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Barriers to adopting least-cost particulate control strategies for Indian power plants

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Future energy growth in India, fueled in large part by coal, is expected to further aggravate the existing problems of particulate air pollution. This paper evaluates strategies for reducing particulate emissions from new and existing coal-fired power plants in India to comply with current and anticipated future emissions standards. The objectives are to identify methods that minimize total power generation costs, and to identify economic and political barriers to adopting these solutions. The technologies considered include conventional electrostatic precipitators, fabric filter collectors, flue gas conditioning, coal cleaning and switching to imported coal. The results suggest that the most significant savings in particulate control costs are realized through a 'systems' approach involving pre-combustion and post-combustion emission control methods. Nationwide savings in generation costs through improved control are estimated at approximately \$0.4–0.7 billion per annum in the year 2002 (in constant 1996 dollars). Least-cost strategies are not currently being used because of capital cost subsidies, lack of domestic technology demonstration and evaluation programs, an emphasis on pollution control versus pollution prevention, and an imperfect domestic steam coal market. Policy measures are proposed to overcome these barriers.

Keywords: India; Coal; Emissions

Motivation

Coal-fired power plants currently generate 64% of the 83.3 GW of electric power in India (GOI, 1996). With reserves of 192 billion tonnes, coal will remain the predominant fuel for power generation (Sachdev, 1992). Coal-fired capacity is expected to grow from 55 GW today to approximately 80 GW by the year 2002. Unless preventive measures are taken, air pollution emissions will increase substantially as a result of new capacity additions.

Particulate emissions already pose a serious environmental problem in India. Recently, the government has responded with increasingly stringent emissions limits for coal-fired power plants. However, a comprehensive evaluation of regional or national-level compliance options and costs has not yet been conducted. It is anticipated that such a study can identify strategies that significantly lower compliance costs relative to the methods current used. The objectives of this paper are to identify such strategies, and the economic and political barriers to adopting lower cost solutions for environmental control.

Scope of analysis

This paper examines a number of technological options for controlling power plant particulate emissions, as well as the policy, economic and institutional factors affecting the choice of control strategies at Indian power plants. The technologies considered in this study all are commercially mature methods. They include: (1) post-combustion controls, including conventional electrostatic precipitators (ESPs), ESPs with flue gas conditioning (FGC), and fabric filtration using a pulse jet baghouse (PJB); (2) pre-combustion methods, consisting of coal cleaning to reduce ash content, or switching to imported low-ash coals; and (3) combinations of the pre- and post-combustion control methods listed above. In this paper, no attempt has been made to account for other ancillary benefits of improved particulate control, such as reduced emissions of hazardous air pollutants.

In addition to technology options, the policy, economic and institutional factors considered in this analysis include: current and projected emissions standards; subsidies to government-owned power generators; rate of return structure for private generators; operation of the domestic coal industry; and the level of technology information available to power plant managers.

Technology and policy issues

Several features of the Indian power generation sector are important to a consideration of least-cost particulate control strategies. These features also explain why studies and models developed for other countries, notably the US, cannot be directly used for Indian power plants.

Operation of the domestic electric utility industry

Almost all of the electrical generation capacity in India is owned by federal or state governments. The power sector is not operated for profit, but used to serve a social agenda, with about 45% of the electricity sold below cost (CMIE, 1995; GOI, 1995a; Baijal, 1997). Financing for power projects is generally provided by a government institution, rather than raised in the capital markets. Privately owned electric utilities make up less than 5% of the total generation capacity, although the federal government is now actively seeking to increase private investments in power generation.

Operation of the domestic coal mining industry

Coal mining in India was nationalized in the 1970s (Bansal and Bhave, 1995). Domestic steam coal can be sold only by the government. The government-owned Coal India Limited (CIL) supplies virtually all of the domestic steam coal. However, private firms can own and operate coal cleaning plants (often referred to as washeries) and end-users can operate captive mines. The federal government is planning to also allow non-government entities to mine and sell coal (Baijal, 1997). Domestic steam coal is in short supply, leading to lost generation at several power plants (Mulla, 1996; Kapoor, 1997). Long-haul coal transport is operated primarily through the Indian Railways, which is also government-owned.

Current and future environmental standards

All Indian power plants are supposed to meet the current federal particulate emissions limit of 150 mg/N m^3 (dry basis, corrected to 12% CO_2). Professionals in the Indian power industry predict a federal limit of 50 mg/N m^3 in the near future. Several Indian plants are already demanding vendor guarantees of emissions below 100 mg/N m^3 for new particulate collector installations (BHEL, 1996; Kumar, 1996; Mulla, 1996). Some state and local governments have set lower regional limits, while international lending organizations such as the World Bank often require emissions below 50 mg/N m^3 for power plants that they finance (Weaver and Schott, 1996). In comparison, the US New Source Performance Standard, in effect since 1978, is approximately 30 mg/N m^3, while current best practice is approximately 5 mg/N m^3.

Power plants in India are at various stages of compliance with environmental requirements (Sharma, 1992; Bhattacharyya, 1995). The general level of compliance is acknowledged to be poor.

