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Optimal Use of Smokestack Scrubber By-Product

Diane Hite, D. Lynn Forster, and Jon Rausch

ABSTRACT

Federal legislation mandates substantial reduction of air pollution emissions from electric utilities. Utilities in Appalachia that use locally mined high-sulfur coal must choose among abatement options such as fuel mixing and smokestack scrubbing technologies. Wet scrubbers are the most frequently adopted abatement technology in Ohio. This paper investigates beneficial reuses of by-product from wet scrubbers. By-product is most often disposed of in landfills, resulting in large external costs. We combine social cost and benefit transfers with a linear optimization model to investigate potential benefits of by-product recycling. Results suggest that significant incentives exist to find beneficial uses for by-product.

Key Words: by-product recycling, environmental economics, flue gas desulfurization technology, social costs, and benefits

Acid rain has long been linked to the deterioration of natural systems and fabricated structures. The primary source of sulfur dioxide (SO_2) and nitrogen oxide (NO_x), as identified by the United States Environmental Protection Agency (EPA), is the combustion of coal used in the production of electricity (Helme and Neme). In particular, the electric utility industry in the Appalachian region of the U.S. has historically mined and used high-sulfur coal, and is a major contributor to atmospheric accumulation of greenhouse gases.

Title IV of the 1990 Clean Air Act addresses emissions associated with the burning of fossil fuels, mandating a 10-million-ton (40%) reduction in the nation's SO_2 emissions (based upon 1980 emission levels) by the year 2000,

and a two-million-ton reduction in NO_x (Claussen). The acid rain program developed by EPA under this title allows individual utility companies to determine the most cost-effective means of achieving these mandated emission reductions. Compliance is expected to be achieved through conservation efforts, use of low-sulfur fuels, purchase of emission allowances, retrofitting of existing plants with pollution control devices, and/or a combination of the above.

Currently the only pollution control device used in existing power plants to reduce SO_2 emissions to mandated levels is flue gas desulfurization (FGD). Through the use of a sorbent,¹ such as limestone, exhaust gases are 'scrubbed' of SO_2 . The prevalent technology today is referred to as the *wet scrubber process*. FGD technologies are capable of decreasing SO_2 emissions by as much as 95%

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¹ In this case, sorbent is a material that adsorbs, or takes up gases and solids, by chemical or physical force.

from unabated levels (EPA). However, the process of scrubbing creates another environmental concern, i.e. disposal of the used sorbent or by-product.

Data based on experience at three American Electric Power Company Ohio plants that use wet scrubber technology allow us to illustrate the significance of the problem of FGD by-product disposal. From 1992–1993 operating records we have compiled the following information on wet scrubbers. The by-product created in Ohio by the scrubbing process amounts to about 0.42 tons per ton of coal burned, creating a significant disamenity. We have also estimated from the data that coal inputs required in the generation of electricity range from 0.32 to 0.37 tons per megawatt (MWh) hour, which translates into approximately 0.15 tons of by-product output per MWh.

According to the *1994 Statistical Abstract of the United States*, net electricity generation in Ohio in 1991 was 132.1 million MWh, of which 88% was coal generated. If all coal-fired generators had burned high-sulfur coal in combination with wet scrubbers, the total FGD by-product associated with 1991 generation would be over 17 million tons per year. The potential enormity of the FGD by-product disposal problem is evident when considering that in 1991 the total solid waste of all types disposed in Ohio landfills totaled 15.9 million tons² (Ohio EPA).

Landfilling of FGD by-product is currently the primary means of disposal. However, it has been suggested that wet by-product has chemical properties that make it valuable as a soil amendment in surface coal mine reclamation and in highway embankment construction and stabilization. Currently, EPA disallows unregulated applications of FGD by-product, although several research sites in Ohio have been established to examine the efficacy and safety of its use in surface mine reclamation and road repairs. Our analysis focuses on wet FGD by-product use in reclamation of current and abandoned surface coal

mines, highway construction and repair, and landfilling in a model based on the state of Ohio. We view the creation of FGD by-product in excess of amounts that can be recycled beneficially as creating a potential social cost.

