Pollution Control Improvements in Coal-Fired Electric Generating Plants: What They Accomplish, What They Cost

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The cost to construct coal-fired electric generating plants in the United States increased significantly during the 1970s. Although inflation in construction wages and material prices was a contributory factor, increased environmental standards played a particularly important role.

A statistical analysis of the capital costs of recently completed U.S. coal–fired generating units indicates that the cost to build a typical coal plant increased by 68% from the end of 1971 to the end of 1978, in addition to inflation in construction labor and materials. Approximately 90% of this *real* dollar increase was spent for improvements in pollution control. In return, emissions of criteria pollutants (sulfur oxides, particulates, and nitrogen oxides) from 1978 plants average approximately 64% less than those from 1971 plants.

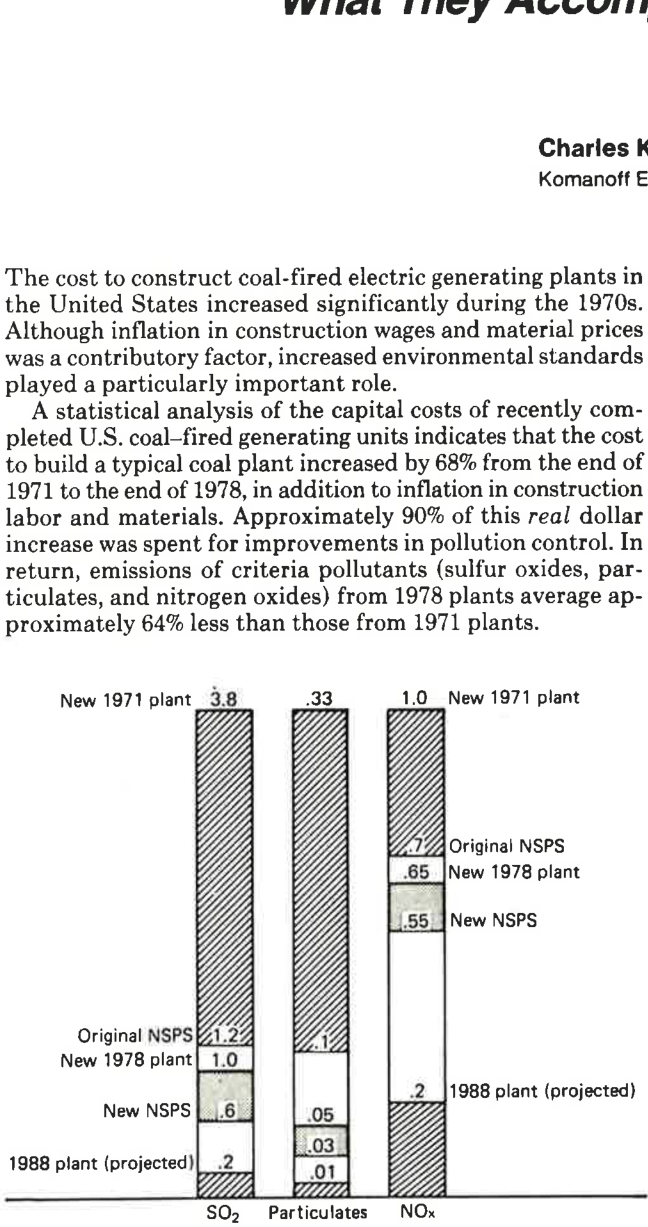

Figure 1. Emissions of criteria air pollutants by new coal plants (lb pollutant/10^6 Btu of coal burned. (Pollutants not drawn to same scale.) 1971 figures are based upon C. Komanoff, *et al., The Price of Power: Electric Utilities and the Environment* (MIT Press, Cambridge, MA 1972), and assume 11,000 Btu/lb coal, 14% ash, 2.2% sulfur, dry bottom boiler, and 97% particulate collection. 1978 figures assume 99.5% particulate collection and 74% SO_2 collection; 1988 projections assume 99.9% particulate collection, 95% SO_2 collection, and 80% NO_x reduction.

For plants completed in the late 1980s, advanced control systems under development appear capable of further reducing emissions by an average of 76%, for an additional 36% in capital costs (in constant dollars). Compared to a 1971 coal plant, this advanced plant would cost approximately 130% more to build (not including construction inflation), but its emissions of criteria pollutants would average 91% less.