Properties of Indian coal

Indian steam coals are characterized by high ash contents of 30–50% and low heat contents of 4500–7500 Btu/lb (2500–4200 kcal/kg). They are typically transported to power plants without even rudimentary cleaning. These coals are low in sulfur (< 0.5%), and the ash is very high in silica and alumina (> 90%). Hence, resistivity of the flyash formed is high (typically 10^{13}–10^{15} Ω cm, compared to about 10^{10} Ω cm for most US bituminous coals). As explained below, this results in low collection efficiencies of the flyash in a conventional ESP. Further, the ash is finely interspersed in the organic matrix, making its removal through conventional coal cleaning relatively inefficient.

Although coal cleaning is not commonly used in India, it is a well-developed commercial process to remove ash from the organic matrix of coal, using a series of crushing and gravity separation processes. Coal cleaning (also known as coal washing) can reduce the ash content of Indian coals from a typical value of 40% down to about 30%, with about 85–95% of the run-of-mine (ROM) coal energy recovered in the cleaned coal. Using cleaned coal instead of ROM coal reduces the costs of coal transport, since less ash is transported. At the power plant, a lower ash content also reduces the costs of particulate control, coal handling and ash handling. Capital and operating costs for a coal cleaning plant typically increase with increasing levels of ash removal.

Experience with particulate collection technologies

ESPs are an established commercial technology that can reduce total flyash emissions to below 10 mg/N m^3. Flyash particles are electrostatically charged by a strong electric field, then collected on large plates by electrostatic attraction. The performance of an ESP is critically dependent on the electrical resistivity of the flyash. At the high resistivities typical of Indian coals, collection efficiency is relatively poor, requiring very large plate collector areas to achieve higher efficiency. Capital and operating costs also increase rapidly with collection area. Nevertheless, the conventional ESP is the only device currently used for particulate control at power plants in India. The ESP fabrication industry in India is well-developed, and capable of building high-quality units for one-third to one-fourth of the equivalent US cost (Bonner, 1996; Kumar, 1996).

Flue gas conditioning (FGC) is a process used with an electrostatic precipitator to improve the collection efficiency of high resistivity flyash. Sulfur trioxide and/or ammonia are injected into the flue gas stream, forming a conductive layer of sulfate ions on the flyash particles, which reduces the electrical resistivity. Use of FGC reduces the capital cost of an ESP since the ESP collector area needed to meet a given emissions standard is reduced. FGC capital costs in India are comparable to US costs, and chemical reagent consumption is the principal operating cost. Reagent costs in India are approximately 50% of the US costs. Although flue gas conditioning is a commercially accepted and widely used technology, it is not currently used in India. One FGC system was installed at an Indian power station several years ago, but was removed because it did not perform as expected (Kumar, 1996). The causes of the failure, however, are hotly debated.

Fabric filter collectors (baghouses) began to be used on power plants in the US in the 1970s. They are an efficient and often cost-effective alternative to ESPs for plants burning low sulfur, high resistivity flyash coals (EPRI, 1995). They work by filtering out the flyash using specially constructed woven fiberglass filter bags that are capable of reducing emissions to 10 mg/N m^3 or lower. The level of controlled emissions is insensitive to the coal ash content or flyash resistivity, though capital and operating costs increase with increasing efficiency. However, they have not been used in India before now, although the Maharashtra State Electricity Board (SEB) is currently retrofitting one of its boilers with a pulse-jet baghouse (Mulla, 1996). Process capital costs for India are about 40% of US costs. Regular replacement of filter bags is a major operational cost. Filter bags are currently imported and their cost is comparable to US costs.

Foreign coal imports

Currently, India imports about one million tons of steam coal per year (Bennett, 1996), which is less than 1% of domestic consumption. Historically, the domestic coal industry has been protected through high import duties on foreign coals. That duty was 86% until three years ago; it is currently at 22%. The import and sale of foreign coal is managed by private firms.

Study methodology

The methodology adopted for this study is outlined in Figure 1. Detailed analytical models were developed to predict the performance and cost of using different control technologies at a representative set of existing and new coal-fired power plants in India. Figure 2 illustrates the structure of a typical control technology model. Each model is composed of several sub-models. Some are derived from first principles whereas others, particularly

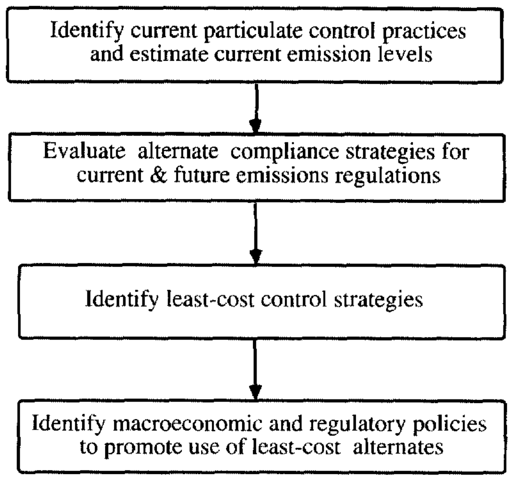

Figure 1 Study methodology

cost sub-models, use empirical data. For example, the capital cost of an electrostatic precipitator is estimated using empirical correlations between cost and volumetric flue gas flow rate, but the flow rate itself is estimated from an engineering heat and mass balance model for a particular power plant. An extensive amount of India-specific data was collected to calibrate these models, such as

- design and operating characteristics of Indian power plants;
- physical and chemical properties of domestic and imported coals;
- domestic engineering, transport, labor and reagent costs; and,
- actual bid amounts for recent pollution control and coal cleaning projects in India.