The objectives of this research are (1) to develop a model to identify the least-cost disposal methods of FGD by-product among four stated alternative end uses from the producer or power plants' perspective, (2) to estimate the quantity of by-product used in each alternative, and (3) to estimate the shadow price associated with each alternative end use. This research also attempts to address some of the more significant social amenities/disamenities associated with FGD by-product disposal, for example, property value losses from landfill activities and gains from reclamation of mine lands. Results from two studies on the social costs of landfills (Hite, 1995a, 1995b) and one study of the social benefits of coal mine reclamation (Friedman and Hitzhusen) are incorporated here to account for such gains and losses. Deterioration of roads and bridges from increased traffic, increased/decreased ground and/or surface water quality from reclamation of both ongoing and abandoned surface mines, or landfilling activities are not directly considered outside of the fact that they may be capitalized in real estate values. However, given the quantifiable impacts on property, we are able to demonstrate a major effect from avoidance of landfilling FGD by-product.

Of 23 power plants in Ohio, three major units (Conesville, Gavin, and Zimmer) and at least one smaller plant (McCracken) have retrofitted their coal burning generators with wet FGD scrubber technology. In this analysis, a least-cost transportation model was developed to estimate the optimal distribution of wet FGD by-product from electric power generating sites to the locations of numerous alternative end uses. We thus analyze the impact of FGD by-product with in-place technology. It is unrealistic to assume that many more plants will be retrofitted in the near future due to uncertainties surrounding impending deregulation of the power industry.

² Slightly under 4 million tons of this was attributable to landfilling of used sorbent.

Alternative Disposal Options

FGD by-product has chemical and physical characteristics that make it attractive for highway construction and repair in Ohio. In particular, soils in many areas of the state are susceptible to slippage, resulting in repeated highway repairs that are not only costly in terms of construction but also damaging to the local infrastructure because traffic through these areas can be delayed significantly and may be detoured from interstates onto local highways. Because FGD by-product has cement-like properties, it is in limited use at test sites in various parts of Ohio for road repairs where soils are unstable. In addition, the by-product is quite appropriate for use in repairs even where soils are stable to contour road beds and embankments.

Limited experience has shown that transportation of FGD by-product is similar to that of other borrow or construction materials. Only slight modification of existing equipment is necessary to transport by-product from the source (power plant) to the destination (highway construction site, coal mine, or landfill), and to apply the by-product to various areas of the state to be used for highway repair and mine reclamation. Under these assumptions, FGD by-product is expected to be back-hauled by trucks from the power plant to various locations throughout the state. Once it has reached the highway repair or mine site, it is expected that conventional techniques will be used to apply the by-product in its final use.

Coal surface mine operations are required by federal statute to reclaim lands that have been mined. During the reclamation phase, lime and borrow materials are used to return mined spoils to a pH level conducive to plant growth and to recontour disturbed landscapes. It has been demonstrated at an abandoned mine test site (the Fleming site in northeastern Ohio) that FGD by-product materials can also be used in conjunction with lime and borrow to reclaim mine lands to higher standards than under current regulations. The estimated amount of FGD by-product material needed to meet surface mine reclamation requirements was derived from data reporting tons of sur-

face mine coal sold in each Ohio coal mining county. The number of acres displaced by surface coal mining in a given year was estimated (ODNR) using these data. Based on FGD by-product application rates used on experimental plots, an estimate for the per-acre quantity of FGD by-product demanded was determined.

The final end use alternative identified is that of landfilling. It is expected that FGD by-product will be landfilled if the available amount of the product is larger than its economical use in highway construction and/or surface coal mine reclamation. At present, landfills dedicated to FGD by-product disposal are quite large, and are generally not constrained in the amount of the by-product that can be accepted. In addition, the landfills are relatively near the power plants or sources of FGD by-product.

Although there appear to be some attractive alternatives to landfilling FGD by-product, a number of constraints to their use in land applications exist. First, the by-product contains trace amounts of potentially toxic substances (primarily heavy metals) that can leach into groundwater. Thus the by-product is regulated, and its use in land applications requires special permitting by Ohio EPA. Another constraint on the use of by-product is that potential end-users find it to be an inferior, or possibly even dangerous, substitute for conventional materials. Finally, the annual acreage of lands strip mined is on the decline, and highway repair usage is limited by engineering and geographic considerations.