Emission Standards for 1970s Plants

The use of coal to generate electricity expanded rapidly in the 1960s and 1970s. U.S. coal-fired generating capacity increased by 80% from 1961 to 1971, and by another 53% to 1978. The resulting increase in coal generated emissions provoked national concern, inspired by massive new pollution sources such as the Four Corners plant in northern New Mexico. Accordingly, starting in the mid-to-late 1960s, some state and local authorities ordered utilities to reduce emissions of particulate matter and sulfur dioxides through fuel switching or improved control devices. And in 1970 Congress passed amendments to the Clean Air Act which created a framework for reducing emissions from existing plants and set national standards for new plants.

The New Source Performance Standards (NSPS) promulgated by the Federal Environmental Protection Agency pursuant to these amendments limited emissions of particulates, sulfur dioxide, and nitrogen oxides from fossil fuel plants whose construction started after August 1971. The NSPS required emissions of these pollutants from new coal plants to be 55% less per unit of fuel burned, on average, than emissions from plants installed in 1971. Some new plants have surpassed the NSPS levels, as Figure 1 shows, as a result of stricter local regulations, state measures needed to satisfy national ambient air quality standards, or utility efforts to keep ahead of regulations. Actual emission rates for coal plants completed in 1978 thus average approximately 64% less than for their 1971 counterparts, as shown in Table I.

Costs of Emission Abatement in the 1970s

The average cost to construct coal plants increased from \$346/kilowatt of capacity for late-1971 completions to

Table I. Emission reductions by typical new coal plants.

	1971–78 Actual	1978–88 Projected	1971–88 Projected
SO_2	74%	80%	95%
Particulates	83%	80%	97%
NO_x	35%	69%	80%
Average reduction	64%	76%	91%

$583/kW for late-1978 plants, as measured in an analysis by Komanoff Energy Associates of the costs of all 116 U.S. coal plants over 100 megawatts completed during 1972–1977.[1] (These and all cost figures in this article are in constant mid-1979 dollars, that is, they have been adjusted to reflect the prevailing prices of labor, materials, and equipment in 1979. They assume, moreover, that the 1978 plant includes a scrubber to remove SO_2, although about half of recent coal plants lack scrubbers, employing low-sulfur coal instead to comply with the NSPS). Approximately 90% of the increase, or $210-215/kW, was accounted for by pollution control systems.

Sulfur Dioxide

The highest cost item added to coal plants during 1971–78 was the SO_2 scrubber. Fifteen plants in the study sample have scrubbers, designed to remove an average of 74% of the SO_2 leaving the boiler, or 3.7 lb of SO_2/million Btu of fuel burned, based on the types of coal used. This is sufficient to reduce emissions to below the 1.2 lb NSPS limit. The scrubbers are "first-generation" devices producing sludge waste.

Controlling for factors such as chronology, location, and multi-unit siting, the scrubber-equipped plants had a 26% higher average cost than the 101 nonscrubber plants in the sample. Based on the $583/kW average cost for a 1978 coal plant with a scrubber, the average scrubber cost was $120/kW, including sludge handling and disposal systems. This is identical to EPA's cost estimate for an equivalent scrubber, but 35% below the estimate in a study of coal plant costs by the Bechtel Corporation for the Electric Power Research Institute (EPRI).[2]

Particulates

Although SO_2 control has dominated most discussions of coal pollution control, utilities achieved greater proportional reductions in particulate emission rates from 1971 to 1978 for new plants. These reductions averaged 83% while SO_2 emission rates fell 74%.

Particulates from coal-fired boilers have traditionally been controlled by electrostatic precipitators (ESP). Typical 1971 plants were equipped with 97%-efficient ESP costing roughly $20/kW. By the end of 1978, average ESP efficiencies had increased to 99.5%, costing $35/kW for conventional high-sulfur coal, and $85/kW for low-sulfur coal.[3] The latter produces highly resistive particulates requiring a much larger ESP collection area and stronger electrostatic field. The average ESP cost of $60/kW is one-half of the cost of a typical first generation scrubber.

The components of the 200% average real cost increase for ESP were approximately as follows:

- 130% increase for efficiency improvements from 97% to 99.5% for a specific coal grade;
- 20% increase for greater collection area needed for lower-sulfur coal (average new-plant sulfur content fell 25–30% from 1971 to 1978);
- 5–10% increase for greater collection area to provide redundancy for higher collection reliability.

(Note: cost increases are multiplicative, not additive.)

Nitrogen Oxides

The average 1978 coal plant emits NO_x at a 35% lower rate than its 1971 counterpart—the smallest reduction among the three criteria pollutants. This has been achieved by replacing horizontal or vertical burner locations with tangential firing, and by boiler modifications to enable boilers to be fired with low excess air and in two combustion stages.

