Chapter 13

Costs and Benefits of Installing Flue-Gas Desulfurization Units at Coal-Fired Power Plants in India

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INTRODUCTION

Coal-fired power plants, in addition to emitting greenhouse gases, are a major source of local pollution and health damages throughout the world. China, the United States, and other countries that rely on coal for electricity production regulate emissions from coal-fired power plants, primarily for health reasons. In the United States, the 1990 Clean Air Act Amendments caused many power plants to switch to low-sulfur coal or to install flue-gas desulfurization units (FGD units, or scrubbers). Subsequent tightening of sulfur dioxide (SO_2) regulations has caused more plants to scrub their emissions. In 2010, power plants with FGD units accounted for 60 percent of the electricity generated from coal in the United States (Schmalensee and Stavins 2013). By 2013, 95 percent of China's coal-fired generating capacity had been fitted with FGD units (Ministry of Environmental Protection 2014).

India, which relies on coal to generate 76 percent of its electricity (CEA 2015), did not regulate SO_2 emissions from coal-fired power plants until December 2015. That lack of regulation may have been due, in part, to the low sulfur content of Indian coal (Chikkatur and Sagar 2007). Indian coal is approximately 0.5 percent sulfur by weight, similar to Powder River Basin (PRB) coal in the United States (Lu and others 2013). However, the population exposed to SO_2 emissions from power plants in India is much greater than that in the United States, as is the amount of coal burned to generate a kilowatt hour (kWh) of electricity. Recent studies suggest serious health effects associated with SO_2 emissions from Indian power plants. Guttikunda and Jawahar (2014) estimate that Indian power plants caused more than 80,000 deaths in 2011; they attribute 30–40 percent of these deaths to SO_2. Cropper and others (2012) suggest that as many as 60 percent of the deaths associated with coal-fired power plants in India may be attributable to SO_2 emissions rather than to directly emitted particulate matter or oxides of nitrogen (NOx).

This chapter analyzes the health benefits and the costs of installing FGD units at each of the 72 coal-fired power plants in India, plants that in 2009 constituted 90 percent of coal-fired generating capacity. We estimate the health benefits of one FGD unit by estimating SO_2 emissions from a plant without an FGD unit and then translating those emissions into changes in ambient air quality. This is accomplished using an Eulerian photochemical dispersion model (CAMx) that allows SO_2 to form fine sulfate particles (smaller than 2.5 micrometers in diameter [$PM_{2.5}$]) in the atmosphere. The impacts of $PM_{2.5}$ on premature mortality are estimated for ischemic heart disease, stroke, lung cancer, chronic obstructive pulmonary disease (COPD), and acute lower respiratory infection (ALRI) using the integrated exposure response (IER) coefficients in Burnett and others (2014).

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We assume that a scrubber will reduce SO_2 emissions by 90 percent. The annual reductions in premature mortality and associated life years lost resulting from use of scrubbers are combined with an estimate of annualized capital and operating costs to compute the cost per statistical life saved and cost per disability-adjusted life year (DALY) averted associated with each FGD unit.

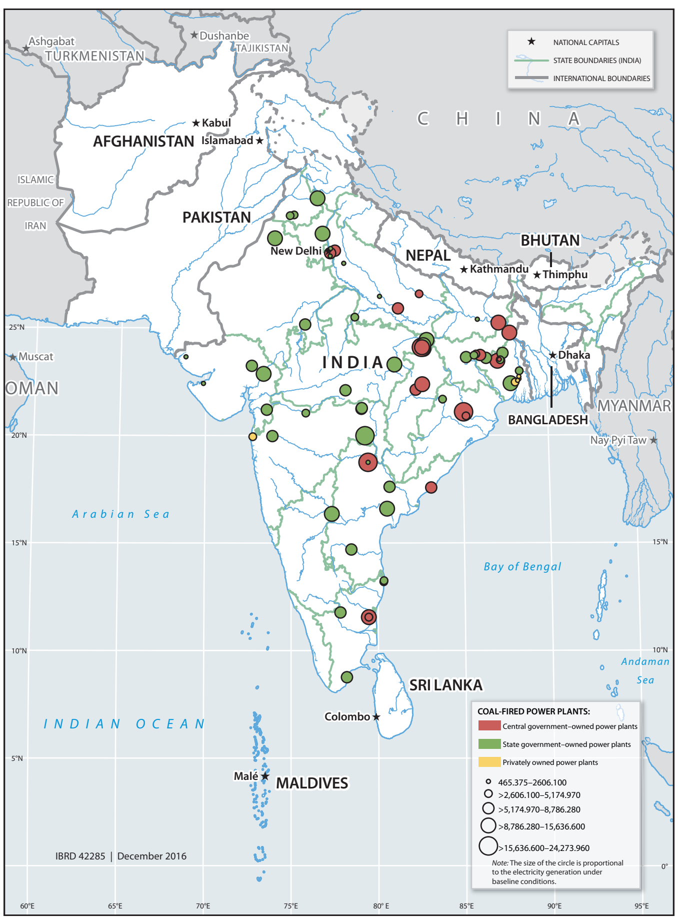
Reducing SO_2 emissions from coal-fired power plants offers additional benefits that we do not quantify. These include improvements in visibility (which yield aesthetic and recreation benefits) and reduced acidic deposition. Acidic deposition can reduce soil quality (through nutrient leaching), impair timber growth, and harm freshwater ecosystems (USEPA 2011).

