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The Health Effects of Coal Electricity Generation in India

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RESOURCES FOR THE FUTURE

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Abstract

To help inform pollution control policies in the Indian electricity sector we estimate the health damages associated with particulate matter, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) from individual coal-fired power plants. We calculate the damages per ton of pollutant for each of 89 plants and compute total damages in 2008, by pollutant, for 63 plants. We estimate health damages by combining data on power plant emissions of particulate matter, SO_2 and NO_x with reduced-form intake fraction models that link emissions to changes in population-weighted ambient concentrations of fine particles. Concentration-response functions for fine particles from Pope et al. (2002) are used to estimate premature cardiopulmonary deaths associated with air emissions for persons 30 and older. Our results suggest that 75 percent of premature deaths are associated with fine particles that result from SO_2 emissions. After characterizing the distribution of premature mortality across plants we calculate the health benefits and cost-per-life saved of the flue-gas desulfurization unit installed at the Dahanu power plant in Maharashtra and the health benefits of coal washing at the Rihand power plant in Uttar Pradesh.

Key Words: coal-fired power plants, particulate matter, electricity, health damages, pollution control, concentration-response function, India

JEL Classification Numbers: Q01, Q51, A53

Contents

The Health Effects of Coal Electricity Generation in India

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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 percent 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 (SO_2), nitrogen oxides (NO_x) and directly emitted particulate matter (PM).[1] In the United States, 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 percent 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 United States, regulation has focused on sulfur dioxide (SO_2) to control fine particles and on nitrogen oxides (NO_x) 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] However there are no direct limitations on emissions of SO_2 or NO_x from coal-fired power plants. An important question is whether more emphasis should be placed on controlling SO_2 and NO_x.

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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.

The answer to this question depends on the benefits of reducing emissions from these pollutants relative to the costs. To help determine this, we estimate the health damages associated with SO_2, NO_x and directly emitted fine particles ($PM_{2.5}$) from individual power plants in India. Our analysis suggests that most deaths attributable to power plants in India are associated with SO_2, followed by NO_x and directly emitted PM. The average number of deaths per plant associated with each pollutant in 2008 was approximately 500 for SO_2, 120 for NO_x and 30 for $PM_{2.5}$. Whether this implies that more emphasis should be placed on controlling SO_2 and NO_x depends 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 SO_2 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 United States, or on 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 SO_2, NO_x and $PM_{2.5}$ vary across plants. In the United States, Muller and Mendelsohn (2009) argue that the efficiency of SO_2 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 SO_2 is 10, and the 5th and 95th percentile are 7 and 12 deaths per thousand tons respectively. (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 United States 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., $PM_{2.5}$) per unit of primary pollutant emitted from a pollution

[3] The range of damages per ton of SO_2 across coal-fired power plants in the United States is much greater, with the standard deviation of damages per ton equal to approximately half the mean (NRC 2010).

source. We estimate intake fractions using equations generated by Zhou et al. (2006) using Chinese data that relate the intake fraction of each pollutant to the population surrounding each power plant and 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 and amount and intensity of pollutants emitted, by plant. 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 percent and natural gas plants for 11 percent of installed capacity; however, thermal power plants accounted for 83 percent 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

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

established the National Hydroelectric Power Corporation and the National Thermal Power 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 (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 percent of generation capacity in India; however, they own a smaller share (9 percent) of coal-fired generation capacity. Thirty-eight percent of coal-fired capacity is owned by the central government and 53 percent 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 United States. 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 percent (see Table 5). In 2008, the U.S. coal-fired power plant fleet had a generation-weighted average efficiency of 32.5 percent, while the top 10 percent of the fleet had an efficiency of 37.6 percent, 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) is 2,856 kcal/kWh, which is 20 percent higher than the average operating heat rate of subcritical plants in the United States 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 percent. This implies that Indian plants will require more energy to produce a kWh of electricity than comparable plants in the United States. 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 percent 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 do state-owned plants.