These modifications reduce combustion temperatures, which in turn reduces formation of NO_x. But in the absence of corrective measures they tend to corrode furnace walls and increase formation of *slag*—solidified molten ash—on boiler tubes, leading to combustion control problems and boiler tube leaks. Many new coal boilers thus have more sophisticated combustion monitors and controls—metered orifices and finely tuned nozzles to enhance air-fuel mixing—and wider spacing between boiler tubes to reduce slagging. Others rely on expanded combustion volume and more widely spaced burners to achieve lower temperatures which inhibit NO_x formation. These design changes added an average of $10/kW to capital costs for a 1978 plant.

Other Environmental Measures

The criteria air pollutants were not the only targets of increased pollution controls in the 1970s. Other areas of expenditures were noise attenuation features, $10/kW; pollution abatement during plant construction, $5/kW; liquid waste systems to treat normal plant waste drains for reuse in the plant or for external discharge, $10/kW; improved ash disposal, $5/kW (fixation and ponding of scrubber sludge are included in the scrubber cost); air pollution monitoring systems, $2/kW; and preparation of environmental reports to state and federal agencies, $3/kW.[4] Increasing usage of cooling towers also added an average of $5/kW.

Table II. Pollution control costs for new coal plants (in mid-1979 $/kW).[a]

Pollutant	1971	1978	1988
Particulates	20	60	65–80
SO_2		120	140–180
NO_x		10	60–90
Solid waste	0–5	5	30–45
Other	5	45	65–75
Total	25–30	240	360–470
Increase	210–215		120–230

[a] Costs include IDC accounting for 8% of total costs.

Recent plants also incurred an average cost of $10/kW for boiler improvements to accommodate variations in coal grade caused by mine safety rules—another environment-related capital cost. The combined cost of the above "miscellaneous" pollution-control improvements for a typical 1978 plant was $50/kW, vs. only $5–10/kW for the same measures in 1971.

Total Costs

As Table II shows, environmental concerns absorbed an average of $240/kW in capital costs for 1978 coal plants, an increase of $210-215/kW above the corresponding expenditures in 1971. This increase equals 90% of the total average 1971–78 increase of $237/kW in the capital costs of typical coal plants reported earlier. The difference, approximately $25/kW, was spent primarily on equipment to improve performance reliability: larger, more durable coal pulverizers, control systems for cycling operation (particularly by utilities with reduced load growth and/or expanded nuclear capacity), greater equipment margins, improved quality assurance, and larger stocks of spare parts.

Emission Standards for 1980s Plants

A revised set of New Source Performance Standards, approximately twice as stringent as the original NSPS, was promulgated by Federal EPA in 1979 pursuant to the Clean Air Act Amendments of 1977. The new NSPS, shown in Figure 1, pertain to plants which commenced construction after September 18, 1978, and thus may affect plants coming into service as early as 1982 or 1983.

The 1977 Amendments also require that new utility and industrial plants built in or near designated pristine ("Prevention of Significant Deterioration" or PSD) areas or polluted ("Nonattainment") areas install the "best available control technology" or achieve the "lowest achievable emission rate," respectively. These guidelines are defined, ambiguously, as the maximum reduction possible for each pollutant, taking into account energy, environmental and economic impacts. They are intended to be "technology-forcing," i.e., to push the utility industry to develop improved controls surpassing the new NSPS. The actual reductions required will be determined by EPA on a case-by-case basis in "new source reviews" performed by EPA in its permitting process.

The new NSPS will thus serve as a floor, rather than a ceiling, to pollution control practice for many new coal plants. Over half of the country either is in a PSD or nonattainment area or will affect such an area via plume transport, and so a majority of new plants may be required to better the NSPS. Some utilities may opt for stricter controls to avert drawn-out negotiations with EPA. Finally, the NSPS are subject to further strengthening as coal-fired generating capacity continues to expand. Although the growth in electricity sales since 1973 has fallen to less than half the historical annual rate, the prohibition of new oil- or gas-fired generators and the worsening prospects for nuclear power ensure that coal plants will provide well over half of whatever capacity increase is required in the 1980s and almost all in the 1990s.

Costs of Emission Abatement in the 1980s

In estimating the costs of additional pollution controls beyond those employed by 1978 coal plants, emission rates for 1988 plants have been assumed to be one-third of those dictated by the NSPS. This will ensure that the cost of control improvements is not underestimated. The cost of these improvements is estimated to be approximately \$190/kW, almost equal to the cost of the controls added between 1971 and 1978.

Sulfur Dioxide

The new NSPS replace the old 1.2 lb/10^6 Btu standard with a set of limits varying with coal sulfur content, as shown in Table III. 90% SO_2 removal is required except when emissions are less than 0.6 lb; below that mark, only 70% reduction is needed. Any SO_2 removed by precombustion coal cleaning or in bottom ash or fly ash (typically 5%) is credited as a reduction.