METHODS

Estimating the Health Impacts of SO_2 Emissions from Power Plants

Our analysis focuses on 72 coal-fired power plants (shown in map 13.1) which in March 2009 constituted 90 percent of the coal-fired generating capacity connected to the grid in India. The size of each circle on the map is proportional to the electricity generated by each plant. State governments owned 45 of the plants, the central government owned 22, and private entities owned 5. Table 13.1 describes the operating characteristics of these plants in terms of installed capacity, electricity generated, and other characteristics. We analyze the impact of plant emissions in 2008–09, the year for which we have information on the sulfur content of coal.[1]

Map 13.1 Coal-Fired Power Plants: All Plants in Dataset



Total coal-fired generating capacity in India doubled between March 2009 and March 2015 (CEA 2015), from 76 gigawatts (GW) to 164.6 GW.[2] Accordingly, our analysis underestimates the health impacts of current SO_2 emissions from the power sector. We note, however, that the plants we analyze remain subject to pollution control laws, and most plants would find it difficult to meet these laws without installing FGD units.

To calculate the SO_2 emissions of each plant, we must know the plant's annual electricity generation, the amount of coal burned per kWh, and the sulfur content of the coal burned.[3] We estimate the cost-effectiveness of FGD units using the Central Electricity Regulatory Commission of India's benchmark operating conditions.[4] These assume that each plant operates at 85 percent of capacity (the median operating capacity for the 72 plants was 79 percent in 2008–09). We use benchmark conditions because actual operating conditions are likely to fluctuate from year to year.

Coal consumption per kWh is based on actual coal consumption per kWh in 2008–09. On average, coal burned per kWh is much higher at Indian power plants than at coal-fired power plants in the United States (0.77 kg/kWh versus 0.47 kg/kWh) (Malik 2013). This difference is due in part to the lower heat content of Indian coal, but it is also due to inefficiencies in plant operation (Chan, Cropper, and Malik 2014). The sulfur content of coal (averaging 0.53 percent sulfur by weight) comes from a survey of Indian power plants conducted by the authors. This finding corresponds closely to figures reported by Lu and others (2013), Garg and others (2002), and Reddy and Venkataraman (2002). Based on benchmark conditions, the 72 plants emit approximately 3 million tons of SO_2 annually.

CAMx, an Eulerian photochemical dispersion model, was run to estimate the impact of each plant's SO_2 emissions on ambient air quality.[5] The model, which includes gas-to-aerosol conversion for SO_2 to sulfates, supports plume rise calculations for each power plant using three-dimensional meteorological data.[6] The model was run separately for each plant, simulating 365 days of emissions, to calculate the increase in annual average fine particle concentrations corresponding to the plant's emissions. The model was run at a 0.25°grid resolution

Table 13.1 Operating Characteristics of Power Plants in the Dataset

Summary Statistics—Actual Operations

	Average	Standard deviation	Median	Minimum	Maximum
Nameplate capacity (MW)	948	674	840	63	3,260
Generation (GWh)	6,393	5,446	5,305	103	26,601
Capacity utilization (%)	75	20	79	11	100
Sulfur content of coal (%)	0.53	0.19	0.5	0.21	2.00
SO_2 emissions (tons/yr)	37,727	31,857	30,423	778	188,010

Note: Number of observations = 72 power plants. Data based on actual operations for the year 2008–09. GWh = gigawatt hour; MW = megawatt; SO_2 = sulphur dioxide.

and combined with 2011 population data to calculate the population-weighted increase in annual average $PM_{2.5}$ concentrations associated with the plant.

