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Utilization of Water Utility Lime Sludge for Flue Gas Desulfurization in Coal-Fired Power Plants: Part I. Supply–Demand Evaluation and Life Cycle Assessment

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Abstract

The feasibility of lime-softening sludge utilization for flue gas desulfurization in coal-fired power plants was evaluated through a supply–demand analysis and a life cycle assessment (LCA). To evaluate the demand and supply of lime sludge to replace limestone on a national scale, the annual amount of lime sludge generated by water treatment utilities in the United States was estimated and compared with the annual amount of limestone used by coal-fired power utilities. To evaluate the environmental sustainability of reusing lime sludge in power plants, an LCA study was performed in which the environmental impact and water footprint of the proposed approach were quantified and these results were compared with the conventional approaches for limestone mining, grinding, and transportation to power plants and lime sludge disposal in landfills. Water utilities across the United States are currently generating approximately 3.2 million tons of lime sludge per year at an estimated disposal cost of approximately US\$90 million, whereas power utilities are using approximately 6.3 million tons of limestone per year. The potential savings that would result from partial replacement of limestone with lime sludge was estimated to be approximately US\$97 million per year. The LCA study showed that the environmental impact of lime sludge utilization in power plants under different scenarios was 2 orders of magnitude lower than that of the landfill disposal option. Furthermore, the water footprint for lime sludge reuse in power plants was almost negligible compared with that of the conventional approaches of disposing of lime sludge at water utilities or using limestone at power utilities.

Keywords

Flue gas desulfurization; limestone; lime sludge; life cycle assessment; environmental impact assessment

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1. INTRODUCTION

According to the U.S. Energy Information Administration,¹ by the end of 2011, 60% of coal-fired power plants were equipped with SO₂ scrubbers. In the SO₂ wet scrubbing process, limestone, which is primarily composed of calcium carbonate, is pulverized to a particle size of <44 µm. Then, a slurry of the pulverized limestone is reacted with flue gas to capture SO₂ and a gypsum by-product, after air oxidation. The transportation and preparation of limestone is an energy-intensive process with a high CO₂ footprint, and it incurs a significant cost, especially if high-quality limestone is not available locally and needs to be transported over long distances. Lime sludge, a by-product of the lime-softening process in water treatment plants, is mostly composed of precipitated calcium carbonate particles and can be considered a potential replacement for limestone in the flue gas desulfurization (FGD) process.

Hundreds of water utilities across the United States generate substantial amounts of lime-softening sludge. For instance, a water treatment plant in the Midwest generates 30,000 tons (dry-weight basis) of lime sludge per year.² The majority of lime sludge generated is handled as waste material, which currently is managed by placement in lagoons or disposal in landfills. This adds as much as 10% to the overall cost of water treatment.³ The beneficial use of lime sludge may eliminate the disposal cost and could potentially generate revenue for water utilities. Some potential beneficial uses of lime sludge include subsurface filling,^{4–6} cement manufacturing,^{7,8} mining industry-related applications, soil pH regulation,⁹ feedstock for new composite materials,^{10,11} and as a replacement for ground limestone in the wet scrubbing process.^{12–14} Reports on the properties of lime sludge samples and experimental data have indicated that lime sludge could be a suitable replacement for limestone in FGD systems.^{2,13,14} Among these studies are three major reports that provided data directly from successful utilization of lime sludge for FGD in power plant tests.

Replacing limestone with locally available lime sludge may benefit the power utilities in several ways: (1) by eliminating the extra cost of transporting high-quality limestone over long distances; (2) by eliminating energy usage for limestone grinding; and (3) by reducing the overall CO₂ footprint of FGD. However, several key aspects must be addressed before commercial reuse of lime sludge in power plants can be considered on a national scale. First, the supply–demand feasibility of replacing limestone with lime sludge needs to be evaluated by comparing the amount of lime sludge generated at water utilities with the amount of limestone used at coal-fired power plants in the United States. Second, the overall potential economic benefit for power and water utilities should be estimated. Third, the overall environmental benefit of reusing lime sludge for FGD application needs to be quantified through a life cycle assessment (LCA) under different scenarios. Fourth, other potential aspects related to lime sludge utilization should be investigated. These may include several technical and non-technical items such as: lime sludge reactivity for SO₂ capture, mercury reemission from the scrubber into the flue gas, leaching of undesirable impurities from the lime sludge into scrubber solutions, transportation and/or onsite storage of lime sludge, readiness of power generation and water treatment industries in different states, and support from local and regional governments.