Table III. SO_2 reductions required under new NSPS (assumes 11,000 Btu/lb coal).

Sulfur content,%	Sulfur content (lb/10^6 Btu)	SO_2 reduction	SO_2 emissions (lb/10^6 Btu)
3.3—6.6	3.0—6.0	90%	0.6—1.2
1.1—3.3	1.0—3.0	70—90%	0.6
Below 1.1	Below 1.0	70%	Below 0.6

The SO_2 reduction required for an average 2%-sulfur coal is 84% (higher for coal with a heating value below 11,000 Btu/lb, and vice-versa). But since sulfur content varies among coal shipments, a higher design efficiency, perhaps as high as 90%, is needed to meet the 30-day continuous averaging requirement, for 2%-sulfur coal.

The 15 scrubbers in the data base employed in this study had an average cost of \$120/kW and an average design removal efficiency of 74%. Studies for EPA suggest that raising SO_2 removal efficiency from 74% to 90% increases scrubber costs by only 1–1½%, or \$1–2/kW.[5] This figure appears questionable, however. Larger pumps are required for the increased volume of liquid needed to ensure that the SO_2 is contacted by the scrubbing reagent. Limestone feed and scrubber sludge handling systems must be expanded proportionally with the amount of SO_2 removed. Additional scrubber modules may also be required to back up malfunctioning modules. Aside from these equipment requirements, design improvements may be needed to eliminate problems of corrosion, scaling, and plugging that have affected many scrubbers to date. Although cost estimates are not readily available, an additional \$20–40/kW beyond the \$120/kW cost of a typical 1978 scrubber appears sufficient to ensure reliable 90% collection.

Further design changes appear likely for most 1988 plants. First, SO_2 removal efficiencies averaging 95% should be anticipated as efforts accelerate to control acid rain. Moreover, as the cost to dispose of scrubber wastes increases to meet new federal regulations and to accommodate public concerns, utilities will move toward regenerable scrubbers which reduce or eliminate production of sludge. Fortunately, these improvements may not require much additional cost beyond the \$20–40/kW increment projected above to comply with the new NSPS. Although the several commercially available regenerable scrubbers appear to be about 15% more expensive than current scrubbers, "third-generation" scrubbers now under development, designed for 95% SO_2 removal while producing saleable gypsum or elemental sulfur, may actually prove less costly than today's regenerable devices.

The advanced scrubbers, all being developed in projects sponsored jointly by utilities and the Electric Power Research Institute, are the Chiyoda Thoroughbred process, the absorption/steam-stripping/Resox process, and the aqueous carbonate process. EPRI expects that all three systems will be ready for commercial orders in 1983 or 1984,[6] at a cost range of \$120–160/kW.[7] But since unforeseen problems may add to costs, it is assumed here for conservatism that the advanced scrubbers will cost \$140–180 per kW, \$20/kW above EPRI's estimate and \$20–60/kW more than the average 1978 scrubber.

Particulates

The new NSPS reduce allowable emissions of particulates from 0.1 to 0.03 lb/10^6 Btu of fuel input. The corresponding increase in the collection efficiency required for an average coal grade (14% ash, 11,000 Btu/lb) is from 99.1% to 99.7%. Electrostatic precipitators at new plants were already averaging 99.5% design efficiencies in 1978, with 99.7% at many plants.

An average emission rate of 0.01 lb/10^6 Btu is assumed here, requiring 99.9% collection efficiencies. This would substantially reduce emissions of fine particulates, the most difficult to capture under current practice. Fine particulates are especially injurious because they more easily bypass the lung's defenses, are the principal carriers of trace metals in coal ash, including toxic compounds containing lead, cadmium, and arsenic, and act as a magnet for other air pollutants, providing them with a passageway into the lungs. They also contribute to the reduction of visibility by scattering visible light—a particular concern in PSD areas.

If electrostatic precipitators are used to attain the higher efficiencies, then the increase from 99.5% to 99.9% collection would almost double particulate control costs, from \$35/kW to \$65/kW for high-sulfur coal, and from \$85/kW to \$150/kW for low-sulfur coal.[8] However, the cost of a 99.9%-efficient ESP for low-sulfur coal would almost certainly far exceed the cost of baghouses providing the same control level.