Indian coal also has much lower heating value than coal mined in the United States 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 United States is between 6,000 and 7,300 kcal/kg (MIT 2007). It is lower in the western United States (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 one kWh of electricity in India, in contrast to values half as large in the United States 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 percent by weight, and lower sulfur content: about 0.5 percent by weight. Based on data from the late 1990s , Garg et al. (2002) report a consumption-weighted ash content of 45 percent; Reddy and Venkataraman (2002) report a consumption-weighted ash content of 39 percent. The corresponding figures for sulfur are 0.51 percent (Garg et al. 2002) and 0.59 percent (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 contents from 26 to 47 percent (with an average of 39 percent) and sulfur contents from 0.33 to 0.8 percent (average 0.48 percent). To put these numbers in perspective, the ash content of

[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.

eastern U.S. coal in the same year ranged from 7.5 to 20 percent, and the sulfur content from 1.0 to 2.5 percent.[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, SO_2, NO_x and ozone are listed in Table 2. The State and Central Pollution Control Boards are responsible for achieving ambient standards, but implementation plans similar to those in the United States 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 percent was prohibited in any thermal power plant located more than 1,000 km from the pithead or in urban or sensitive or critically polluted areas. At the time the regulation was issued, it was 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 percent. Zamuda and Sharpe (2007) estimate that in 2005-2006, only 5 percent of

[8] Reliance on coal from the Appalachian and Illinois basins in the United States has declined over time. Currently, 30 percent of coal comes from the Powder River Basin in southeastern Montana and northeastern Wyoming. PRB coal has a sulfur content below 0.5 percent, 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).

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

domestic coal used in power plants was washed. They also note that beneficiation plants were operating at only 44 percent 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 2000–2001, 63 percent of plants did not comply with these standards; in 2006-07, 28 percent 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] SO_2 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, which constituted 88 percent of the total installed coal-fired generation capacity in the country.

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[11] Officials at the Central Electricity Authority report that most plants have low-NO_x burners, although this is not required by law (CEA personal communication 2011).

[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 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.

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 percent. The average heating value of coal is approximately 3,625 kcal/kg; and, on average, 770 grams of coal are burned to produce one 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 do private and central government 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 percent of private plants, 23 percent of state plants and 14 percent 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 they are 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 in flue gas on the average age of generating equipment, average age squared, heating value of coal and ownership dummies explains 51 percent 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 electrical generating unit (EGU) raises particulate concentrations by about 3.5 percent. An increase in the heating value of coal by 1,000 kcal/kg is associated with a 0.25 percent reduction in SPM concentrations. Concentrations are significantly lower at private plants than at state

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

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, SO_2 and NO_x emitted, as well as on the emissions intensity (in 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 $PM_{2.5}$, assuming a ratio of $PM_{2.5}$/SPM of 0.29. Calculating sulfur emissions requires data on the sulfur content of coal as well as on coal consumption. Since this is not available at the plant level, we calculate emissions based on the default value of 0.5 percent sulfur by weight for all plants. Our calculations of NO_x emissions are based on information provided by the CEA that NO_x concentrations in flue gases are about 400 ppm with a limited range of variation between plants.

The quantity of pollutants a plant emits each year reflects the total electricity generated by that plant, the amount of coal it uses per kWh, and its emissions per ton of coal burned. Pollution intensity (i.e. quantity of pollutant per kWh generated) 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 government owned plants. The pollution intensity of SO_2 emissions is, on average, higher at Indian than at U.S. coal-fired power plants, in spite of the low sulfur content of Indian coal. The median SO_2 pollution intensity at U.S. plants in 2005 was 8.9 pounds per MWh; the mean was 12.3 pounds per MWh (NRC 2010): at Indian plants, (see Table 6) the median SO_2 intensity 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 United States and the fact that over one-quarter of U.S. coal-fired plants have scrubbers. The average pollution intensity of NO_x emissions is also higher at the plants in our database than at plants in the United States. On average, NO_x intensity at U.S. plants in 2005 was 4.10 pounds per MWh, compared with 4.6 pounds per MWh for Indian plants (see Table 6).