Model Development

We analyze a least-cost transportation model under different scenarios, all on a per-annum basis. The baseline includes four source nodes (power plants) that currently create wet FGD by-product materials. Use as by-product for highway construction and repair in 88 Ohio counties, for soil amendment at 21 ongoing coal surface mine reclamation sites, and as fill at four landfill sites located near the power plants constitute the demand nodes. We restrict the model to Ohio since surrounding states' environmental agencies have different

regulatory restrictions and may be politically constrained to dispose of scrubber by-product from local utilities before accepting output from utilities in surrounding states.

The baseline model is analyzed first without including estimated externalities. In the next analysis, we simply add the social cost of landfilling to the landfill tipping fee, and subtract the benefits of mine reclamation from the application costs of reclaiming ongoing mines.

The problem then becomes the determination of the amount of FGD by-product material shipped to each of the alternative end uses, given that the cost of distribution and application of the by-product is known or can be estimated. Thus, the decision variable, x_{ij} , equals the number of tons of by-product material shipped from each source i to each destination j annually given some cost-per-unit shipped.

The transportation model estimated is:

$$(1) \quad \text{Minimize cost} = \sum_i^m \sum_j^n c_{ij} x_{ij}$$

$$(2) \quad \sum_{j=1}^n x_{ij} \leq a_i \quad (i = 1, 2, \dots, m)$$

where $m = 4$ power plant sites;

$$(3) \quad \sum_{i=1}^m x_{ij} = b_j \quad (j = 1, 2, \dots, n)$$

where $n = 113$ end uses including 4 landfills, 21 mine reclamation counties, and 88 road repair counties; and

$$(4) \quad x_{ij} \geq 0 \quad (i = 1, 2, \dots, m; \\ j = 1, 2, \dots, n).$$

where a_i is the number of tons of FGD by-product material available at the i^{th} power plant or source; b_j is the maximum number of tons of by-product required at each destination or alternative use j (e.g. county for highway construction, reclamation site, or landfill); and c_{ij} is unit transportation and application cost from each source i to each destination j .

Equation (1) represents the minimization of total distribution costs, assuming a linear cost

structure for shipping, processing, and application of the wet FGD by-product material. Equation (2) introduces the constraint that the quantity of by-product shipped from power plant i to each alternative end-use destination j be less than or equal to the quantity of by-product material available at source a_i . Equation (3) states that the quantity of by-product shipped from each source i to each destination j must be equal to the maximum quantity of by-product demanded at that destination. Finally, equation (4) constrains tons of by-product shipped from each source i to each destination j to be non-negative.

Supply, Demand, and Cost Estimates

In all three models, estimates pertaining to the quantity of wet FGD by-product demanded at various nodes for the highway construction/repair end use alternative have been adjusted for a 10% rate of adoption. It is expected that the by-product will not be appropriate for all highway repairs where borrow is used; thus we assume a conservative rate of adoption. However, it is important to note that the model can be re-estimated assuming various levels of adoption. Historic county-level data were used to estimate the average annual amount of fill material used for road repair in each county (ODOT).

Linear distances from the power plant or source of wet FGD by-product to the center of each county were calculated. Once these distances were determined, costs associated with moving by-product the specified distance were determined, based on estimates obtained in interviews with representatives of electric utilities. It is expected that wet FGD by-product will be transported in much the same manner as current highway repair materials. Thus, an estimate of \$0.10 per ton per mile was used. In addition to moving the product from the source to the destination, an application expense is incurred. Again, the application of wet by-product is expected to be similar to that of borrow materials, which has an estimated application charge of \$3.50 per ton (ODOT). This includes equipment costs for

earth moving equipment to manipulate the by-product.

Transportation of wet FGD by-product to surface coal mine reclamation sites is also expected to cost \$0.10 per ton per mile. Application of by-product is expected to be at levels that are significantly higher than application rates associated with highway use, potentially as much as 250 tons per acre. We assume that the equipment used in distributing the by-product (e.g. a bulldozer or equivalent type of reclamation machinery) will be similar to road repair equipment so that application costs would not vary significantly; thus we estimate costs of \$3.50 per ton.

Cost estimates for landfilling were obtained from interviews with representatives of electric utilities. All landfilling activities are regulated by Ohio EPA and are required to follow stringent guidelines; the regulation costs are borne almost entirely by the utility. Electric power plants have estimated that it costs about \$27.50 per ton of material to landfill wet FGD waste and meet current EPA guidelines. The \$27.50-per-ton landfill-disposal cost estimate is comparable to statewide tipping fees at commercial landfill operations in Ohio in the mid-1990s (Ohio EPA).