The baghouse, or fabric filter, is a veteran particulate control device in cement- and steel-making consisting of numerous suspended filter bags which trap the particulates from flue gases. It has only recently begun to be applied to utility boilers, with the advent of synthetic fibers (primarily fiberglas) that can withstand combustion gases from coal. The half-dozen small coal-fired boilers with baghouses have all performed reliably for several years, with particulate emission rates averaging 0.02 lb/10^6 Btu, within the new 0.03 lb standard.[9] Although the largest of these boilers is only 44 MW, baghouses are built in small modules, leading EPA to conclude that scaling up to larger boilers should pose no problem. The Agency has cited the successful initial operation of a baghouse on the new 350-MW Harrington-2 unit of Southwestern Public Service, with 28 12.5-MW baghouse modules, to support this view.[10]

EPA estimates that baghouses will cost approximately \$54/kW for low-sulfur coal and \$48/kW for high-sulfur, in 1979 dollars.[11] (Baghouse performance efficiency is primarily a function of the fabric used and is only slightly dependent on coal type.) Although these costs pertain to the new NSPS 0.03 lb standard, baghouses guaranteed to this standard may achieve 0.01 lb in actual operation. However, in view of the embryonic status of baghouses on full-size utility boilers, utilities would insist upon more conservative design and construction to be assured of achieving a 0.01 lb emission rate. Thus, 25 to 50% is added to the EPA figures, giving baghouse costs of \$60–72/kW and \$68–80/kW for high- and low-sulfur coal, respectively.

The high-sulfur baghouse cost is comparable to the \$65/kW estimate for an equivalent ESP. For low-sulfur coal, a baghouse is clearly cheaper than a 99.9%-efficient ESP at \$160/kW (indeed, the cost of a baghouse is roughly equivalent to that of a 99.3%-efficient ESP for low-sulfur coal). Averaging the two coal types, the cost of 99.9% particulate control for a 1988 coal plant should range from \$65/kW to \$80/kW, or \$5–20/kW more than the \$60/kW average for a 1978 plant. In this instance, a new control technology appears likely to reduce, significantly, the rate of cost increase required to improve pollution control.

Nitrogen Oxides

The new NSPS reduce the former NO_x limit of 0.7 lb/10^6 Btu to 0.6 lb for bituminous coal and 0.5 lb for subbituminous coal. These levels can be achieved with further application of staged combustion and low excess furnace air which, in conjunction with tangentially-fired burner design, have enabled recent plants to meet the 0.7 lb limit.

The only cost associated with this modest NO_x reduction would be approximately \$5–10/kW for further design modifications to prevent the changed combustion practices from corroding boiler tubes, and for monitoring and control systems to maintain combustion parameters within the requisite narrow range. Although EPA contends that operating boilers within the 0.5–0.6 lb limit need not cause tube damage, utilities are likely to incorporate preventive design features.

The new NO_x limit appears to be the minimum average level achievable through combustion modification with present boiler technology. This would explain why the new NSPS require only a 45% average reduction in NO_x emissions compared to 1971 plants, versus 91% for particulates and 84% for SO_2. Lenient treatment of NO_x will end, however, as utilities' coal use expands and pressure builds to reduce the conversion by sunlight of NO_x and hydrocarbons into smog in oxidant nonattainment areas. An emission rate around 0.2 lb/10^6 Btu for new plants is probably necessary to keep utility NO_x emissions constant to the end of the century,[12] and EPA is considering promulgating such a standard in the 1980s.

Reducing NO_x emissions below the new 0.5–0.6 lb standard will require further changes in furnace design and perhaps an NO_x flue gas treatment process. Two new furnace designs being tested at the pilot stage have achieved emission rates under 0.2 lb without reducing efficiency or corroding boiler surfaces.[13] These are the Distributed-Mixing Burner, which EPA is funding, and Babcock & Wilcox's Primary Combustion Furnace, cosponsored by EPRI. Both operate by staging combustion, first in a water-cooled, low-oxygen environment designed to retard corrosion and inhibit oxidation of nitrogen present in coal, and second in an oxygen-rich environment where carbon combustion can be completed. Costs have not been estimated but should not exceed \$20–30/kW (relative to uncontrolled 1971 plants), since essentially modifications rather than new systems are involved.

Ultimately, however, flue gas treatment of NO_x will be required, either if the new furnace designs prove inadequate or to reduce emissions well below 0.2 lb. In fact, the latter may be required for some new plants in PSD or nonattainment areas in the 1980s. This would provide an inroad for applying the new technology at all future plants.

The most promising NO_x treatment processes are several "dry" systems using gaseous ammonia to reduce NO_x to molecular nitrogen. Called "selective catalytic reduction" (SCR), these processes have recently been employed at Japanese oil-fired power plants, reducing emissions by 50% without affecting operating performance. They have been tested on coal-fired plants only at the 1 MW scale, however, and commercial development is said to be 5 to 10 years away.