[16] SO_2 and NO_x emissions data are missing for plants for which coal consumption data are missing. $PM_{2.5}$ 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 and for secondary 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., $PM_{2.5}$) per unit of primary pollutant emitted from a pollution source. For example, if Q is emissions of $PM_{2.5}$ from a power plant in grams per second, ΔC_i is the change in ambient $PM_{2.5}$ 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 ΔC_i is greater than 0.[17] If the average annual intake fraction for $PM_{2.5}$ for a power plant were $1x10^{-5}$, this would mean that for every metric ton of $PM_{2.5}$ 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.

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-

[17] In Zhou et al. (2006) the average breathing rate is 20 m^3 per day.

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 3,360 km by 3,360 km. We examine the impact of each power plant in our database on an 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) $$IF * Q / BR = \sum_i P_i \Delta C_i .$$

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

(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

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

(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 cardiopulmonary mortality coefficients from Pope et al. (2002). Because Pope et al. (2002) relate premature mortality to $PM_{2.5}$, we convert estimates of SPM to $PM_{2.5}$ assuming a ratio of $PM_{2.5}$ to SPM of 0.29 (USEPA AP-42). We use SO_2 and NO_x emissions for each power plant to estimate the contribution of the plant to sulfates and nitrates, which we add to directly emitted $PM_{2.5}$.

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, only a few time-series studies relating air pollution to mortality 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 PM_{10} on daily mortality as time-series studies conducted in the United States (the NMMAPS (National Morbidity, Mortality, and Air Pollution Study)) and Europe (the APHEA project) (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 $PM_{2.5}$ using a Cox proportional hazard model. Separate coefficients are reported for exposures in 1979–1983 and 1999–2000.

Transferring all-cause mortality coefficients from Pope et al. (2002) to India may be inappropriate for two reasons: the levels of $PM_{2.5}$ in India are higher than in the United States, and the distribution of deaths by cause in the United States 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 United States in the 1979–1983 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 also lends credence to our analysis. 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 (ICD-9 codes 401–440 and 460–519). In the United States in 2007, 42.5 percent 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 percent (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 calculate the impact of air pollution on premature mortality in India, Pakistan, Bangladesh and Sri Lanka. Approximately 16 percent 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 $PM_{2.5}$, SO_2 and NO_x 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 SO_2, 120 with NO_x and 30 with $PM_{2.5}$. The table also presents information on the damages per ton of

[19] Pope et al. (2002) also find a significant impact of $PM_{2.5}$ 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 percent of deaths in India.

pollutant, which can be calculated for all plants. Damages per ton are, on average, greater for directly emitted $PM_{2.5}$ than for SO_2 or NO_x. There are, on average, 23 deaths per 1,000 tons of $PM_{2.5}$, 10 deaths per 1,000 tons of SO_2, and 9 deaths per 1,000 tons of NO_x.

Two results from Table 7 deserve emphasis: the first is that more deaths are attributable to SO_2 emissions than to either directly emitted particulates or NO_x. Although SO_2 is associated with fewer deaths per ton than $PM_{2.5}$, plants emit many more tons of SO_2 than they do of $PM_{2.5}$. (Recall that all plants use electrostatic precipitators.) NO_x is also associated with more deaths than $PM_{2.5}$ for the same reason. This suggests that more emphasis be placed on policies to control SO_2. The second is that the variation in deaths per ton of pollutant across plants is small: deaths per 1,000 tons of $PM_{2.5}$ range from 15 (5th percentile) to 29 (95th percentile). For SO_2, they range from 7 (5th percentile) to 12 (95th percentile). This variation is due solely to differences in plant location and 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 United States.