The goal of this study was to evaluate the feasibility of a sustainable and economically attractive approach to reusing the lime-softening sludge generated from drinking water treatment utilities for capturing SO₂ in the wet scrubbers of coal-fired power plants. This article is focused on investigating the first three key aspects (listed in the previous paragraph) by performing a supply–demand feasibility analysis, an economic evaluation, and a comparative LCA to evaluate the feasibility of lime sludge reuse at coal fired power plants. In Part II of this work, some other technical aspects of lime sludge utilization were investigated; including the performance of various lime sludge samples for SO₂ capture from a simulated flue gas, the mercury reemission from the scrubber, and leaching of undesirable impurities from lime sludge.¹⁵

2. METHODOLOGY

2.1. Evaluation of Limestone Demand and Lime Sludge Supply

The annual steam-electric plant operation and design data (EIA-767) database was used to estimate the total amount of limestone used by coal-fired power utilities in the United States.¹⁶ The total amount of lime sludge generation by water utilities was obtained as follows. First, data from the Safe Drinking Water Information System (SDWIS)¹⁷ was used to compile a list of water treatment facilities in the United States that actively practice lime softening by means of the lime–soda ash addition method (process code 500) and whose count for population served is 10,000 or greater. Next, reports of average lime sludge production from several facilities in Kansas and Iowa^{2,12} were used to estimate an average value for the annual amount of lime sludge produced per person. This value was based on the availability of information in the open literature and was restricted to only these specific areas. Finally, the total population served by facilities performing lime softening, as recorded in the SDWIS, was multiplied by the average amount of lime sludge produced per person to estimate the current amount of lime sludge production in the United States.

2.2. Life Cycle Assessment Methodology

2.2.1. Goal and Scope Definition—Life cycle assessment is a tool used to quantify the total environmental impact (EI) of a process. The “cradle-to-grave” LCA methodology set forth in the International Standards for Life Cycle Assessment (ISO 14040 and ISO 14044)¹⁸ evaluates the impact of a process over its entire life span, from the extraction of raw product materials from the earth to the disposal of materials at process termination. A comparative LCA study was conducted to compare the total EI generated by current limestone mining and processing for FGD scrubbers with the EI resulting from the reuse of lime sludge generated by water treatment plants in FGD scrubbers. To highlight and quantify the environmental benefit of lime sludge recycling in power plants, a third LCA case was also included for the disposal of lime sludge in landfills. This LCA study includes the following three cases under different scenarios for uncertainty analysis:

- Case 1: Limestone is mined and processed, and then transported to power plants and ground to <50 µm size. The average transportation distances considered were from 5 to 100 miles for different scenarios representing the distance from power plants to limestone mines.

- Case 2: Lime sludge (20–80% moisture content) is transported from water treatment plants to power plants. The average transportation distance varies from 5 to 100 miles.
- Case 3: Lime sludge (20–40% moisture content) is transported from water treatment plants to landfills for disposal. The transportation distance varied from 5 to 100 miles.

This LCA study was performed to illustrate environmental sustainability of lime sludge utilization under specific assumptions. Other case studies may consider other assumptions such as partial implementation of lime sludge utilization at power plants at a national scale or other boundaries for the LCA investigation.

2.2.2. Life Cycle Impact Assessment Methodology—The total EI scores were calculated by using GaBi LCA software version 6.0 developed by Thinkstep (Leinfelden-Echterdingen, Germany).¹⁹ GaBi software was also used to interpret the results by performing data normalization and comparison. The U.S. Environmental Protection Agency impact assessment methodology TRACI 2.1 was used to categorize the EI into eight impact categories.²⁰ These included impacts on resources–fossil fuels, global warming, smog potential, ozone depletion, human toxicity–cancer, eutrophication potential, ecotoxicity potential, and acidification potential. Because each impact category has a different unit, results for each impact category were normalized (by using the “TRACI 2.1, USA 2008, including biogenic carbon [person equivalents]” normalization factors) and weighted (by using the “Thinkstep LCIA Survey 2012, North-America, TRACI 2.1, including biogenic carbon [person equiv. weighted]” weighting factors) before they were summed to determine an overall impact score.