Social Cost and Benefit Estimates

Social cost adjustments were made to the tipping fees for each of the landfills as well as for the use of FGD by-product in mine reclamation. Based on a cost transfer procedure described below, the social cost additions to landfill tipping fees were as follows: Conesville, \$0.31/ton; Gavin, \$1.27/ton; McCracken, \$7.13/ton;³ and Zimmer, \$1.42/ton. These reflect impacts on real estate values in the areas around landfills, and are greatly affected by landfill size as well as population densities and property values near landfills.

³ The scarcity of landfill space within a 60-mile radius of the McCracken Plant contributes to the higher social cost at this site since transporting by-product becomes uneconomical. In addition, the landfill from which this social cost was estimated was in fact the landfill used by McCracken for by-product disposal in the early 1990s.

In addition to the social costs of landfills, the benefits of strip mine reclamation are accounted for in our model, based on a hedonic price analysis of homes in mine impacted areas of eastern Ohio (Friedman and Hitzhusen). In this model, the social benefits of strip mine reclamation were estimated as avoided social costs incurred by homeowners living near unreclaimed strip mines. The estimated social benefit derived from this research amounts to \$0.02 per ton of FGD by-product used in mine reclamation. This amount is negligible, but it represents an upper limit on the social benefits of by-product because it assumes all the reclamation benefits are attributed to just one input into the reclamation process.

The social costs for landfilling FGD by-product that we employ in this analysis were derived from a cost-transfer procedure (Hite 1995b) that uses the hedonic price model (HPM) to account for social costs. Previously, such techniques have mainly been applied to transfer social benefits via the travel cost model (e.g. Boyle and Bergstrom; Crutchfield et al.). In brief, the methodology used here consists of transferring social costs that were estimated for four landfills in Franklin County to the landfill demand nodes in our transportation model. The transfer model explicitly accounts for the fact that the disamenity effect of a landfill is directly related to its life expectancy.

To implement the cost-transfer model, we used an HPM to obtain compensating variation (CV) estimates of the social costs of landfilling in Franklin County, Ohio at varying stages of landfill life expectancy (Hite 1995a). In general, the HPM controls for structural and neighborhood characteristics of a home while isolating the impact that environmental quality has on property values, and has been widely used in evaluating environmental quality (see Kiel and McClain; Driscoll, Alwang, and Dietz). In the case at hand, the environmental characteristic of interest was the distance of a home to a landfill, and property value impacts attributable to the landfill's proximity as well as the life expectancy of a landfill were estimated. The HPM was based on a sample of households located within 3.25 miles of a

landfill, and social costs were measured empirically by compensating variation estimates of willingness to pay of the sample households to live at a distance of 3.25 miles rather than at their actual distance from a landfill.

To carry out the cost transfer, the CV estimates were used to calculate the net present value (NPV) of social cost of a landfill for a representative household in a census block group falling within a 3.25-mile radius of Franklin County landfills. The empirical social cost measures were then used as the dependent variable in a predictive model that included explanatory variables at census block group (CBG) levels as follows:

$$\begin{aligned}
 (5) \quad \log((NPV)_i) \\
 &= a_0 + a_1 \text{Demographics}_i \\
 &\quad + a_2 \text{Neighborhood}_i \\
 &\quad + a_3 \text{Housing Characteristics}_i \\
 &\quad + a_4 \text{Landfill Life Expectancy}_i \\
 &\quad + a_5 \text{Distance to Landfill} + \epsilon_i,
 \end{aligned}$$

where i represents each of the 249 CBGs in the sample. According to the model, the average NPV of social costs for a given CBG can be explained by factors such as demographic, neighborhood, and property characteristics, along with landfill life expectancy and distance to landfill. The relevant demographic characteristic used in the model is percentage of black households in a CBG; the neighborhood characteristics include percentage vacant residences in a CBG along with percentage of households with private wells; property characteristics include average home value, number of rooms, number of bedrooms, and year the structure was built; the landfill life expectancies for four landfills range from -11 years (closed 11 years) to 25 years; and distances to landfill are based on the weighted average linear distance of a CBG to the nearest landfill.