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, they 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 percent ash content (CEA 2010), only 5 percent 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 and improves its heating value: it also removes small amounts of other substances, such as sulfur and hazardous air pollutants. The use of washed coal improves the combustion efficiency of a plant (less coal needs to be burned to produce electricity). Per unit of heat input, particulate and sulfur emissions are reduced, as are flyash disposal costs and the cost of transporting coal. 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 2,000 MW plant that in 2008 produced 17,000 GWh of electricity, using coal with a sulfur content of 0.39 percent and an ash content of 43 percent. We assume that using washed coal would reduce the ash content of coal burned to 35 percent and the sulfur content to 0.34 percent and would raise the heating value of coal by 17 percent. 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 percent, 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 $PM_{2.5}$ emissions, and reductions in sulfur emissions. Tons of $PM_{2.5}$ and SO_2 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 $PM_{2.5}$ emissions. This is particularly significant because the coal used at Rihand has a sulfur content of 0.39 percent, which is lower than the average for Indian coal. Our estimates assume that NO_x emissions are essentially proportional to the energy throughput of the boiler. The assumption of unchanged electricity generation thus implies unchanged emissions of NO_x.

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 the range of

estimates of the value of a statistical life (VSL) for India which, conservatively estimated, ranges 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.

Various scrubber technologies exist: in the United States wet scrubbing is the most common. The U.S. EPA's AP-42 database indicates that a wet scrubber can achieve up to 95 percent SO_2 removal; equipment suppliers claim SO_2 removal efficiencies of up to 99 percent 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 percent.[22]

Capital costs of wet scrubbers range from $100 to $200 per KW while the auxiliary power required for operation ranges from 1.0 to 3.0 percent of plant output, depending on coal sulfur level and removal level (MIT 2007). Operating costs of FGD units in the United States average 0.16 cents/kWh[23] and range 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 percent 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 operations and maintenance (O&M) cost for a FGD

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[21] Bhattacharya et al. (2007) report a preferred VSL estimate of Rs 1.3 million (2006 Rs) 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.

[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.

is instead taken as the average figure for the United States, the effect is to increase the lcoe by a further 6 percent (see Appendix for details).

Assuming coal with 0.5 percent sulfur content and an SO_2 removal rate of 80 percent, 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 percent of the levelized cost of electricity (see Appendix). Benefits will be lower at plants burning coal with sulfur content lower than 0.5 percent. The benefits of installing a scrubber with an 80 percent 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 SO_2 at the Dahanu plant are among the lowest of all plants in our database.

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, SO_2 and NO_x 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 SO_2 emissions (Chikkatur and Sagar 2007). This paper suggests that more emphasis should be placed on direct SO_2 controls. The current approach—relying on tall stacks—mirrors the approach taken in the United States 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 United States, 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 SO_2 emissions from coal-fired power plants, makes SO_2 the main pollutant of concern from a health standpoint.

Whether the use of FGDs to reduce SO_2 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 value of a statistical life for India), in spite of the fact that the deaths per ton of SO_2 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 due mainly to the lower quantity of coal burned per kWh generated as well as to small reductions in the sulfur content of coal burned. The percentage reduction in SO_2 emissions due to coal washing at the Rihand plant (see Table 9) is 25 percent. Due to the importance of sulfates versus directly emitted PM, the reduction in SO_2 emissions conveys more health benefits than the 30 percent reduction in directly emitted $PM_{2.5}$.

Our estimates can also be used to calculate a lower bound to monetary damages per ton of $PM_{2.5}$, SO_2 and NO_x, given appropriate estimates of the VSL for India. These damages could be used to calculate pollution taxes, as well as to conduct benefit-cost analyses of specific pollution control strategies.

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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 Center.[25] The F-factor calculation requires a value for the oxygen content of flue gas—this was taken as 4 percent (personal communication from CEA). The resulting emissions rate for SPM was converted to $PM_{2.5}$ using data on particle size distribution from the U.S. EPA's AP-42 methodology.