The water depletion impact category was assessed by using the ReCiPe methodology that was available from GaBi software.¹⁹

2.2.3. Inventory Analysis—The first LCA case covers limestone mining, processing (including grinding to a particle size of $\sim 50 \mu\text{m}$), and transportation to a power plant. In Case 2, transportation of the partially (lagoon-) dried lime sludge to the power plants was considered. In Case 3, the EI of lime sludge transportation and landfill disposal were considered.

Case I was treated as a baseline for this LCA study (dry limestone basis). The transportation distance for the baseline case was set to 5 miles, and the diesel usage per mile was 0.000114 kg. For Cases 2 and 3, the lime sludge was transported as a wet solid, but a side-by-side comparison was made for the three cases on a dry basis, where 1 ton of dry limestone was equal to 1.25 tons of wet lime sludge with a 20 wt % water content. The inventory inputs in this study were normalized to 1 kg of limestone equivalent (1.25 kg of lime sludge). All cases were assumed to have the same life span. The library of processes was obtained from the GaBi Professional database.¹⁹ The libraries in the GaBi Professional databases contained all the related EI information (i.e., emission data, energy consumption, and material production data) to which many of the inputs and outputs identified in the life cycle inventory could be linked.

2.2.4. Uncertainty Analysis.—An uncertainty analysis was conducted to assess the variations in the LCA outcomes. Two main uncertainty variables were considered in the study—transportation distance and water content in the lime sludge. Transportation distance was varied from 5 miles in the baseline case to 100 miles, whereas water content in the lime sludge was varied from 20% in the baseline case to 80% for Case 2, and from 20% to 40% for Case 3. These variables were adjusted to cover several scenarios in which the transportation distance varied from 5 miles in the baseline case to 25, 50, 75, and 100 miles for Cases A, B, C, and D, respectively.

The uncertainty associated with our life cycle inventory was estimated by using a statistical sampling method and by parameter variation or scenario analysis.²¹ Statistical sampling was conducted by using the Monte Carlo analysis in Microsoft Excel 2016 as explained elsewhere.²²

3. RESULTS AND DISCUSSION

3.1. Evaluation of the Demand and Supply

To evaluate the feasibility of replacing limestone with lime sludge on a national scale, an overall assessment of a potential market for lime sludge produced by the power utilities was obtained by estimating the total amount of lime sludge generated by water utilities compared with the total amount of limestone used by coal-fired power utilities in the United States.

Following the previously described methodology for estimating lime sludge generation, the average lime sludge production rate was first estimated. Reported data indicated that eight water utilities in Iowa and four water utilities in Kansas, serving a population of approximately 1,371,000, generated a yearly amount of approximately 111,700 tons of lime sludge on a dry basis (Table 1). This amount was equivalent to an average rate of 0.081 tons of dry lime sludge per person for each year. A survey of the SDWIS database for major water treatment plants that are equipped with the lime-softening process indicated that 38,880,057 people are served by these utilities in the United States. Therefore, the total yearly amount of lime sludge generated (on a dry basis) by the major water utilities could be estimated at roughly 3.2 million tons. This estimation was similar to another estimation in the literature of 4 million to 5 million dry tons of lime sludge per year.¹³ It should be noted that these values are estimates of the current production and do not include any existing stockpiled lime sludge. According to the reported annual cost of lime sludge disposal in the City of Des Moines, Iowa, in 2004,² the cost of disposal per ton was estimated at \$20/ton on a dry basis (\$28.26/ton adjusted for inflation, assuming a 2.5% inflation rate). The estimated cost of disposal of 3.2 million tons lime sludge is approximately US\$ 90 million.