Epidemiological research has found consistent associations between premature mortality and $PM_{2.5}$. Pope and others (2002) report significant impacts of exposure to $PM_{2.5}$ in cities in the United States on all-cause, cardiopulmonary, and lung cancer mortality. This work formed the basis of early studies of the global burden of air pollution (Cohen and others 2004). More recent studies of the Global Burden of Disease (GBD) (Lim and others 2013) use meta-analyses of epidemiological studies from several sources to quantify the impact of a wider range of $PM_{2.5}$ exposures on cardiovascular and respiratory deaths, as well as deaths from lung cancer and ALRI (Burnett and others 2014). The 2013 GBD estimates that 587,000 deaths in India in 2013 were attributable to ambient air pollution (GBD 2013 Risk Factors Collaborators 2015).

Premature mortality associated with the increase in annual average $PM_{2.5}$ concentrations for each plant was calculated as the product of baseline deaths (by cause) and the fraction of deaths attributable to sulfates. The fraction of deaths attributable to sulfates for each disease is given by $1\text{-}\exp(\beta^*\Delta C)$, where β is the change in the relative risk attributable to a one microgram per cubic meter change in $PM_{2.5}$, and ΔC is the population-weighted change in ambient $PM_{2.5}$ concentrations associated with SO_2 emissions from the plant. The β coefficients were calculated using the IERs for ischemic heart disease, stroke, lung cancer, COPD, and ALRI developed by Burnett and others (2014) and reported by the Institute for Health Metrics and Evaluation (IHME).[7] For each disease, the change in relative risk (β) was evaluated at the population-weighted annual average exposures for India used in the 2010 Global Burden of Disease (Brauer and others 2012).[8] Baseline deaths by age and cause were obtained from the IHME.[9]

We also calculate the years of life lost (YLL) associated with mortality attributable to SO_2 emissions. We estimate that, on average, each death is associated with 25.54 YLL, a figure close to that reported in the 2013 GBD. DALYs lost because of $PM_{2.5}$ are the sum of YLL and years lived with disability (YLD). In the 2013 GBD, 97 percent of DALYs associated with ambient air pollution are YLL. We have not calculated the YLD associated with SO_2 emissions; therefore, our estimates of the health benefits of emissions reductions understate total health benefits.

Estimates of Health Effects Associated with SO_2 Emissions

Our calculations suggest that approximately 15,500 deaths in 2013 were attributable to SO_2 emissions from the 72 plants, with stroke (7,600) and ischemic heart disease (4,200) accounting for the majority of deaths. Table 13.2 reports the distribution of deaths and DALYs (by cause) for the 72 plants. These deaths, in the aggregate, are associated with approximately 400,000 YLL.[10] If the plants in our study were to operate under benchmark operating conditions at capacity factors of 85 percent, the deaths attributable to SO_2 emissions would increase to approximately 17,900 per year, with an associated 457,000 YLL.

The number of deaths per plant varies from more than 1,300 to fewer than 20. The 30 plants with the highest number of deaths account for 78 percent of the total deaths and 56 percent of the total generation capacity. The 20 plants with the highest number of deaths account for 65 percent of total deaths. Deaths per plant are correlated with total emissions ($r = 0.38$) and also with the size of the exposed population. Population density in India is highest in the north of India, which is also the part of India with the highest levels of ambient $PM_{2.5}$. Therefore, it is not surprising that the 30 plants with the highest number of deaths (map 13.2) are located in northern India.

Costs and Benefits of FGD Units

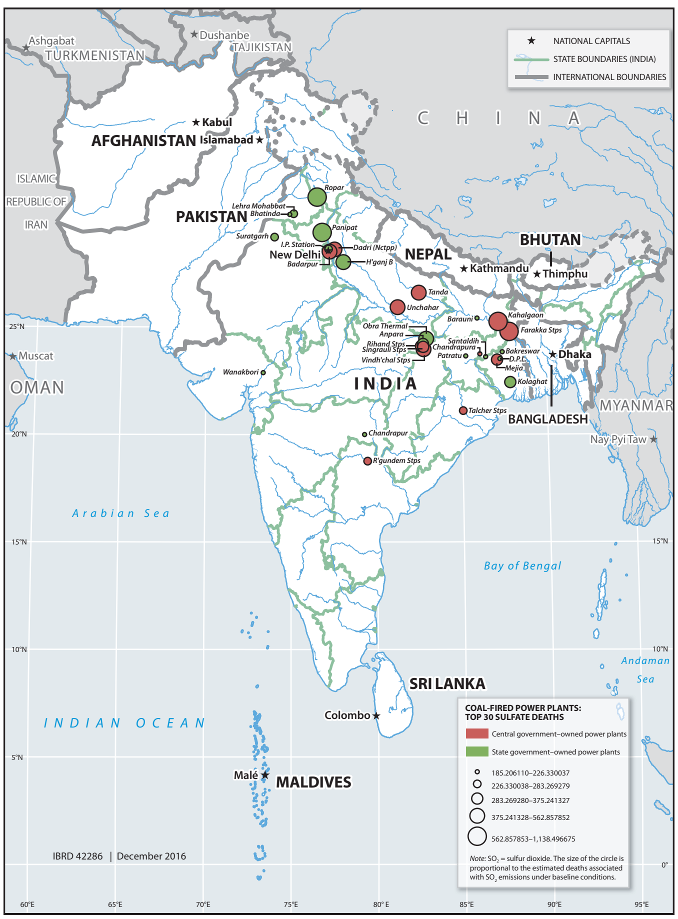
An FGD unit is an end-of-pipe technology that removes SO_2 from combustion gases before they exit the smokestack. Flue gases are treated with an alkaline