The estimated model is reported in Table 1; except for the landfill variables, data used for the estimate were obtained from 1990 US Census STF3-A data tapes. The estimated model fits the data quite well, with all vari-

Table 1. Predictive Model for Benefits Transfer

Variable	Estimated Parameter
Intercept	-43.5200 (-12.03) ^a
% Black	-0.0056 (-5.31)
% Vacant	-0.0347 (-6.00)
% Private Well	-0.0031 (-2.06)
Average Home Value	0.0068 (10.16)
Average # Rooms	0.2403 (3.25)
Average # Bedrooms	-0.3450 (-2.43)
Average Year Built	0.0225 (12.36)
Life Expectancy of Landfill	0.0868 (26.78)
Distance to Landfill	-0.1274 (-2.98)
R ²	0.93

^a Numbers in parentheses are t-statistics.

ables significant at the 99.9% level. Of particular interest in the model are the variables related to the landfills, i.e. distance to landfill and landfill life expectancy. As distance to the landfill increases social costs decrease, and as landfill life expectancy increases social costs increase. The model also supports the intuition that social costs will increase with increased property values as observed directly from the model coefficient for housing value. In addition, social costs decrease in more rural areas as measured by the negative coefficient on percentage of homes in a CBG that have private wells. Housing characteristics such as number of rooms and bedrooms are included as their relationship varies when comparing housing stock in older urban areas to suburban and rural areas. The social costs increase with number of rooms in a house, which is an obvious result. Less obvious is the negative coefficient on the number-of-bedrooms variable. Because of the heterogeneity of the underlying sample, we find no multicollinearity between

Table 2. Optimal Use of FG By-Product

	Conesville	Gavin	McCracken	Zimmer	Total Shipped
Highway (tons)	136,085	285,015	15,590	223,455	660,187
Mines (tons)	525,645	1,313,545	0	0	1,839,189
Landfill (tons)	0	134,360	0	1,309,300	1,443,660
Total (tons)	661,730	1,732,920	15,590	1,532,755	3,942,995
% Highway	20.57%	16.45%	100.00%	14.58%	16.74%
% Mines	79.43%	75.80%	0.00%	0.00%	46.64%
% Landfill	0.00%	7.75%	0.00%	85.42%	36.61%
Total	100.00%	100.00%	100.00%	100.00%	100.00%

number of rooms and number of bedrooms, and can only hypothesize that perhaps more affluent families have fewer children and thus fewer bedrooms relative to house size.

Using census data corresponding to the model in equation (5), we were able to predict the NPV of social costs for the remote landfills in which FGD by-product is disposed. The actual disposal of by-product generally takes place in sparsely populated rural areas where social costs are relatively low; note, however, that the McCracken power plant, located in Columbus, uses a Franklin County landfill where higher social costs are incurred. The social costs for the landfills accepting FGD by-product were predicted on a per-CBG basis at various distances up to 3.25 miles from the landfill. These were then multiplied by the number of affected households in each CBG and summed to obtain aggregate NPV of social cost at each landfill. Using data from Ohio EPA, the total tons of FGD that would be disposed of over the life of each landfill were estimated, and the per ton social costs were estimated as $(\Sigma \text{ NPV of Social Cost})/(\text{Total Tons Landfilled})$.⁴ A similar procedure was carried out to estimate the social benefits of reclaiming strip mines.

Results

Table 2 shows a summary of shipments by source and by disposal option. In the scenario

presented in this analysis, 16.74% of wet FGD by-product would be used in highway construction and repair and 46.64% would be used in mine reclamation; however, the amount of FGD by-product greatly exceeds anticipated demand and 36.61% of the by-product will be landfilled. The results imply that significant new beneficial uses for by-product would be required in order to change the outcome of our model since amounts of by-product allocated to highway repair and mine reclamation are equal to the demand constraints specified in the model.

The results of the linear transportation model suggest that the optimal disposal scheme for wet FGD by-product would cost \$70.1 million annually (3.9 million tons at \$18 per ton) if the full social costs of landfilling were considered; social costs in this scenario amount to \$2 million per year. This is in stark contrast to the costs if no alternatives for recycling exist, in which case social cost alone is \$4.7 million per annum, and full costs of landfilling, including social costs, are \$115.6 million per annum or \$30 per ton.