The estimated amount of limestone consumption by FGD scrubbers in the United States (in year 2005) was about 6.3 million metric tons. This estimation is based on the latest available data reported in the annual steam-electric plant operation and design data (EIA-767) database.¹⁶ When comparing the lime sludge production rates with the rates of limestone consumption for FGD applications (3.2 million vs. 6.3 million metric tons, respectively), generated lime sludge from water utilities can potentially supply about half of the limestone demand for FGD application. Taking into consideration that the amount of lime sludge

produced annually in the United States is also backed by existing stockpiled lime sludge, this resource could serve as a reliable, cost-saving alternative for FGD operations.

The amount of potential savings that would result from replacing 3.2 million tons of limestone with lime sludge was estimated at approximately US\$97 million per year (Table 2). This estimation was based on the overall benefit of lime sludge reuse for water and power utilities. A value of \$4.00/ton (\$6.39/ton adjusted for inflation) for limestone purchase, \$1.00/ton (\$1.60/ton adjusted for inflation) for limestone grinding, and \$0.80/ton-mile (\$1.28/ton-mile adjusted for inflation) for lime sludge transportation was assumed.¹² A cost of \$0.19/ton-mile was used as the limestone transportation cost.²³ The average limestone and lime sludge transportation distances were assumed to be 30 and 7 miles, respectively, based on the average distance of power plants to limestone mines or water utilities (those generating lime sludge) in the state of Illinois. The average distance values were estimated based on the location information provided in the maps of relevant reports.^{24,25} The total savings achievable by replacing limestone with lime sludge was the sum of money saved by eliminating lime sludge disposal costs, eliminating limestone purchase costs, reducing transport costs, and eliminating grinding costs, minus the cost incurred by transporting the lime sludge.

3.2. Environmental Impact Assessment

The total weighted scores for the three LCA cases were calculated and are compared in Figure 1a. The comparison is based on the overall EI score for each case (i.e., a higher score is indicative of a higher negative impact on the environment) and the percentage contribution of each EI category to the overall EI score. The EI of lime sludge reuse in power plants (Case 2) is approximately 2 orders of magnitude less than if it were disposed of by landfilling (Case 3) or as part of the traditional mining and processing of limestone for power plants (Case 1). This result clearly quantifies the environmental sustainability of lime sludge reuse for flue gas cleanup in coal-fired power plants. Furthermore, the contributions of each impact category for each case are presented (Figure 1b). The contribution of each impact category to the overall EI of Case 1 is as follows: 27.2% smog potential, 24.7% global warming potential, 16.54% resource fossil fuel, 13.9% acidification potential, 7.7% eutrophication potential, 5.7% human toxicity potential, 4.1% ecotoxicity potential, and negligible ozone depletion potential.

In Case 1, when limestone is mined, processed, and transported to power plants, limestone mining and processing generate the majority of the EI (97.6% of the overall EI), whereas limestone transportation to the power plant is accountable for only 2.4% (Figure 2a). The contributions of each impact category for each case are also presented (Figure 2b). These results were expected because mining and grinding, in general, are known for their substantial EI resulting from the associated energy use and waste generation.²⁶ The GaBi database used in this analysis (limestone flour, 50 μ m) models limestone mined in quarries by common mining techniques, such as drilling, blasting, and excavating. The database calculates the EI of the chemical usage and heavy machinery operation, such as diesel-driven excavators, drillers, and dumpers. The EI of limestone processing is also modeled,

which includes limestone crushing, conveying, grinding, and sizing as well as the equipment used, such as vibratory screens and multi-step roller mills.¹⁹

In Case 2, lime sludge is collected from the dewatering lagoon at the water treatment plant. Because lime sludge is assumed to be dried naturally by settling, evaporation, and infiltration, lime sludge transportation is the only component analyzed. Thus, the largest portion of the overall EI (73%) is associated with the diesel consumption during lime sludge transportation, whereas truck use accounted for 26.8% of the total impact (Figure 3a). The contribution of each process unit to each EI category is shown in Figure 3b. The overall EI generated by Case 2 is categorized as follows: approximately 47.6% of the EI resulting from lime sludge transportation is the impact on resource fossil fuel, 26.2% is global warming potential, 7.3% is smog potential, 5.4% is acidification potential, 4.7% is human toxicity potential, 4.5% is eutrophication potential, 4.3% is ecotoxicity potential, and the ozone depletion potential is negligible (Figure 3b).