An EPRI-sponsored study has estimated that SCR systems achieving NO_x emission rates of 0.05–0.1 lb with coal firing will cost \$40–90/kW.[14] The lower cost would obtain if new furnace designs enable partial treatment to be employed. Adding the estimated \$20–30/kW cost of furnace changes to the low end of the range, the cost to reduce NO_x emissions to 0.2 lb or below should be in a range of \$60–90/kW. This estimate is consistent with a \$60–80/kW range projected in a recent in-house EPRI study.[15]

Other Environmental Measures

New coal-fired plants are subject not only to air pollution standards but also to regulations governing solid and liquid waste, noise, and construction effluent. These regulations added approximately \$40–45/kW to the average cost to construct coal plants from 1971 to 1978, and will require further cost increases in the 1980s.

Utility solid waste—fly ash, bottom ash and scrubber sludge—was brought under federal regulation by the 1976 Resource Conservation & Recovery Act (RCRA). Compliance will require that holding ponds for scrubber sludge and ash be lined, at costs estimated by Ebasco Services to be approximately \$30/kW and \$5/kW, respectively.[16]

The former cost could be reduced if regenerable scrubbers which recycle waste products are used, as was assumed in projecting scrubber costs earlier. Conversely, costs could rise if ash and sludge are designated as hazardous wastes under RCRA (final RCRA regulations will be promulgated in the early 1980s). Impermeable liners would be required to reduce leaching of trace metals, and disposal could be limited to special geological formations which may lie at considerable distances from the plant site. Balancing these considerations, a cost estimate of \$30–45/kW for improved waste disposal appears reasonable, although costs could be lower or higher than this range.

Other areas which contributed to 1971–1978 cost increases will also add new costs to late 1980s plants. Waste water treatment will become more demanding to reduce effluent discharged in conjunction with ash sluicing, boiler cleaning, feedwater and scrubber makeup, and general plant usage to zero or near-zero levels. EPA noise attenuation guidelines set under the Federal Noise Control Act will increasingly be applied by local regulators, adding to costs of pulverizers, fans and other noisy plant machinery. Concerns such as construction pollution, effluent monitoring, and fugitive emissions from coal piles may also precipitate increased requirements. Based on a literature review, the cost of these "miscellaneous" environmental protection measures could double from 1978 to 1988, contributing another \$30–40/kW for a total of \$65–75/kW.[17]

A final potential source of major costs is the use of dry cooling to reduce the water loss associated with wet cooling towers. Dry cooling towers would be extremely expensive, with costs estimated at \$140–185/kW (assuming successful development of an ammonia phase tower, and including \$10–30/kW to replace the generating capacity consumed by the towers during hot, peak periods).[18] Nevertheless, dry towers may eventually be required in the water-short West if steam-electric plants proliferate there. This would provide an example of a cost that is incurred because expansion of the number of facilities encounters a resource constraint.

Total Costs

The total increase in the capital costs of environmental controls estimated above for a typical 1988 plant, compared to 1978 practice, ranges from \$120–230/kW. The range reflects substantial conservatism in both the individual cost estimates and the projected emission targets (which are three times as stringent as the new NSPS). Moreover, the long lead times of most regulatory standards for coal plants makes it unlikely that regulations not anticipated here will significantly affect the costs of late-1980s plants. Nevertheless, using past cost experience as a guide, actual costs are more likely to be at the upper than the lower part of the range. For purposes of cost comparison, a single figure of \$190/kW is used here to project the average cost of 1978–1988 control improvements.

This would be only slightly less than the \$210–215/kW average cost of coal pollution control improvements from 1971 to 1978. The major sources of that increase were the first-generation scrubber (a cost actually shared by the 1971–78 and 1978–88 periods but explicitly assigned here to the prior period) and a high-efficiency electrostatic precipitator. The biggest new cost anticipated for 1978–88 is for improved nitrogen oxide control; with lesser increases for regenerable scrubbers and solid waste management. Despite the large, further reductions in SO_2 and particulate emission rates projected here for late-1980s plants, the necessary cost increases are likely to be limited by new control devices such as baghouses which are more expensive than current systems at today's control levels but appear less expensive at very high efficiencies.

