Coal	32	3552	3523	338	3	4238	4303	219	2	3868	3868	614

Table 6. Distribution of Emissions and Emissions Intensity

	All Plants, 2008							
						Percentile		
	# obs	Mean	Std Dev	5th	25th	Median	75th	95th
Min SPM recorded (mg/Nm3)	75	117	118	24	65	103	132	216
Max SPM recorded (mg/Nm3)	75	207	271	61	116	143	187	535
Mid-point SPM (mg/Nm3)	75	162	192	42	96	127	153	352
PM 2.5(tons/year)	63	1288	1766	79	301	873	1363	3454
PM 2.5 (g/Mwh)	63	227	389	48	102	143	208	496
SO2 (tons/year)	68	44254	36068	5047	16475	40260	60174	119518
SO2 (g/Mwh)	68	7147	1024	5735	6290	6937	7863	8788
NOx (tons/year)	68	12944	10550	1476	4819	11776	17601	34959
NOx (g/Mwh)	68	2091	299	1677	1840	2029	2300	2570

	State-owned				Center-owned				Private-owned			
	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev
Min SPM recorded (mg/Nm3)	49	139	122	138	20	90	84	35	6	26	26	6
Max SPM recorded (mg/Nm3)	49	254	157	324	20	127	128	51	6	88	86	32
Mid-point SPM (mg/Nm3)	49	197	139	228	20	109	106	41	6	57	58	16
PM 2.5(tons/year)	41	1398	886	2090	17	1368	1000	837	5	117	79	66
PM 2.5 (g/Mwh)	41	283	171	473	17	140	117	58	5	64	46	34
SO2 (tons/year)	44	37682	38475	26098	19	67310	50512	47743	5	14475	11141	10095
SO2 (g/Mwh)	44	7455	7446	1004	19	6592	6567	621	5	6549	6198	1428
NOx (tons/year)	44	11022	11254	7634	19	19688	14775	13965	5	4234	3259	2953
NOx (g/Mwh)	44	2181	2178	294	19	1928	1921	182	5	1916	1813	418

Table 7. Distribution of Deaths Attributable to Emissions - All Plants 2008

				Percentile				
	# obs	**Mean**	**Std Dev**	**5th**	**25th**	**Median**	**75th**	**95th**
Deaths (All pollutants)	63	659	523	95	273	554	883	1638
Total deaths per plant due to								
PM 2.5	63	29	43	2	8	19	39	76
SO2	63	499	407	71	208	407	645	1297
NOx	63	123	95	21	50	103	169	299
Deaths per ton of emission of								
PM 2.5	89	0.023	0.005	0.015	0.019	0.023	0.027	0.029
SO2	89	0.010	0.002	0.007	0.010	0.011	0.011	0.012
NOx	89	0.009	0.002	0.006	0.007	0.009	0.011	0.012
Deaths (per Gwh)	63	0.099	0.024	0.067	0.083	0.097	0.110	0.133
Total deaths (per Gwh) per plant due to								
PM 2.5	63	0.005	0.010	0.001	0.002	0.003	0.005	0.010
SO2	63	0.074	0.015	0.049	0.063	0.073	0.083	0.100
NOx	63	0.019	0.005	0.013	0.016	0.018	0.021	0.027