Table 13.2 Deaths and DALYs Associated with SO_2 Emissions, by Plant

Cause	Deaths			DALYs		
	Mean	25%ile	75%ile	Mean	25%ile	75%ile
COPD	18.5	5.5	20.1	351	104	392
Stroke	106	31.4	115	2,230	660	2,490
IHD	58.8	17.4	63.8	1,350	399	1,510
ALRI	29.9	8.9	32.5	1,510	449	1,690
Lung cancer	2.3	0.68	2.6	60.1	17.8	67.1
All causes	216	64	241	5,500	1,630	6,150
All causes, benchmark conditions	249	77.3	301	6,360	1,974	7,690

Note: ALRI = acute lower respiratory infection; COPD = chronic obstructive pulmonary disease; DALY = disability-adjusted life year; IHD = ischemic heart disease; SO_2 = sulphur dioxide.

Map 13.2 Coal-Fired Power Plants: Top 30 Sulfate Deaths



substance that reacts with the acidic SO_2 to form a by-product that is removed before flue gases are emitted. In a wet limestone FGD (wFGD) unit, gases are treated with limestone slurry, which is sprayed on the gas in an absorber unit. Gypsum, which can be sold commercially, is produced as a by-product. Approximately 85 percent of the scrubbers installed in the United States are wet scrubbers (USEPA 2004).[11] Another rapidly expanding technology is seawater FGD (swFGD) units. These units use the alkalinity of seawater to remove SO_2 from the flue gases; the by-product is water, which is then treated and discharged back into the sea. Seawater FGD units are capable of reducing SO_2 emissions up to 95 percent, depending on the technology used.[12]

Both scrubber technologies are in use in India. The Indian Supreme Court required the installation of an FGD unit at the Dahanu plant in Maharashtra. FGD units are also in operation at the Trombay and Udupi plants (table 13.3).[13] Both Dahanu and Trombay have swFGD units. Seawater FGD units have lower capital costs and much lower variable costs than wFGD units, but they can be installed only in coastal areas. We assume that FGD units installed at plants in coastal areas are swFGD units, and that FGD units installed at all other locations are wFGD units.

The estimates of FGD unit costs are based on tariff orders issued by State Electricity Regulatory Commissions (SERCs) for power plants that currently operate an FGD unit or for plants that are planning to install one in the near future (table 13.3). We also use information from tariff determination norms and calculations of benchmark capital costs used by the Central Electricity Regulatory Commission (CERC 2009).[14]

Table 13.4 shows the assumptions used to construct the cost estimates. We assume a capital cost of US$84,000/MW for a swFGD unit (MERC 2009, 2011) and a cost of US$109,000/MW for a wFGD unit, based on 250 MW units.[15] For smaller units, we assume that the elasticity of capital costs with respect to installed capacity is −0.3 (Cichanowicz 2010). The greater costs for wFGD units reflect the expenditures for reagent handling and by-product disposal facilities. In contrast, swFGD units discharge their water by-product back into the sea and do not require as much capital investment.