Finally, an additional \$20/kW is likely to be absorbed in the cost of typical late-1980s plants to pay for improved operating reliability and for higher "real" interest costs as construction periods lengthen. The projected pollution control improvements would then account for 90% of the estimated cost increases (aside from construction inflation) in coal plant capital costs from 1978 to 1988—equalling the 1971–78 percentage. The 1988 coal plant would be 36% more expensive (in real terms) but 76% less polluting than a 1978 plant, and 129% costlier but 91% better controlled than its 1971 counterpart, with pollution equipment responsible for nine-tenths of the increased real costs (Figure 2). Finally, under these circumstances, the two periods, 1971–78 and 1978–88, would show the same percentage increase in coal plant capital costs relative to the expansion in coal generating capacity[19]—a not illogical result considering the role of coal sector expansion in forcing improvements in coal pollution control practice.

Other Pollution Control Costs

Although this article has addressed only the impact of coal pollution controls on plant capital costs, improved controls also affect fuel costs, operating and maintenance (O&M) costs, and performance reliability (capacity factor). The heat, steam, and electricity required to run pollution control equipment reduce thermal efficiency and increase fuel consumption. O&M costs are raised by the limestone and other material requirements of scrubbers, by disposal costs for ash and sludge, and by the personnel needed to operate control devices. And breakdowns in control equipment or gas and moisture carryover can impair plant availability, although increased use of redundant scrubber modules is reducing this effect.

Quantification of these costs is beyond the scope of this article, but the costs of improved controls clearly weigh far more heavily on capital costs than on fuel costs, O&M costs, or reliability. Capital costs tend to account for 40% of total coal generating costs, and will more than double in real terms from 1971 to 1988, almost exclusively because of improved pollution control. Fuel costs average 50% of total generating costs but will increase only 5–10% because of control equipment. O&M costs may double (or more for high-sulfur coal burning plants without regenerable scrubbers) but only account for 10% of base generating costs. And even a 5 percentage point drop in capacity factor caused by problems with control equipment, from 70% to 65%, could be offset through a modest 8% increase in installed capacity, i.e., in capital costs. Thus, although costs can vary greatly among different plants, capital costs appear to be the vehicle for more than two-thirds of the total impact of pollution control improvements on the cost of coal-generated electricity.

Alternative Coal Combustion Technologies

This article has not considered the potential of new coal-burning technologies to achieve pollution control levels comparable to those specified here for 1988 plants, at lower cost. Considerable R&D effort is being devoted to new technologies, however. The most promising is fluidized bed combustion, in which the fuel rests on a layer of small, inert par-

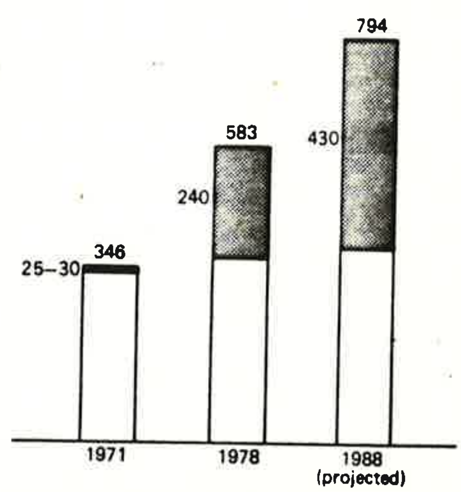

Figure 2. Coal plant capital costs (in 1979 constant \$/kW). Years refer to date completed. Shaded areas indicate environmental protection costs.

ticles suspended by forced air. It has been used in specialized industrial applications for several decades but has only recently been examined for electricity generation.

Fluidized bed combustion has many prospective advantages over conventional combustion: ability to burn limestone directly with coal to capture SO_2 without a scrubber; combustion below the temperature of atmospheric generation of NO_x; and formation of a dry, powdery ash which is less damaging to plant equipment than conventional ash and also contains fewer heavy metals.[20]

The cost of coal plants employing fluidized bed combustion is widely predicted to be no greater and possibly less than that of conventional coal-fired plants, assuming both must meet the new NSPS. Similar forecasts have been applied to gas turbine cycles operating with fluidized bed combustors or integrated low-Btu coal gasifiers. Initial operation of commercial-size prototypes is not likely until 1984 at the earliest, however, so it is doubtful that commercial plants could be operating before 1990.

Moreover, cost estimates for these new technologies are somewhat speculative, and could rise if design modifications or flue gas treatment are required to meet new standards. Fluidized bed combustors, for example, can presently remove approximately 85% of SO_2 through contact of limestone with coal in the combustor, but higher control levels may require scrubbers (although refinements such as limestone recycle may allow 95% capture or greater).

A different technology, coal cleaning, holds the promise of reducing flue gas treatment costs by removing impurities from coal at the mine. Current physical cleaning processes using crushing and flotation separation can remove half or more of the ash and a third of the sulfur from coal, substantially reducing the design requirements of emission control devices. Although only a small fraction of utility coal is cleaned today, increased costs for coal transportation, waste disposal and boiler outages—all of which are mitigated by cleaning—may make physical cleaning more economically attractive. Physical cleaning may be especially attractive as an alternative to retrofitting controls to reduce emissions from existing coal plants.