Additional technical details of these models are provided in earlier papers (Lookman and Rubin, 1997; Rubin *et al*, 1997) and technical reports (Kalagnanam and Rubin, 1994a, b).

The costs and feasibility of different particulate control methods were estimated for three existing power plants and two new power plants. Case study plant designs and locations were chosen to represent the diverse operating conditions of power plants in India. Three locations (Table 1) were used to represent plants located at the mine-mouth, along the coast (far from mines), and at an intermediate distance from the mine.

Design data for the case study plants are summarized in Table 2. Accurate emissions data generally are not available, so that current emissions were estimated from the coal composition and design of the existing electrostatic precipitator. Note that particulate emissions from two of the three existing units exceed the current federal limit of 150 mg/N m^3. New power plants built in 250 and 500 MW sizes (as currently proposed for new plants in India) were also considered for this study.

Coal data used for this study are summarized in Table 3. For imported coal, the cost is at the port, after

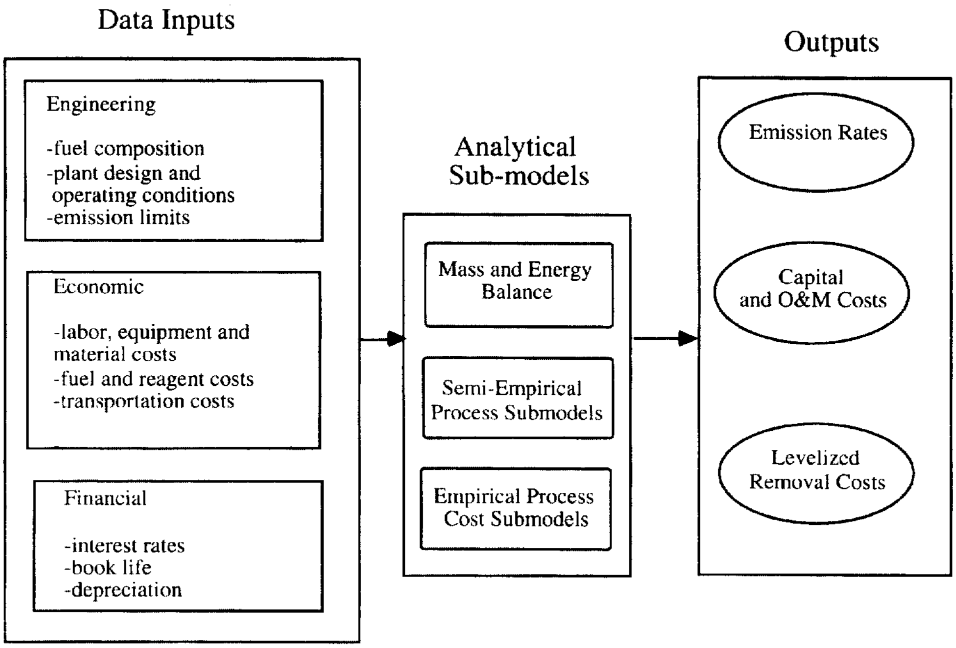

Figure 2 Structure of a typical particulate control technology model

Table 1 Case study plant locations

Plant location	Distance from coal mine (km)	Domestic coal transport cost ($/ton)
Rihand (Mine-mouth – Central India)	50	4.00
Koradi (Interior – Western India)	500	8.82
Tuticorin (Coastal – Southern India)	1500	23.00

Table 2 Design data for case study power plants

Capacity (MW gross)	Year of commissioning	Estimated current emissions (mg/Nm^3)	Estimated remaining life (ys)
Existing units			
120	1970	930	10
210	1980	420	14
500	1990	110	24
New units			
250	1996	50	30
500	1996	50	30

unloading. The costs for run-of-mine coal and domestic coal transportation are taken to be the prices set by the government. It is unclear what the price of coal would be if the coal mining sector were privatized. Some reports suggest that the mining industry is subsidized by the government (Bansal and Bhave, 1995), which would suggest that government intervention has resulted in artificially low prices. On the other hand, the coal mining sector

Table 3 Coal cost and quality data

Coal type	Energy content	Ash content		Price	
	(Btu/lb)[a]	(%)	(lb/MBtu)[a]	($/ton)[a]	($/MBtu)[a]
Run-of-mine	6291 (3498)	42.1	66.92 (120.70)	10.50 (9.55)	0.83 (3.29)
Cleaned	7595 (4233)	30	39.51 (71.27)	15.36 (13.96)	1.01 (4.01)
Imported	11 340 (6305)	14	12.35 (22.28)	61.50 (55.91)	2.71 (10.75)

[a]SI equivalents of the British units are shown in parentheses. These are kcal/kg for energy content, mg/kcal for ash content, and $/metric ton and $/Gcal for price.

is a government-owned monopoly, protected from competition from foreign coal through import duties. If the industry were privatized, and import duties removed, competition might result in lower prices, suggesting that government intervention has resulted in artificially high prices. For cleaned coal, the cost is the price of run-of-mine coal plus cleaning costs estimated using the coal cleaning model developed for this study.