Finally, the results of Case 3 (lime sludge disposed in landfills) are shown in Figure 4. The contribution of each process unit to each EI category is shown in Figure 4b. The main components evaluated in this figure are lime sludge transportation to landfills and the landfill treatment process. The highest impact factor was associated with disposal of lime sludge in landfills (98.7%). In the absence of a landfill database for lime sludge disposal, the best available landfill database in the GaBi software (i.e., glass/inert waste landfill database) was used to model lime sludge disposal. However, the selected model includes gas, leachate, and sludge treatment for a 100-year deposit, in addition to the sealing materials (clay, mineral coating, polyethylene film) and diesel for the compactor. The high EI associated with lime sludge disposal in landfills is due to the impact of landfill gas, leachate, and sludge. It should be noted that these model assumptions might generate overestimations for relatively inert materials, such as lime sludge generated by drinking water utilities.

3.3. Depletion of Water Resources

The environmental sustainability of lime sludge reuse at power plants (i.e., Case 1) should be evaluated further by comparing its water footprint with those of the other options (i.e., Cases 1 and 3). Water depletion analysis is the assessment of freshwater use and consumption, both directly and indirectly, over the full life cycle of a product or process and is indicative of the overall freshwater use. Depending on the life cycle of different scenarios, each case might have a different impact on the depletion of freshwater resources that are required for electricity generation, fuel, and material production for the processes. Therefore, water resource depletion could be another vital factor in decision making between reusing lime sludge and mining limestone. Results indicated a water resource depletion of 0.032 m³ per kg limestone equivalent for Case 1 and 0.011 m³ per kg limestone equivalent for Case 3 that were caused by the mining and landfill processes, respectively, whereas the freshwater consumption from reusing lime sludge in power plants was almost negligible. The analysis of water resource depletion further highlights the benefit of recycling lime sludge to power plants.

3.4. Uncertainty Analysis

Major input parameters that could significantly affect the outcome of an LCA for the selected scenarios include both the water content of the lime sludge and the transportation distance required to haul limestone or lime sludge to power plants or landfills. To create a more comprehensive picture of the EI of each case, an uncertainty analysis was conducted by using a targeted scenario analysis. A scenario analysis is an investigation of the effect of a single inventory adjustment (while other parameters remain unchanged) on the EI of a process, including analysis of extreme process conditions. Results showed that hauling distance had a significant impact in the case in which transportation was considered the main contributor to the overall EI (i.e., Case 2; see Figure 5). In the other cases, either limestone mining or the landfilling process contributed the most to the overall EI; thus, the variation in distance had a limited impact on the overall EI. When the distance was changed from 5 to 25 miles, the overall EI increased by 9.6% for Case 1, 400% for Case 2, and 5.0% for Case 3. A further increase in the transportation distance led to a greater increase in the overall EI for all cases.

Water content in the lime sludge may be different for different plants depending on the size of the water treatment plant, the amount of lime sludge produced, and the dewatering techniques utilized. In the baseline case, water content was set at 20%, which may represent the moisture content of a relatively dry sample stored at ambient conditions. To get the same functional unit, input lime sludge amounts would increase because of an increase in water content for Cases 2 and 3. The results indicated that in Case 2, the water content change increased the overall EI by 33.6% for Case 2A, 100% for Case 2B, and 300% for Case 2C (Figure 6). The water content in lime sludge had a pronounced effect because lime sludge transportation was responsible for the majority of the overall EI, as described for Case 2. The water content of lime sludge had an indirect impact on transportation because of the additional trucks and energy consumption required to transport the wet lime sludge compared with the relatively dry form. In Case 3, there is a limitation on the water content of solid waste that can be disposed of in a landfill; thus, only Case 3A was considered. Similar to Case 2, the increase in water content resulted in a 33.6% higher overall EI (Figure 6).