References and Notes

1. The analysis is described in C. Komanoff, *Power Plant Escalation: Nuclear and Coal Capital Costs and Economics* (Komanoff Energy Associates, 1980; forthcoming). Costs include interest during construction in constant dollars, accounting for 8% of total costs.
2. "Cost Analysis of Lime-Based Flue Gas Desulfurization Systems for New 500-MW Utility Boilers," PEDCo Environmental, Inc., 1979, and "Coal-Fired Power Power Plant Capital Cost Estimates," Bechtel Corp., EPRI AF-342, 1977. All cost estimates have been adjusted to mid-1979 price levels.
3. "Electric Utility Steam Generating Units: Background Information for Proposed Particulate Matter Emission Standards," EPA, July 1978, Table 8.2. Costs converted to mid-1979 dollars, with $10/kW and $15/kW added for high- and low-sulfur coal, respectively, for conservatism.
4. These estimates are drawn, with modifications, from three valuable surveys of coal pollution control costs by the power industry: R. R. Bennett & D. J. Kettler, "Dramatic Changes in the Costs of Nuclear and Fossil-Fueled Plants," Ebasco Services, New York, 1978; K. E. Yeager, C. R. McGowin and S. B. Baruch, "Potential Impact of R & D Programs on Environmental Control Costs for Coal-Fired Power Plants," EPRI, Palo Alto, CA, 1979; and C. R. McGowin and K. E. Yeager, "Advanced Programs for Utilization of Coal for Electric Power Generation," EPRI, 1979.
5. PEDCo Environmental, Inc., *op. cit.*, Figures 4–1 and 4–2.
6. "Shifting SO_2 from the stack," *EPRI Journal* (18, July/August 1979).
7. K. E. Yeager *et al.*, *op. cit.*, with costs converted from 1976–1980 mixed current dollars (assuming 8% inflation and interest rates) to mid-1979 constant dollars.
8. The modified Deutch equation predicts a 70% cost increase to improve ESP efficiency from 99.5% to 99.9%, but it may understate cost increases at very high efficiencies.
9. EPA, July 1978, *op. cit.*, Table 4–5.
10. "New Stationary Source Performance Standards, Electric Utility Steam Generating Units," Part II, EPA, *Federal Register* 33600 (June 11, 1979).
11. EPA, July 1978, *op. cit.*, Table 8–1, adjusted to 1979 price levels.
12. EPRI projects a 60% increase in utility NO_x emissions between 1979 and 2000 even if a 0.2 lb standard takes effect in 1985. However, the projection assumes 6% annual growth in fossil-electric generation. (*EPRI Journal*, "Controlling oxides of nitrogen" (26 June 1979).) This is over twice the post-1973 rate and far greater than would obtain under energy policies fostering improvements in end-use efficiency.
13. *Ibid.*, p. 25.
14. "NO_x Control for Western Coal-Fired Boilers: Feasibility of Selected Post-Combustion NO_x Control Systems Study," Stearn-Rogers, Inc., 1978. EPA estimates the installed cost of SCR systems to be approximately $36/kW, or less than half EPRI's estimate for a full system. (J. David Mobley, "Status of EPA's NO_x Flue Gas Treatment Program," in EPRI FP-1109-SR, "Proceedings: Second NO_x Control Technology Seminar," July 1979. See also Session B Questions & Answers in same volume.)
15. D. P. Teixeira, "NO_x Control Technology for Coal Fired Power Plants," EPRI, 1979.
16. R. R. Bennett & D. J. Kettler, *op. cit.*, estimate $21/kW (lined sludge pond) and $4/kW (lined ash pond), expressed in mixed current dollars concluding in 1978. Assuming a mid-1975 midpoint for expenditures and incorporating the 37% inflation in coal plant construction from mid-1975 to mid-1979 gives the costs in the text.
17. The 1978 base cost of $30/kW for "other measures" which was doubled to estimate 1988 costs excludes $10/kW for increased boiler flexibility to accommodate varying coal grades.
18. K. E. Yeager, *et al.*, *op. cit.*
19. Installed coal-fired capacity increased 53% during 1971–78 and is likely to increase approximately 60% during 1978–88. The respective average real cost increases are 33% and 36%, not counting scrubbers—a cost increase which could reasonably be apportioned equally to the two periods.
20. See *Power Engineering*, *83*(11): (1979), for a current review of fluidized bed development status and design features.