Table 13.3 FGD Units in India, Planned and Operational

Location	Company	State	Status of FGD unit	Capacity	Manufacturer	Type
Trombay	TATA Power	Maharashtra	Operating	Unit 5: 500 MW	ABB	Seawater
Trombay	TATA Power	Maharashtra	Operating	Unit 8: 250 MW	—	Seawater
Ratnagiri	JSW	Maharashtra	Under construction	1,200 MW (4 units × 300 MW)	Alstom	Seawater
Udupi	LANCO	Karnataka	Operating	1,200 MW (2 units × 600 MW)	Ducon	Wet limestone
Dahanu	RELIANCE	Maharashtra	Operating	500 MW	Ducon	Seawater
Bongaigaon	NTPC	Assam	Under construction	750 MW	BHEL	Wet limestone
Vindhyachal, stage V	NTPC	Madhya Pradesh	Planned	500 MW	BHEL	Wet limestone
Mundra, stage III	ADANI	Gujarat	Planned	1,980 MW	—	Seawater

Note: FGD = flue-gas desulfurization; MW = megawatt; — = not available.

Table 13.4 Operating Characteristics for Cost Calculations: Baseline Assumptions

	Benchmark	
Capacity utilization (%)	85	
Capital discount rate (%)	8	
Plant life (retrofit) (yrs)	20	
	FGD Unit Type	
	Wet limestone	**Seawater**
Capital costs (US$/MW)	$109,091	$84,364
Fixed operating costs (US$/MWh)	$0.473	$0.364
Electricity costs (US$/kWh)	$0.0636	$0.0636
Auxiliary consumption (%)	1.5	1.25
FGD unit efficiency (%)	90	90
Retrofit cost factor (%)	30	30

Note: The capital costs above are derived from information for the Dahanu (seawater FGD unit) and Bongaigaon (wet FGD unit) power plants. In both cases, the costs reflect installation of an FGD unit in a new plant and not a retrofit. Costs are increased by 30 percent to reflect the higher costs of retrofitting a scrubber. FGD = flue-gas desulfurization; kWh = kilowatt hour; MW = megawatt; MWh = megawatt hour.

As a comparison, these figures are slightly lower than wFGD unit prices in the United States prior to the post-2006 spike in prices.[16] Capital and operating costs per plant are summarized in table 13.5. We note that the cost per ton of SO_2 removed implied by our calculations is, on average, US$613 (2013 US$).

To calculate the health benefits of installing an FGD unit, we assume that the FGD unit will remove 90 percent of SO_2 emissions. Because of the linearity of sulfate formation and the approximate linearity of relative risk for a small change in concentrations, this reduction in emissions implies a 90 percent reduction in deaths attributable to SO_2 emissions. An important question is the period over which this reduction would occur. Apte and others (2015) assume no lag between emissions reductions and the associated reductions in deaths. USEPA (2011) assumes that 80 percent of the reduction in $PM_{2.5}$ mortality is achieved within five years of the reduction in emissions. We view our calculations as representing the benefits of a scrubber that has been in operation for at least 5 years and therefore assume that 80 percent of the reduction in mortality has been achieved in calculating lives saved and DALYs averted.

RESULTS

Our benchmark calculations suggest that requiring all 72 plants in our study to install scrubbers would save 12,890 lives and 329,000 DALYs annually, at an average cost of US$131,000 per life saved or US$5,140 per DALY averted (table 13.6).[17] The cost per life saved (CPLS) of installing a scrubber, however, varies greatly across plants, from US$24,700 to US$1,244,000, depending on the magnitude of the plant's emissions and the size of the exposed population. If plants are ranked by their CPLS, retrofitting scrubbers at the 30 most cost-effective plants would save approximately 9,200 lives at an average cost of US$67,000 per life saved or US$2,600 per DALY averted.[18] Requiring scrubbers at the 30 plants with the highest deaths associated with SO_2 emissions would save more lives and DALYs (10,060 and 257,000, respectively) at a higher average CPLS of US$96,000. This finding is not surprising: lives saved (the denominator when calculating CPLS) is increasing in the number of deaths associated with the plant when operating without an FGD unit; hence, CPLS is negatively correlated with deaths attributable to baseline SO_2 emissions for each plant ($r = -0.43$).[19]

Table 13.5 Capital and Operating Costs of FGD Unit Installation per Plant

Summary Statistics: Benchmark Operations

	Average	Standard deviation	Median	Minimum	Maximum
SO_2 emissions (tons/yr)	42,678	30,344	36,405	2,704	169,192
FGD unit capital costs (US$, millions)	133	95.4	119	10.9	462
Operating costs, fixed (US$, millions)	3.3	2.4	3.0	0.22	11.5
Operating costs, variable (US$, millions)	6.7	4.8	6.0	0.4	23.2
Total annual FGD unit cost (US$, millions)	23.5	16.9	21.1	1.77	81.7

Note: Number of observations = 72 power plants. Calculations based on benchmark capacity utilization of 85 percent. FGD = flue-gas desulfurization. SO_2 = sulphur dioxide.