Emissions of SO_2 were estimated assuming that 7.5 percent 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 percent 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 500 MW subcritical

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

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

   Our cost analysis (and the CEA's) 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 (PLF) and also to 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 $PM_{2.5}$ emissions was estimated for an 8 percent reduction in coal ash content assuming that 80 percent of coal ash goes to fly ash, of which 99.84 percent 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 operations and maintenance (O&M) cost for a FGD is instead

[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.

taken as the average figure for the United States,[28] the effect is to increase the lcoe by a further 6 percent.

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

500 MW plant with no FGD	1.134
500 MW plant with FGD: O&M cost from Dahanu regulatory hearing	1.233
500 MW plant with FGD: O&M cost from EIA data for U.S.	1.296
500 MW 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 Coal India Limited price for thermal coal in 2010, including royalty and similar charges but excluding value added tax.

Estimation of Health Damages using Intake Fractions

Zhou et al. (2006) used CALPUFF, a Gaussian dispersion model recommended by the U.S. 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. 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 100 km, 500 km and 1,000 km from the plant, and beyond 1,000 km but within the overall domain). R^2s for these models ranged between 0.89 and 0.96.

[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.

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., populations living within 100 km, 500 km and 1,000 km 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 1,000 km) 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.

[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 0-100 km	Pop 100-500 km	Pop 500-1,000 km	Pop >1,000 km	Precipitation
SO_2	0.96	9.9E-08**	1.3E-08**	3.0E-09	1.8E-09**	-6.3E-10
PM_1	0.96	1.5E-07*	2.3E-08**	1.1E-08**	3.9E-09**	-1.7E-09**
PM_3	0.92	1.4E-07*	1.7E-08**	6.4E-09	3.0E-09**	-2.4E-09**
PM_7	0.91	9.9E-08**	8.9E-09*	3.1E-09	1.5E-09*	-1.2E-09**
PM_{13}	0.89	6.7E-08**	4.3E-09	9.4E-10	7.3E-10	-4.6E-10*
SO_4	0.95	2.4E-08	7.9E-09*	6.9E-09**	2.6E-09**	-1.2E-09**
NO_3	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.

Tables and Figures

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. *www.cea.nic.in/reports/monthly/executive_rep/mar10/8.pdf.* Accessed online December 29, 2011.

Table 2. Ambient Air Quality Standards for PM, SO_2 and NO_x in India [a]

Pollutants	Concentration in Ambient Air: Industrial, residential, rural and other areas		Ecologically sensitive areas (notified by central government)	
	Time weighted Averages			
	24 hourly[c, d] Standard ($\mu g/m^3$)[b]	Annual [c] Standard ($\mu g/m^3$)[b]	24 hourly[c,d] Standard ($\mu g/m^3$)[b]	Annual[c] Standard ($\mu g/m^3$)[b]
Sulphur Dioxide (SO_2)	80	50	80[g]	20[g]
Nitrogen Dioxide (NO_2)	80	40	80[g]	30[g]
Particulate Matter(RPM)				
PM_{10}	100	60	100	60
$PM_{2.5}$[h]	60	40	60	40
Ozone[h]	180[d,f]	100[e,f]	180[d,f]	100 [e,f]

a. National Ambient Air Quality Standards (NAAQS) adopted November 18, 2009.
b. $\mu g/m^3$: microgram per cubic meter.
c. Annual average: arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.
d. 1-hourly
e. 8-hourly
f. 24-hourly, 8-hourly, or 1-hourly monitored values, as applicable, should be complied with 98 percent of the time in a year. However, 2 percent of the time, these may be exceeded, but not on 2 consecutive days of monitoring.
g. Standards are applicable uniformly across residential and industrial areas, with the exception of these more stringent standards for NO_2 and SO_2 in the Ecologically Sensitive Areas.
h. Fine particulate matter ($PM_{2.5}$) and Ozone standards were added in 2009. Other new parameters, such as arsenic, nickel, benzene and benzo(a) pyrene have been included for the first time under NAAQS based on CPCB/IIT Research, World Health Organization guidelines and European Union limits and practices (See Department of Environment and Forests, Government of NCT of Delhi, 2010).