Australian Newlands coal is used as the representative imported coal; its cost and ash content is similar to other imported coals. Steam coal from the Talcher coal field of India was used as the domestic run-of-mine coal since its energy and ash content are similar to the average for Indian steam coals (Sachdev, 1992, 1996). Cleaned coal composition is estimated using the coal cleaning model developed by the authors. Values for key cost and performance parameters for the cleaning plant were selected based on data obtained by the US Department of Energy, and from private companies building coal cleaning plants in India (Gollakota and Rao, 1996; Sharpe, 1996). These data are presented in Table 4.

Table 4 Key costs and performance parameters for a modern coal cleaning plant in India

Parameter	Value
Capacity	550 short tons per hour of ROM coal (500 metric tons per hour)
Annual throughput	2.75 million short tons of ROM coal (2.5 million metric tons)
ROM ash content	42%
Cleaned coal ash content	30%
Recovery of ROM coal energy in cleaned coal	93%
Total plant capital cost	$22.5 million
Total annual operating cost	$ 2.8 million

Note that coal cleaning is not expected to reduce the sulfur content of Indian coals. The sulfur in these coals is in an organic (rather than pyritic) form, chemically bonded to the rest of the organic coal matrix. This makes it impossible to remove using physical coal cleaning methods. However, other environmental benefits of coal cleaning, such as a reduction in trace metal emissions associated with coal ash, may accrue.

The objective of this analysis is to identify least-cost pollution control and power generation strategies for electric utilities in India. Given the current trend in India (and elsewhere throughout the world) toward privatization of the electric power industry, our least-cost analysis takes the perspective of utilities as business entities required to operate without gross distortions from government subsidies. Accordingly, the nominal cost of capital for power projects is 18%, which is typical for the private sector in India. The typical inflation rate in India is 10.5%. Thus, the real cost of capital used for this study is 7%, and is similar to that used for other recent studies of power generation costs in India (Hagler Bailly, 1994). The costs of existing generation and pollution control equipment are treated as sunk costs. A capacity factor of 0.65 is used to levelize costs for all cases. This value approximates the average capacity factor of Indian power plants (GOI, 1996). Generation costs are levelized over the estimated remaining life of the power plant. A constant currency conversion rate of 36 Indian Rupees (Rs.) = $1 US is assumed, and all costs are reported in constant 1996 dollars. Later, we discuss the effects of market distortions introduced by current practices among government-owned Indian utilities.

Cases analyzed

A total of 174 cases were analyzed (Table 5) representing different combinations of plant type, plant location and particulate control strategy. For existing power plants, compliance strategies were examined for emission limits of 150 and 50 mg/N m^3. Additional cases assumed a 30 mg/N m^3 limit, comparable to the 1978 US federal standard. For new power plants, compliance options focused on the anticipated future Indian federal limit of 50 mg/N m^3, with several cases assuming tighter standards of 30 and 15 mg/N m^3.

Summary of least-cost control strategies

The control strategy yielding the lowest levelized generation cost at each case study power plant is shown in Table 6 for the 150 and 50 mg/N m^3 emissions limits.

A Monte Carlo approach (Clemen, 1990) was used to test the robustness of the results of Table 6 using simulation software (Lumina, 1996). This approach is favored over traditional sensitivity analysis since the effect of changing several variables simultaneously can be

Table 5 Cases modeled for new and existing power plants

Plant type →	Existing plants						New plants			
Emission limit (mg/Nm^6) → →	Current	30	50	50	150	150	15	30	50	50
Power plant size (MW) →	120	210	120	120	120	120	500	500	250	250
	210		210	210	210	210			500	500
	500		500	500		500				
Plant location										
Coastal	x	x	x		x		x	x	x	
Interior	x			x		x				
Mine-Mouth	x			x		x				x
Coal used										
ROM	x	x	x	x	x	x	x	x	x	x
Cleaned		x	x	x	x	x	x	x	x	x
Imported		x	x		x		x	x	x	
Post-combustion control method										
Add collector area to existing ESP		x	x	x	x	x	NA	NA	NA	NA
Install FGC + add collector area		x	x	x	x	x	NA	NA	NA	NA
PJBH			x	x	x	x			x	x
ESP	NA	NA	NA	NA	NA	NA	x	x	x	x
ESP + FGC	NA	NA	NA	NA	NA	NA	x	x	x	x

x = cases modeled; NA = not applicable.

Table 6 Least-cost generation strategies for case study power plants

Emission limit →	150 mg/Nm³			50 mg/Nm³		
Plant location → Size (MW) ↓	Mine-mouth	Interior	Coastal	Mine-mouth	Interior	Coastal
Existing plants						
120	R, ESP	C, ESP	C, ESP	R, FGC	C, ESP	C, ESP
210	R, ESP	C, ESP	C, ESP	R, FGC	C, FGC	C, FGC
500	NA	NA	NA	R, FGC	R, FGC	C, ESP
New plants						
250	NA	NA	NA	C, FGC	NA	I, FGC
500	NA	NA	NA	C, FGC	NA	I, FGC

Key: R = run-of-mine coal; C = cleaned coal; I = imported coal; ESP = electrostatic precipitator; FGC = ESP with flue gas conditioning; NA = not applicable