Shadow prices for wet FGD by-product are calculated as the difference between landfilling (non-binding constraint) and highway use or coal surface mine reclamation options (both binding constraints). It would be expected that as the distance from the power plant increases, the cost to move the by-product also increases, resulting in lower imputed value or shadow price for binding end-use options farther from the source or power plant. That is, the difference between landfilling and shipping wet FGD by-product material greater distances

⁴ Although we use an average cost measure here, we assume that since social costs of landfilling should be fairly directly related to tons landfilled that, over the life of a landfill, the difference between marginal and average costs should be negligible.

would be smaller. Thus, land application sites in counties located farther from wet FGD by-product sources would have lower shadow prices resulting in reduced cost savings to utility companies as compared to application at sites closer to a power plant.

Another interpretation of the shadow prices is that they represent the amount the power plant would be willing to pay for the disposal of an additional ton of by-product in each end-use alternative. For example, the calculated shadow price for Williams county, the most distant county with the lowest shadow prices, is \$3.29 per ton, suggesting that the power plant should be willing to pay an FGD by-product user up to \$3.29 to take an additional ton of wet FGD by-product as opposed to landfilling it at a cost of \$27.50 per ton.

The costs of landfilling (both the amount of the tipping fee and the social cost) are important determinants of the FGD by-product's optimal use; here we assume a \$27.50 per ton tipping fee. At this price level, use of the by-product in road repair and coal surface mine reclamation dominates landfilling. As much FGD by-product as possible is allocated to construction and reclamation uses. The implication is that it costs less for FGD by-product to be transported to the farthest corners of the state to be used in road repair or mine reclamation than to be landfilled. When social costs are added to the tipping fee, the financial incentive to find an alternative to landfilling is even more pronounced.

Using the linear optimization model, we conduct sensitivity analysis to determine the effect of landfilling costs on FGD by-product uses; that is, we vary the landfill tipping fee and rerun the transportation model in order to see the way optimal use of FGD by-product changes. The expectation is that landfilling costs have an important impact on alternative uses. If landfilling costs were lower, more FGD by-product would be landfilled and less would be used in road repair and mine reclamation.

Figure 1 illustrates the sensitivity of FGD by-product use to landfilling tipping fees in the linear optimization model. A reduction of tipping fees from \$27.50 to about \$20 per ton

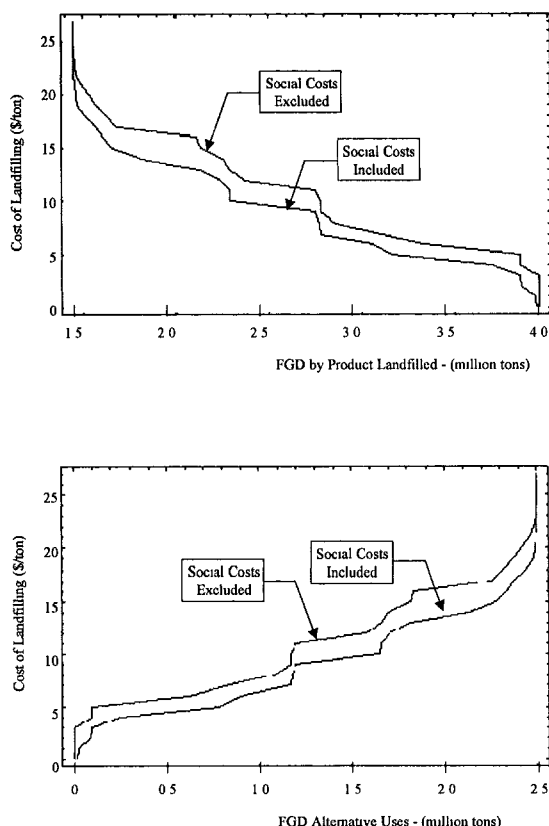


Figure 1. Effects of Landfilling Cost on Quantities of FGD By-Product Landfilled and Used in Alternative Uses (Road Repair and Surface Mine Reclamation)

has relatively little impact on alternative uses. Landfilling remains a high-cost disposal option. However, as costs drop below \$20 per ton, landfilling becomes competitive with use of by-product at distant road repair or mine reclamation sites. With \$10-per-ton tipping fees, the rate at which the by-product is landfilled increases, and the amount of FGD by-product used in road repair and reclamation is reduced by about 50% compared to the amount used when tipping fees are \$20 per ton.