Source: Central Pollution Control Board, Government of India. Accessed on April 2, 2012: http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php.

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/Nm^3
210 MW & above		150 mg/Nm^3

Source: Central Pollution Control Board website, accessed on April 2, 2012
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: Central Pollution Control Board, Government of India. http://www.cpcb.nic.in/ Accessed on April 2, 2012.

Table 5. Distribution of Plant Performance Indicators 2008

	All Plants, 2008							
				Percentile				
	# obs	Mean	Std Dev	5th	25th	Median	75th	95th
Nameplate capacity (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
De-rated 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				Privately owned			
	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev
Nameplate capacity (MW)	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
De-rated Capacity (MW)	57	697	630	493	22	1339	1025	862	11	307	260	158
Net Generation (GWh)	57	3996	2891	3384	22	9104	7398	6905	8	2327	2226	1641
Net Efficiency (GWh/Joule)	39	0.28	0.28	0.04	6	0.25	0.26	0.03	2	0.33	0.33	0.01
Design Heat Rate (Kcal/kWh)	39	2405	2350	177	6	2507	2484	141	5	2301	2314	77
Operating Heat Rate (Kcal/kWh)	39	2866	2770	432	6	3116	3016	410	5	2460	2454	151
Specific Coal Consumption (Kg/kWh)	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 (Kcal/Kg)	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/Nm^3)	75	117	118	24	65	103	132	216
Max SPM recorded (mg/Nm^3)	75	207	271	61	116	143	187	535
Mid-point SPM (mg/Nm^3)	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
SO_2 (tons/year)	68	44254	36068	5047	16475	40260	60174	119518
SO_2 (g/MWh)	68	7147	1024	5735	6290	6937	7863	8788
NO_x (tons/year)	68	12944	10550	1476	4819	11776	17601	34959
NO_x (g/MWh)	68	2091	299	1677	1840	2029	2300	2570

	State-owned				Center-owned				Privately owned			
	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev	# obs	Mean	Median	Std Dev
Min SPM recorded (mg/Nm^3)	49	139	122	138	20	90	84	35	6	26	26	6
Max SPM recorded (mg/Nm^3)	49	254	157	324	20	127	128	51	6	88	86	32
Mid-point SPM (mg/Nm^3)	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
SO_2 (tons/year)	44	37682	38475	26098	19	67310	50512	47743	5	14475	11141	10095
SO_2 (g/MWh)	44	7455	7446	1004	19	6592	6567	621	5	6549	6198	1428
NO_x (tons/year)	44	11022	11254	7634	19	19688	14775	13965	5	4234	3259	2953

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
SO_2	63	499	407	71	208	407	645	1297
NO_x	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
SO_2	89	0.010	0.002	0.007	0.010	0.011	0.011	0.012
NO_x	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
SO_2	63	0.074	0.015	0.049	0.063	0.073	0.083	0.100
NO_x	63	0.019	0.005	0.013	0.016	0.018	0.021	0.027