Table 7 Probability distributions used for key variables

Variable	Nominal value[a]	Uncertainty distribution multiplier[b]
Base plant		
Real interest rate	7%	Triangular (0.85, 1, 1.15)
Plant capacity factor	65%	Triangular (0.85, 1, 1.15)
Coal handling equipment capital cost	calc	Uniform (0.9, 1.1)
Ash handling equipment capital cost	calc	Uniform (0.9, 1.1)
Imported coal price at dock ($/MBtu)	2.71	Uniform (0.8, 1.2)
Domestic coal transport cost ($/ton)	calc	Uniform (0.9, 1.1)
Coal cleaning		
ROM coal energy recovered in cleaned coal	93%	Triangular (0.97, 1, 1.03)
Energy value of coal cleaning rejects as a multiple of ROM coal energy value	0.5	Triangular (0.5, 1, 1.5)
Capital cost of coal washery ($M)	22.5	Triangular (0.85, 1, 1.15)
Annual O&M cost of coal washery ($M/year)	2.8	Triangular (0.85, 1, 1.15)
Particulate control		
ESP capital cost	calc	Uniform (0.9, 1.1)
Flue gas conditioning system capital cost	calc	Uniform (0.9, 1.1)
H (multiplier to effective migration velocity when using FGC)	2	Triangular (0.85, 1.15)

[a]calc = calculated from analytical model.
[b]The probability distributions used in the stochastic simulation are the nominal values multiplied by the uncertainty distribution multipliers. Uniform distributions are characterized by minimum and maximum values, and triangular distributions by minimum, mode and maximum values.

observed. Further, this approach provides estimates of the probabilities of realizing different values, whereas sensitivity analysis simply identifies extreme and switch-over values without providing any information about their likelihood. Probability distributions in Table 7 were used to represent uncertainties of key variables, including cost of capital. Results of the analysis are summarized below.

Fuel choice

For existing power plants, this study indicates that switching from ROM to cleaned coal will reduce generation costs for units located more than 400–500 km from the coal mines. The break-even transportation distance is shorter for older and smaller units. For new units, generation costs using cleaned coal are lower than ROM coal even at mine-mouth power plants. Savings accrued through lower capital and operating costs for ash, fuel handling and particulate control equipment more than compensate for the added expense of building and operating a coal cleaning facility. A probabilistic analysis suggests that these results are robust. Figure 3 presents the cumulative distribution function of breakeven distances for two existing plants. As seen in the figure, the 90th percentile breakeven distance is within 100 km of the nominal (deterministic) values.

The use of imported coal was evaluated only for the coastal case study location, which is 1500 km from the domestic coal mines. Deterministic results suggest that burning imported coal instead of cleaned domestic coal results in cheaper generation for new coastal plants, but more expensive generation for existing plants. Figure 4 presents the probabilistic results showing the cumulative distribution of net savings in total generation costs using the least-cost coal identified from a deterministic analysis.

As seen from Figure 4, there is a 45% probability that the least-cost coal identified from a simple deterministic analysis might in fact lead to more expensive generation (ie, negative savings) when uncertainties are considered.

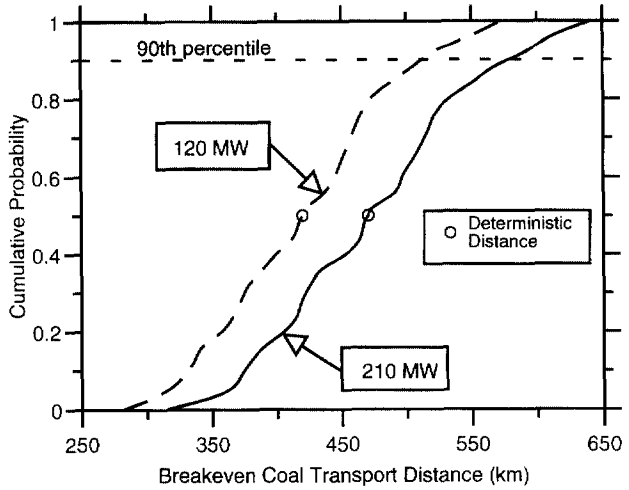

Figure 3 Cumulative probability distribution of break-even transport distances (existing 120 and 210 MW plants, 150 mg/N m^3 standard, conventional ESP)

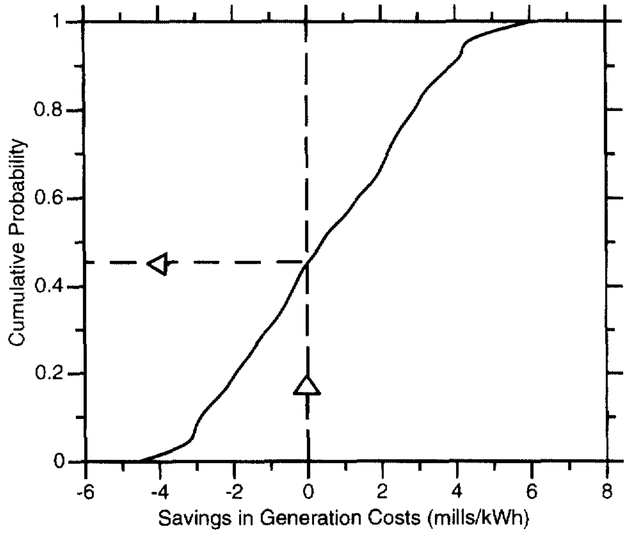

Figure 4 Cumulative probability distribution of savings in total generation costs using cleaned instead of imported coal (existing 210 MW plant, coastal location, 50 mg/N m^3 emission standard)

In particular, small changes in the delivered coal costs can alter the least-cost generation choice. It should be noted, however, that imported coal is artificially more expensive than domestic coals because of the 22% import duty on foreign coal. If this distortion is removed, the financial benefits of switching to imported coal will be markedly increased.