Table 13.6 Cost-Effectiveness of FGD Unit Installation, US$

	Total lives saved	Total cost (millions)	Cost per Life Saved, by Plant			Total DALYs averted	Cost per DALY Averted, by Plant		
			Median	Minimum	Maximum		Median	Minimum	Maximum
All plants	12,890	$1,691	$167,000	$24,700	$1,244,000	329,000	$6,540	$967	$48,713
30 plants with lowest CPLS	9,196	$615	$62,490	$24,707	$137,474	235,000	$2,447	$967	$5,383
30 plants with most deaths	10,061	$965	$111,980	$24,707	$381,676	257,000	$4,385	$967	$14,944
30 largest plants (MW)	7,910	$1,164	$251,980	$33,439	$1,244,127	202,000	$9,866	$1,309	$48,713

Note: Calculations based on benchmark operating conditions (capacity factor of 85 percent), assuming an FGD unit removes 90 percent of flue gases. The number of lives saved (or DALYs averted) is the number saved five years after installation, holding population and death rates at 2013 levels. CPLS = cost per life saved; DALY = disability-adjusted life year; FGD = flue-gas desulfurization; MW = megawatt.

However, identifying plants with the lowest CPLS may be difficult from a policy perspective. A more likely option would be to require the largest plants to scrub their emissions. The 30 largest plants in terms of installed capacity account for 61 percent of sulfate deaths. Requiring them to be retrofitted with FGD units would save approximately 7,910 lives and 202,000 DALYs, at an average CPLS of US$147,000 (US$5,760 per DALY averted). This approach clearly delivers fewer health benefits per dollar spent than requiring the plants associated with the largest number of deaths and DALYs to scrub their emissions. Although economies of scale exist in scrubber installation, and although deaths are positively correlated with plant size, the effectiveness of a scrubber also depends on the size of the exposed population; the largest plants are not necessarily those with the largest exposed populations.[20]

To maximize the number of lives saved for a given amount spent, plants with the lowest CPLS would be retrofitted first. These are not necessarily the largest plants. The benefits of installing a scrubber depend on the size of the exposed population, which depends on plant location. The 30 plants with the lowest CPLS associated with SO_2 emissions are primarily located in densely populated northern India, primarily in Uttar Pradesh, West Bengal, Punjab, Haryana, and Jharkhand.

Our estimates are sensitive to assumptions about scrubbing costs, as well as to assumptions about health impacts. Our baseline discount rate of 8 percent is a social discount rate, equal to the rate of interest on government bonds in India. If this is replaced by the weighted private cost of capital, which we estimate to be 11.2 percent, the CPLS would increase by 14.3 percent, from US$131,000 to US$150,000.[21] Reducing capacity factors from the benchmark level of 0.85 to 0.68 would increase the CPLS by approximately 20 percent. At the same time, our estimate of the impact of a cessation lag is quite conservative. We effectively assume that only 80 percent of the ultimate mortality benefits of scrubbing will be received. Eliminating the cessation lag would reduce the CPLS by 20 percent.

We also note that retrofitting power plants with scrubber units would increase the cost of electricity. In Cropper and others (2012), we estimate that a swFGD unit would increase the levelized cost of electricity by approximately 9 percent. A wFGD unit could increase the cost by up to 15 percent.

DISCUSSION

Compared to coal mined in the rest of the world, domestic coal in India has high ash content but low sulfur content. Since 1984, regulations have limited particulate matter emitted directly from coal-fired power plants; however, before December 2015, no regulations existed that would limit secondary particle formation by restricting emissions of SO_2 or NOx.[22] Plants are, however, subject to minimum stack height requirements and plants generating 500 MW of electricity or more are required to leave space to allow for an FGD unit retrofit in the future. Plants generating between 210 and 500 MW of electricity must have stacks at least 220 meters in height; units that generate more than 500 MW of electricity must have stacks at least 275 meters in height. Taller stacks decrease ambient SO_2 concentrations by causing the particulate matter they emit to be dispersed over a larger area, but they do not eliminate exposure, especially in densely populated areas.

In December 2015, the Ministry of Environment, Forests and Climate Change issued limits on SO_2 emissions.[23] Plants built before 2017 that generate more than 500 MW of electricity are restricted to SO_2 emissions of 200 milligrams per cubic meter (mg/Nm^3); plants that generate less than 500 MW are restricted to SO_2 emissions of 600 mg/Nm^3.[24] A plant burning coal that contains 0.5 percent sulfur by weight emits approximately 1,350 mg/Nm^3, thus violating current standards. Retrofitting the plant with an FGD unit would permit the plant to achieve the Ministry's standards.[25] Currently, three plants in India have installed FGD units—Dahanu (Maharashtra), Trombay (Maharashtra), and Udupi (Karnataka). According to the Central Electricity Authority, eight FGD units either are in operation or are in the planning stages (table 13.3).