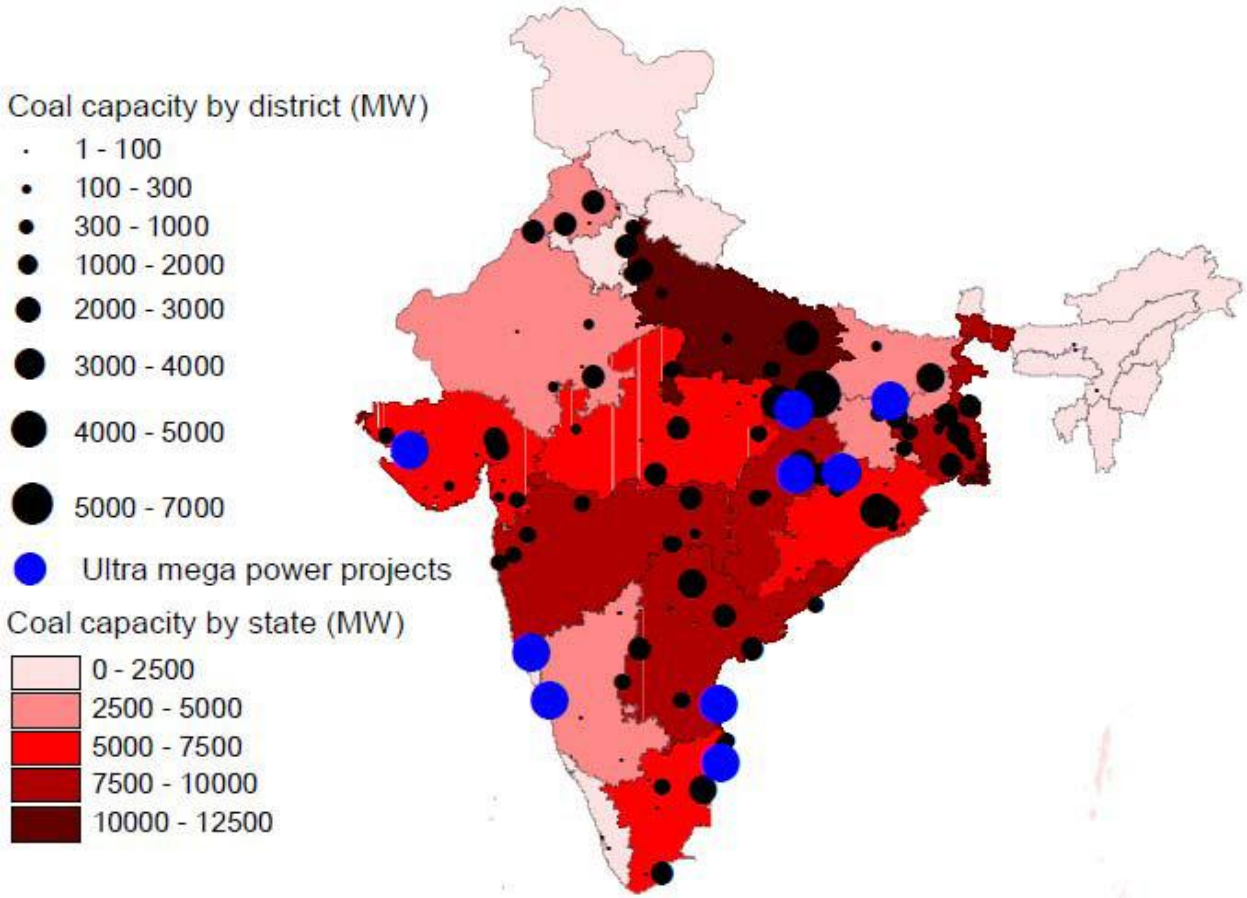
Table 8. Distribution of Deaths Attributable to Emissions by Plant Ownership Status 2008

	State-owned				Center-owned				Privately 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
SO_2	41	418	370	283	17	804	640	530	5	130	114	81
NO_x	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
SO_2	56	0.011	0.011	0.001	22	0.010	0.011	0.002	11	0.009	0.010	0.001
NO_x	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
SO_2	41	0.076	0.077	0.017	17	0.072	0.072	0.008	5	0.062	0.059	0.017
NO_x	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 at Rihand Thermal Power Station, 2008

	Unwashed coal	Washed coal	% reduction due to washing
Coal usage (`000 tons)	10903	9322	14%
$PM_{2.5}$ (tons/year)	1732	1207	30%
SO_2 (tons/year)	77854	58032	25%
NO_x (tons/year)	25828	25828	0%
Total deaths (all pollutants)	1241	990	20%
Total deaths due to			
$PM_{2.5}$	43	30	30%
SO_2	934	696	25%
NO_x	264	264	0%
Deaths (per GWh)	0.074	0.059	20%
Total deaths (per GWh) due to			
$PM_{2.5}$	0.0026	0.0018	30%
SO_2	0.0548	0.0409	25%
NO_x	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.