Post-combustion particulate control

The results of this study suggest that using flue gas conditioning (FGC) reduces generation costs at all plants burning ROM coal for emission standards of 50 mg/N m^3 or tighter. FGC is also cost-effective for new 500 MW units regardless of the coal used. Because a smaller ESP is required, the savings in ESP construction costs offset the capital and operating costs of the FGC system. A probabilistic analysis suggests that these results are robust across a variety of assumptions, all of which yield a positive cost savings relative to use of an ESP only. Pulse jet baghouses, on the other hand, do not currently appear to be cost-effective for use in India for emission standards down to 50 mg/N m^3. (Baghouses were not evaluated for lower emissions levels because of data limitations.) In India, baghouses are projected to have higher capital and operating costs than ESPs. While baghouses can be built more cheaply in India than in the US, the savings currently are not as great as for ESPs. Further, the regular replacement of filter bags required for the pulse jet system results in higher operating expenses compared to an ESP, especially since bags must be imported. The development of a domestic manufacturing industry for baghouses and fabric filter bags, or requirements for stricter emission levels below 50 mg/N m^3, might alter the comparative economics in the future.

Aggregate results for India

Applying the case study results to the entire Indian power generation system yields a preliminary estimate of how generation costs can be reduced by implementing least-cost control methods. These estimates (Table 8) are based on the current and expected distribution of power plants with respect to geographic location, age and rated capacity, and assume that all plants will shortly have to comply with a 50 mg/N m^3 particulate emission standard. Savings for new units are based on a projected addition of 25000 MW of new coal-fired generation in the next five years (Baijal 1997). The estimates in Table 8 suggest that plant-level solutions for improved particulate control using flue gas conditioning can yield savings on the order of \$35–60 million/yr relative to the current approach. However, the savings through systems-level solutions, most significantly through coal cleaning, are an order of magnitude higher, on the order of \$320–550 million/yr.

Note that these estimates are based on conservative assumptions. For example, no credit has been given for secondary benefits of reducing coal ash content. These benefits include reduced erosion of boiler tubes, higher boiler efficiency, greater plant availability, and higher output. Consideration of such benefits would increase the savings obtained through the use of coal cleaning and imported coal.

Factors favoring non-economic choices of particulate control strategies

Although the estimated savings in generation costs are of the order of \$0.4–0.7 billion per year, in practice, none of

Table 8 Savings in generation costs possible through least-cost control methods in 2002 (constant 1996 dollars)

Control technology	Existing units		New units		Total savings ($M/yr)
	Applicability	Savings ($M/yr)	Applicability	Savings ($M/yr)	
Coal cleaning	1/3rd of current capacity	75–150	All	250–400	325–550
Flue gas conditioning	1/2 of current capacity	15–25	Most	20–35	35–60
Imported coal	none	–	All coastal units	25–40	25–40
Total	–	90–175	–	295–475	385–650

the least-cost measures identified in this study are widely used at the current time. Power plants located even 1500 km from coal mines use unwashed run-of-mine coal, and the conventional ESP, without flue gas conditioning, continues to be the principal method of particulate control. The only alternate control technology installed at a single power plant is the pulse jet baghouse – although this study suggests it is currently the most expensive particulate control method for India. Some possible reasons as to why such non-economic choices are made are identified in this section.

Technological inertia

Particulate control system design practices that were optimal 10–20 years ago continue to be used today even though they no longer result in least-cost generation. This is because the design basis for a typical new coal-fired power plant has changed in three important aspects: (1) the size of a new plant has more than doubled, (2) ash content of the coal has nearly doubled, and (3) particulate emissions standards have been tightened by nearly an order of magnitude.

For older power plants, a conventional ESP was the most economical particulate collection method. However, for a new plant today, the collector area required for a conventional ESP is massive. Augmenting the ESP with flue gas conditioning would reduce the ESP collector area by 50%, reducing overall particulate control costs by 7%. Yet, the conventional ESP without FGC is still being used at all new installations although it is no longer the least-cost control method. Lack of adequate economic information might have lead to reinforcing technological inertia.

Lack of coal choice

Although power plant managers fully appreciate the benefits of burning coal with lower ash content, they have little control over the quality of the coal supplied to them. Coal India Limited is effectively the sole supplier of domestically mined steam coal in India, and power plants must simply accept whatever coal they receive. Since they cannot control coal quality, power plant operators simply over-design their plants for the worst coals.