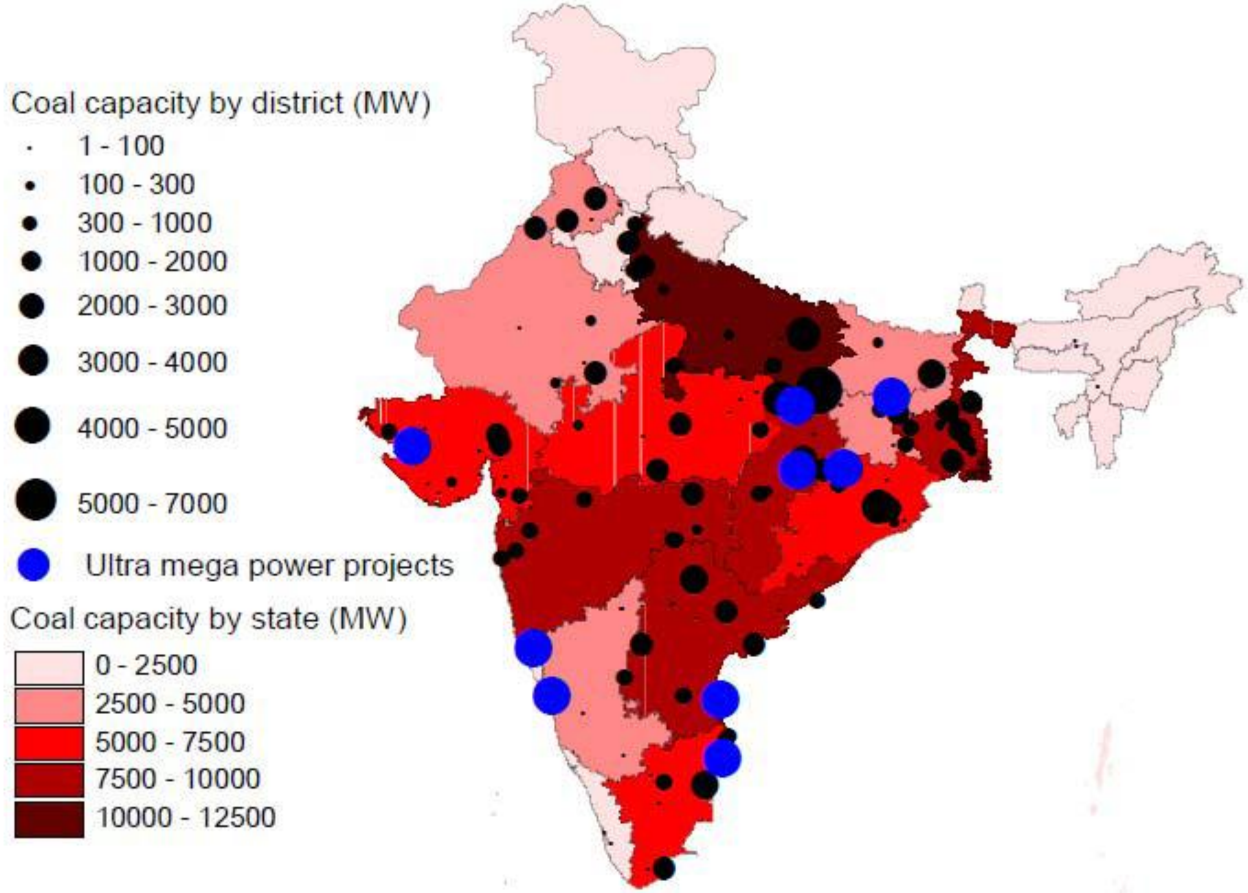
Table 8. Distribution of Deaths Attributable to Emissions by Plant Ownership Status 2008

	State-owned				**Center-owned**				**Private-owned**			
	# obs	**Mean**	**Median**	**Std Dev**	**# obs**	**Mean**	**Median**	**Std Dev**	**# obs**	**Mean**	**Median**	**Std Dev**
Capacity	57	697	630	493	22	1339	1025	862	11	307	260	158
Total Deaths (All pollutants)	41	557	502	373	17	1047	835	671	5	171	151	106
Total deaths per plant due to:												
PM 2.5	41	31	19	52	17	33	28	19	5	3	2	2
SO2	41	418	370	283	17	804	640	530	5	130	114	81
NOx	41	103	100	65	17	199	159	120	5	36	34	23
Deaths per ton of emission of:												
PM 2.5	56	0.023	0.023	0.004	22	0.023	0.025	0.006	11	0.022	0.022	0.006
SO2	56	0.011	0.011	0.001	22	0.010	0.011	0.002	11	0.009	0.010	0.001
NOx	56	0.009	0.009	0.002	22	0.009	0.010	0.003	11	0.008	0.009	0.002
Total Deaths (per Gwh)	41	0.103	0.100	0.026	17	0.095	0.091	0.012	5	0.082	0.078	0.024
Total deaths (per Gwh) per plant due to:												
PM 2.5	41	0.007	0.004	0.012	17	0.003	0.003	0.002	5	0.002	0.001	0.001
SO2	41	0.076	0.077	0.017	17	0.072	0.072	0.008	5	0.062	0.059	0.017
NOx	41	0.019	0.018	0.005	17	0.019	0.018	0.004	5	0.018	0.018	0.006

Table 9. Effects of Coal Washing on Rihand Thermal Power Station, 2008

	Unwashed	Washed Coal	% reduction due to washing
Coal Usage (`000 tons)	10903	9322	14%
PM2.5 (tons/year)	1732	1207	30%
SO2 (tons/year)	77854	58032	25%
NOx (tons/year)	25828	25828	0%
Total Deaths (all pollutants)	1241	990	20%
Total deaths per plant due to			
PM 2.5	43	30	30%
SO2	934	696	25%
NOx	264	264	0%
Deaths (per Gwh)	0.074	0.059	20%
Total deaths (per Gwh) per plant due to			
PM 2.5	0.0026	0.0018	30%
SO2	0.0548	0.0409	25%
NOx	0.0155	0.0155	0%

Figure 1. Distribution of Coal-Fired Power Plant Capacity



Source: Uwe Remme, Nathalie Trudeau, Dagmar Graczyk and Peter Taylor, Technology Development Prospects for the Indian Power Sector, Information Paper, IEA, February 2011.

Note: Ultra mega power projects (UMPPs) are power projects planned by the Government of India to reduce power shortages. They are supercritical plants with a minimum capacity of 4 GW.