Our analysis suggests that the emphasis placed on SO_2 controls is warranted. The historic approach—relying on tall stacks—mirrors the approach taken in the United States in the 1980s to achieve local air quality standards. Although Indian coal has lower sulfur content than coal mined in the eastern United States, a greater amount of coal is used to produce a kWh of electricity in India because of the low heating value of Indian coal. In addition, the increase in imported coal with higher sulfur content will potentially increase the average sulfur content of coal used in Indian power plants. The large numbers of people exposed combined with the magnitude of SO_2 emissions from coal-fired power plants makes SO_2 a key pollutant of concern from a health standpoint.

CONCLUSIONS

Our analysis suggests that retrofitting existing plants with FGD units could yield significant health benefits. Requiring all 72 plants in our sample to retrofit FGD units would save almost 13,000 lives (330,000 DALYs) annually at an average cost of US$131,000 per life saved (US$5,140 per DALY averted). However, considerable heterogeneity exists in the CPLS across plants. Targeting the retrofitting regulation to plants with lower CPLS would be more cost-effective.

For any of the policy options considered, a relevant question is whether the CPLS is less than the value of the associated mortality reductions, measured in terms of what people are willing to pay for them. In the United States and other Organisation for Economic Co-operation and Development (OECD) countries, the value of mortality risk reductions is measured by the value per statistical life (VSL)—the sum of what people would pay for small risk reductions that sum to one statistical life saved.[26] Both the United States and OECD countries have adopted official values for the VSL that are used in benefit-cost analyses of environmental policies. Whether FGD units pass the benefit-cost test requires an estimate of the VSL for India.

Estimates of the VSL for India could be based on empirical studies conducted in India or could be transferred from United States and OECD values, taking into account differences in incomes. Empirical estimates of the VSL in India range widely, from US$57,000 (Bhattacharya, Alberini, and Cropper 2007) to US$407,000 (Madheswaran 2007).[27] Transferring the USEPA's VSL from the United States to India at current exchange rates (using an income elasticity of one) implies a VSL of US$250,000.[28] This suggests that a program to retrofit FGD units on all 72 power plants in our study would pass the benefit-cost test, on average. FGD unit installation also would pass the benefit-cost test on an individual plant basis at most of the plants in the study, including the 30 plants with the lowest CPLS.[29]

Because big plants are easier to target, regulations that would require the retrofitting of FGD units at the largest plants (those with the largest installed capacity) might be possible. The CPLS averaged over the 30 largest plants in our sample is US$147,000, suggesting that this regulation would, on average, pass the benefit-cost test. However, targeting the installation of FGD units to plants with the highest number of deaths would save more lives per dollar spent.

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NOTES

World Bank Income Classifications as of July 2014 are as follows, based on estimates of gross national income (GNI) per capita for 2013:

- Low-income countries (LICs) = US$1,045 or less
- Middle-income countries (MICs) are subdivided:
  a) lower-middle-income = US$1,046 to US$4,125
  b) upper-middle-income (UMICs) = US$4,126 to US$12,745
- High-income countries (HICs) = US$12,746 or more.