Financing government-owned generators

The analysis of the costs of different control options is based on conventional norms of business practice, where loans are repaid, and expenses such as interest charges and fuel costs are paid at full face value. In India, gross distortions occur for government-owned power generators. Capital for these plants is often provided by the government in the form of loans. The interest and capital on these loans is routinely waived, significantly reducing the true cost of capital for a power plant project (GOI, 1995b; GOI, 1996; Srinivasan, 1996). Such financial concessions encourage the use of large and expensive ESPs for particulate control, rather than a smaller and cheaper ESP with flue gas conditioning (FGC). Further, the purchase of reagent for FGC from private companies are 'hard' costs compared to the 'soft' cost of government-supplied capital. This provides a disincentive to opt for control methods that have significant operating costs but lower capital costs.

Rate of return structure for independent power producers

The method used by the Indian government to set electricity sale prices for independent power producers (IPPs) encourages them to choose more expensive emission control methods that result in higher electricity rates. IPPs are provided a fixed allowance of 2.5% of capital cost for their O&M costs regardless of actual O&M costs (GOI, 1994). Therefore, when given an option, an IPP will prefer an emissions control system with a high capital cost but low actual operating cost, since such a system increases the project's profitability. This is illustrated in Table 9, where particulate control costs for a new 500 MW plant using a conventional ESP is compared with costs of using an ESP with FGC. The ESP with FGC reduces the overall cost of electricity to consumers by $150 000/y compared to the conventional ESP alone. However, because the conventional ESP has a higher allowance for operating expenses (due to its higher capital costs), an IPP will prefer this option since it increases the project's profits – in this case by $170000/y.

Lack of institutional incentives

Coal consumption in India has increased by 8% per annum since 1975 (Sachdev, 1992). To meet this demand,

Table 9 Comparison of actual versus allowable O&M expenses for different particulate control options ($M/yr) (new 500 MW unit burning cleaned coal, 50 mg/Nm³ emissions standard, mine-mouth location)

Control option	Conventional ESP	ESP with FGC	Difference (conventional ESP–ESP with FGC)
Levelized particulate control cost ($M/year)[a]	2.30	2.15	0.15
Levelized O&M allowance ($M/y)[b]	0.32	0.25	0.16
Levelized actual O&M cost ($M/y)[c]	1.30	1.40	– 0.10
Difference between allowance and actual O&M cost ($M/year)	– 0.98	– 1.15	0.17

[a]Includes both capital and O&M costs.
[b]Equal tp 2.5% of capital cost.
[c]Actual O&M cost is higher than the allowance because the particulate control system includes ash handling equipment, which has higher maintenance costs per unit of capital cost than other plant equipment.

the priority of the coal producers has been to maximize production rather than improve coal quality (Bates, 1993). Interviews with officials at Coal India Limited and government officials in the Ministry of Coal suggest that increasing production rather than improving coal quality is still the primary goal of the coal mining industry.

Although management at the government-owned electric utility companies are well aware of the benefits of using cleaned coal, they view their role in the electricity production process as limited to burning coal to produce power; coal cleaning is a service that should be provided by the coal suppliers. Thus, since neither the coal producer nor coal users are interested in constructing coal cleaning facilities, coal cleaning has become an orphan issue in India—a good concept, but without anyone actually interested in implementing it.

Irrational coal pricing system

In India, steam coal is classified into four grades, ranging from D (least ash) to G (highest ash) based on coal energy content. Although the coal energy content can vary by as much as 16% within a particular grade, the price of coal for each grade is still set on a *unit mass basis.* This grade-based system leads to perverse coal energy pricing trends. As seen in Figure 5, the *nominal* coal energy prices, based on the average coal energy content for each grade, follow a logical trend, decreasing in cost with decreasing quality (ie increasing coal ash content). However, the trend for the price of coal energy *within* each grade is the exact opposite, with coal energy price *increasing* with decreasing coal quality. While it is not known whether coal producers actually exploit this anomaly, it perversely encourages them to add as much overburden (ie rocks and other debris) as allowed for a particular grade because the overburden too is sold at the price of coal. It is also a strong disincentive to implement rudimentary coal cleaning, which is the most cost-effective method of reducing power plant particulate emissions. In contrast, coal prices for international trade are typically specified on a *unit energy basis,* and typically decrease if ash content is above specified levels. A coal

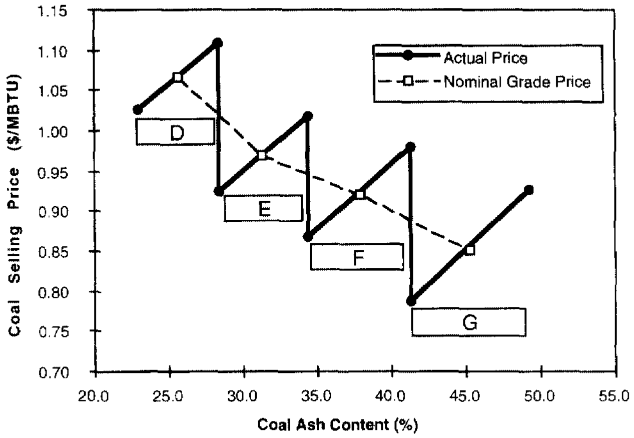

Figure 5 Comparison of actual with nominal sale price of coal in India. Note: Nominal coal energy price is calculated at the average ash content for the grade. Coal prices are typical for coal from the Raniganj coal fields located in the state of West Bengal (Sachdev 1997). These prices were current as of 1 April 1997. Actual coal energy prices are computed assuming a constant moisture content of 5.7% and a constant energy content of 12052 Btu/lb (6701 kcal/kg) on a moisture and ash free basis. This is the moisture and energy content of the ROM coal used for this study

supplier now has a strong incentive to maintain or improve coal quality, naturally aligning the interests of the coal producers and consumers.