Including social costs in the calculation of landfill costs has some impact on FGD by-product use. Adding social costs (Conesville, \$0.31 per ton; Gavin, \$1.27 per ton; McCracken, \$7.13; and Zimmer, \$1.42 per ton) to the tipping fee results in a reduction in the quantities of by-product landfilled over the

range of landfilling costs tested in the sensitivity analysis. For example, if the landfill tipping fee is \$10 per ton, about 2.7 million tons are landfilled. However, if social costs are added to the \$10-per-ton tipping fee, the amount of by-product landfilled drops to about 2.2 million tons.

In summary, the analysis indicates that at the current level of landfill tipping fees, there is a substantial financial incentive for power plants to find alternative uses for FGD by-product. Road repair throughout the state and surface mine reclamation in the eastern third of the state appear to be economically viable uses. Undoubtedly, other FGD by-product markets could be developed, e.g. use as a soil amendment to acidic agricultural soils or use in the production of dry wall and other gypsum-based products. However, the potential for these uses is susceptible to consumer acceptance and may not provide substantive outlets for excess by-product. When social costs of landfilling, i.e. the reduction in property values near landfills, are added to landfill tipping fees, the incentive for finding alternative uses for FGD by-product becomes even greater.

Conclusion

In the Introduction we demonstrated that 80% adoption of FGD technology would double the annual solid waste stream in Ohio based on current demand for electricity. A number of factors will possibly augment demand for electricity in the future, further increasing the potential for FGD by-product generation. First, as population grows, so will demand for final products, resulting in an increase in the amount of electricity used as a factor of production. Second, population growth will put pressure on utilities to supply residential and commercial demand for electricity. Third, since heaviest electric demand occurs in the summer months due to air conditioning, as population increases so will the use of air conditioning; if, as many scientists believe, global warming is a reality, the problem will be exacerbated. Between 1970 and 1990, the population of Ohio grew by 1.78% (10,657,000 to

10,847,000), while that of the total US increased by 21.87%. It is notable in this context that net electric generation in Ohio between 1970 and 1990 increased by 14.79% or 0.7% per year (110.2 billion kilowatt hours to 126.5 billion kilowatt hours), and between 1990 and 1991 net generation increased by 4.4% (126.5 billion kilowatt hours to 132.1 billion kilowatt hours). Thus, steady growth in electric usage may be expected in the future.

At the same time that utilities face growth in demand for electricity, they will be forced to achieve compliance with the mandates of the 1990 Clean Air Act. Thus power plants will have to encourage reduction in demand for electricity, use fuels lower in sulfur, purchase emission allowances, retrofit existing power plants with clean air technology, or some combination of the above. Currently, the only clean air technology available to existing power plants is flue gas desulfurization (FGD) technology. EPA has estimated that this technology can reduce SO_2 by as much as 95%. However, wet FGD technology creates another environmental concern: disposal of the used sorbent. Based on experience at the four power plants currently equipped with scrubbers, nearly four million tons of wet FGD by-product are produced annually in Ohio alone.

The objective of this research was to estimate a least-cost disposal model for the movement of by-product to alternate uses at various geographic locations throughout Ohio. In doing so, total disposal costs and quantities disposed at alternative sites were derived. Two current end-use alternatives for FGD by-product were identified in addition to landfilling: highway repair and construction and coal surface mine reclamation. Under our most realistic assumptions, landfilling can be expected to be the disposal option for about 36% of the total by-product produced, while use in highway repair and surface coal mine reclamation would account for about 17% and 47% of the total, respectively. On average, alternative applications of wet FGD by-product represent a per-ton savings of approximately \$12.

The potential for use of wet FGD by-product in highway repair exists throughout the state, while use in surface coal mine reclama-

mation is important in the eastern one-third of the state. Yet of the alternative disposal options identified, a significant portion of wet FGD by-product is landfilled. Given the limits of the current beneficial end uses, landfilling will remain an important alternative. However, electric utilities have a significant economic stake in supplying wet FGD by-product to coal mine reclamation operations and Ohio highway repairs. Furthermore, substantial incentives exist to find additional uses for FGD by-product in order to avoid both the private and social costs of landfilling.

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