1. The Indian fiscal year runs from April 1 of each year through March 31.
2. Average installed capacity of all coal-fired plants in March 2015 was 1,067 MW, and median installed capacity was 950 MW, which is slightly larger than for our 72 plants.
3. Total emissions of SO_2 are calculated using the sulfur content of coal and coal consumption, as well as assumptions about the volume of flue gases per ton of coal burned.
4. The CERC's benchmark operating conditions are used in tariff setting by the central government (CERC 2009). We also use these benchmark conditions in calculating the annualized cost of operating an FGD unit.
5. See http:// www.camx.com.
6. The meteorological data (wind, temperature, pressure, relative humidity, and precipitation) are derived from the global reanalysis database of the National Center for Environmental Prediction (NCEP) and processed through the Weather Research and Forecasting (WRF) meteorological model at a one-hour temporal resolution.
7. See http://ghdx.healthdata.org/record/global-burden-disease-study-2010-gbd-2010-ambient-air-pollution-risk-model-1990-2010.
8. Specifically, we evaluated the change in relative risk at the population-weighted ambient concentration of $PM_{2.5}$ within a 100 kilometer radius surrounding each plant, computed using the supplementary material from Brauer and others (2012). Concentrations ranged from 15 to 46 $\mu g/m^3$, with a mean of 27 $\mu g/m^3$.
9. We use death rates by age and cause reported in the 2013 Global Burden of Disease. https://cloud.ihme.washington.edu/index.php/s/b89390325f728bbd99de0356d3be6900?path=%2FIHME%20GBD%202013%20Deaths%20by%20Cause%201990-2013.
10. YLL are calculated for each cause of death by multiplying the number of deaths by the average number of life years lost based on the age distribution of deaths. YLL are then summed across all five causes of death.
11. Dry scrubber technologies (including spray dry scrubbers and circulating fluidized bed scrubbers) have lower capital costs than wFGD units and lower removal rates. These are much less commonly used than wFGD units (Carpenter 2014), and we have no cost data on their operation in India. Therefore, we do not analyze them as a control option.
12. USEPA's AP-42 database indicates that a swFGD unit 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.
13. The only plants in table 13.3 that are in our sample are the Trombay, Udupi, and Vindhyachal plants.
14. The CERC is responsible for tariff determination for all central government–owned power plants and those selling inter-state power. The guidelines established by the CERC are also used by individual state SERCs in their tariff calculations. All costs in Indian rupees (Rs^k) have been converted to US$ using an exchange rate of US$1 = 55$Rs^k$ and are thus in 2013 US$.
15. Personal communication with an NTPC (India's largest power utility) engineer. NTPC is involved in setting up a new plant in Bongaigaon, Assam, that will have a wFGD unit installed. The FGD unit is being provided by an Indian company, BHEL. According to online sources, BHEL reports a rule of thumb cost estimate for a wFGD unit of US$90,700/MW. We use the more conservative estimate.
16. https://www.eia.gov/electricity/annual/html/epa_09_04.html. See also Muller (2016).
17. The average CPLS of requiring all plants to scrub their emissions is the total cost listed in table 13.6 (US$1.69 billion) divided by the lives saved. Similarly, the average cost per DALY averted is US$1.69 billion divided by the DALYs averted (329,000).
18. A ranking based on CPLS is identical to a ranking based on cost per DALY. A simplifying assumption underlying the calculations (as in the 2013 GBD) is that the age distribution of the population and death rates by age and cause are uniform throughout the country.
19. Twenty-one of the plants with the lowest CPLS are also the plants with the largest number of deaths associated with SO_2 emissions.
20. The 13th largest plant in the sample, based on installed capacity, has the highest CPLS (US$1,244,000). The plant is located in the south of India and has a smaller exposed population than plants in northern India.
21. Our estimate of the private cost of capital is based on a debt-equity ratio of 70–30, the private rate of return on capital allowed by the CERC (15.5 percent), and the assumption that the plant can borrow at a rate of 9.3% (the Bank of India base rate at the time of writing).
22. Prior to December 2015, emission limits for total suspended particulates called for units below 210 MW to emit no more than 350 mg/Nm^3 and units greater than 210 MW no more than 150 mg/Nm^3. The use of coal with ash content exceeding 34 percent is prohibited in any thermal power plant located more than 1,000 km from the pithead or in urban, sensitive, or critically polluted areas. http://cpcb.nic.in/Industry_Specific_Standards.php.
23. *Gazette of India*, December 8, 2015. Ministry of Environment, Forests and Climate Change Notification. S.O. 3305(E). Environment (Protection) Amendment Rules, 2015.

24. Plants built after 2017 may emit no more than 100 mg of SO_2 per Nm^3. These plants certainly would require FGD units; however the cost of installing scrubbers when plants are built is lower than the cost of retrofitting them.
25. A referee notes that the 600 mg/Nm^3 standard could be achieved by installing a dry scrubber, which would have lower capital costs than a wFGD unit.
26. To illustrate, if each of 10,000 people were willing to pay US$100 over the coming year to reduce their risk of dying by 1 in 10,000 during this period, on average, one statistical life would be saved and the VSL would equal US$100 × 10,000 or US$1,000,000.
27. Both values were obtained by converting Indian rupees (Rs^k) to US$ using the average exchange rate for 2007 and then converting to 2013 US$ using the Consumer Price Index.
28. USEPA's official VSL is US$7.4 million (2006 US$), implying a VSL to per capita income ratio of 159:1 (USEPA 2011). Applying this ratio to per capita income in India in 2014–15 (US$1,570) yields a VSL of US$250,000.
29. Forty-seven of the 72 plants have a CPLS of less than US$250,000; 64 have a CPLS of less than US$407,000.

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