Soft payment policies to other government institutions

Coal India Limited, which supplies all of the domestically mined steam coal, and the Indian Railways, which transports most of the coal to non-pithead stations, are both government-owned corporations. They traditionally have tolerated erratic payments by electric utility companies. Several State Electricity Boards (SEBs) have outstanding debts equal to a year's receipts (GOI, 1995a). This suggests that generators treat payments to government-owned institutions as 'soft' payments which can be ignored for long periods of time. In contrast, foreign coal supply is managed by private companies who generally require 'hard' payment prior to delivery of the coal. Therefore, generators will prefer domestic coal over imported coal even if a detailed site-specific analysis indicates that switching to imports will significantly reduce generation costs.

Policies to promote least-cost strategies

This section suggests some policy options to encourage the use of the least-cost pollution control measures identified through this study.

Invest in coal cleaning

Currently, the federal and State governments are subsidizing the costs of pollution control by providing loans at below-market rates for installing pollution control equipment at power plants, such as oversized ESPs. While such investments do result in cleaner air, they have a negative rate of return. Further, because of the additional O&M costs of the ESP, overall power generation costs increase relative to no control. In contrast, the results of this study suggests that if this capital were to be re-directed towards constructing coal cleaning facilities, this investment could have a positive rate of return and also reduce generation costs. However, a particulate emissions control strategy which incorporates coal cleaning requires considerably more capital than one which relies solely on post-combustion controls. The federal government can mobilize private investment in emissions reduction by encouraging investments in private coal washeries, as described below.

Provide financial guarantees for private coal washeries

The Coal Mines Nationalization Act of 1973 was amended in June 1993 to allow private firms to own and operate coal washeries for a host power plant. Note that private washeries can only provide a coal cleaning service. They cannot simply buy ROM coal and sell the cleaned coal in the market. The only private washery proposal that has proceeded toward commercialization is with BSES, a private power generation and distribution company with a strong earnings record (Sharpe, 1996). However, private firms are unlikely to enter into long-term coal cleaning contracts with government-owned coal-fired power plants, majority of which (60%) are owned by State Electricity Boards (SEBs) that have been operating at a loss for the past several years, with losses increasing from year-to-year (GOI, 1995a).

The federal government could encourage private equity participation in coal cleaning projects by providing a sovereign guarantee of payment if the SEB-owned power plant defaults on its obligations. The guarantee could be similar to that already provided for private power projects that sell electricity to an SEB. The amounts at risk would be relatively small. For example, the capital cost for a washery designed to clean coal for a 500 MW power plant is $20–25 million. In comparison, the total capital cost of a 500 MW power plant, for which sovereign guarantees already have been given, is of the order of $500–600 million. By facilitating the use of cleaned coal, the federal government not only will reduce emissions, but also reduce generation costs at SEB plants. This will improve the financial viability of SEBs, reducing their risk of default, making it unlikely that the federal government would have to actually honor the sovereign payment guarantees.

Rationalize coal pricing

As seen earlier, the price of coal on a unit energy basis currently increases with increased ash content within a coal grade, so that the poorer the coal quality, the higher its selling price within that grade. This pricing structure should be rationalized, with the price of coal set on a Btu basis and penalty provisions added for excessively high ash content. This will also encourage coal producers to promptly make marginal reductions in coal ash content, which, as stated earlier, is typically the most cost-effective method of reducing particulate emissions from power plants.

Promote demonstration projects and information exchange

Interviews with power plant personnel in different organizations suggest that reliable and unbiased information about the performance and cost of alternative pollution control techniques for Indian power plants is not currently available. Plant personnel are hesitant to rely upon data collected at foreign power plants, since it is difficult for them to verify such data or evaluate whether similar results can be expected in India. The Indian government and other organizations such as the US Agency for International Development (USAID) should address this information vacuum by creating an effective forum for technology demonstration and evaluation programs in India. A program of information dissemination, based on recent experience in India and elsewhere, also should be mounted. Such a forum could also make available to vendors of different particulate control technologies the operating data they need to adapt their process to work best under Indian conditions. This could reduce the costs of technology development and technology transfer from other parts of the world to India.

Conclusion

The public health impacts of air pollution, and the expected growth in coal use for power generation, have led to calls for more stringent controls on particulate emissions in India. The results of this study suggest that the imposition of tighter particulate emission controls on coal-fired power plants in India will raise the cost of power generation if conventional control methods are pursued. However, significant national cost savings can be made by switching to least-cost particulate control strategies. Relative to current practice, such strategies can reduce the absolute cost of power generation *even while reducing the level of particulate emissions.* Furthermore, the relative savings from least-cost strategies increase as the particulate emission standard become tighter. Most of these savings are accrued through using cleaned coal instead of run-of-mine coal. In some cases, new post-combustion technology and coal imports yield additional savings. This study also shows how the federal government of India can play a key role in overcoming the many institutional barriers that currently prevent adoption of least-cost control strategies.

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