4. CONCLUSIONS

In this work, we evaluated a sustainable and economically attractive approach to using lime sludge waste generated at water treatment utilities for FGD application in coal-fired power plants. This was achieved by assessing the lime sludge supply and limestone demand and by conducting a detailed LCA. By reusing lime sludge, water utilities can eliminate the cost of lime sludge disposal and substantially improve their environmental sustainability. Likewise, by replacing limestone with lime sludge provided by local water treatment plants, power utilities can (1) eliminate the cost of limestone transportation over long distances, (2) eliminate the energy-intensive grinding stage of limestone preparation, and (3) improve the overall environmental sustainability of power generation. More specific findings and conclusions of this work are summarized below:

- Water utilities across the United States are currently generating approximately 3.2 million tons of lime sludge annually. The estimated annual disposal cost of lime sludge across the United States is US\$90 million.
- The estimated amount of limestone consumption by FGD scrubbers in the United States (in year 2005) was about 6.3 million metric tons. Therefore, generated lime sludge from water utilities can potentially supply about half of the limestone demand for FGD application.
- The potential savings that would result from partial replacement of limestone with lime sludge was estimated at approximately US\$97 million per year.
- The LCA study under different scenarios showed that the EI associated with lime sludge utilization was 2 orders of magnitude lower than the EI results from lime sludge disposal in landfills. A longer transportation distance and a higher water content considerably increased the negative EI of landfill disposal.
- In Case 1 of the LCA, when limestone was mined, processed, and transported to power plants, limestone mining and processing were responsible for 97.6% of the overall EI, whereas limestone transportation to the power plant was accountable for only 2.4% of the overall EI. For Case 2 (lime sludge reused in power plants), the total EI was mainly affected by lime sludge transportation, of which 73% was associated with diesel consumption and 26.8% was associated with truck use. For Case 3 (lime sludge disposed of in landfills), the main components included transportation of the lime sludge to landfills and the landfill operation and treatment process. For this case, the landfill component accounted for 98.7% of the total EI.
- The water resource depletion analysis of the different cases indicated that freshwater consumption from reusing lime sludge in power plants was almost negligible, compared with lime sludge disposal or the conventional approach of transporting and utilizing mined limestone at power plants. The analysis of water resource depletion further highlighted the benefit of recycling lime sludge to power plants.

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Figure 1.

Side-by-side comparison of the EI of the LCA cases considered: a) overall EI scores, b) contribution of each EI category. AP, acidification potential; ETP, ecotoxicity potential; EP, eutrophication potential; HTC, human toxicity–cancer; OD, ozone depletion; SP, smog potential; GW, global warming; RFF, resources–fossil fuels.

Figure 2.

a) Overall EI scores of limestone mining, grinding, and transportation for use in power plants (Case 1); b) categorized contribution of each EI category to each process unit of the limestone mining case. RFF, resources–fossil fuels; GW, global warming; SP, smog potential; OD, ozone depletion; HTC, human toxicity–cancer; EP, eutrophication potential; ETP, ecotoxicity potential; AP, acidification potential.

Figure 3.

a) Overall EI scores of lime sludge transportation for use in power plants (Case 2); b) categorized contribution of each EI category to each process unit in the case of lime sludge reuse. RFF, resources–fossil fuels; GW, global warming; SP, smog potential; OD, ozone depletion; HTC, human toxicity–cancer; EP, eutrophication potential; ETP, ecotoxicity potential; AP, acidification potential.

Figure 4.

a) Overall EI scores of lime sludge transportation and landfilling (Case 3); b) categorized contribution of each EI category to each process unit in the lime sludge landfilling case. RFF, resources–fossil fuels; GW, global warming; SP, smog potential; OD, ozone depletion; HTC, human toxicity–cancer; EP, eutrophication potential; ETP, ecotoxicity potential; AP, acidification potential.

Figure 5.
Effect of transportation distance on the overall EI.

Figure 6.
Effect of water content in lime sludge on the overall EI.

Table 1.
Estimation of the Average Lime Sludge Generation Rate Based on Reported Data for
Water Utilities in Iowa and Kansas in the United States^a

state	Location	year of report	estimated population	lime sludge generated (dry basis, ton/yr)	rate (ton/person-yr)
Iowa	Des Moines	2011	400,000	30,700	0.077
Iowa	Cedar Rapids	2011	128,000	16,000	0.125
Iowa	West Des Moines	2011	52,000	3,600	0.069
Iowa	Ames	2011	50,000	5,170	0.103
Iowa	Newton	2011	21,000	3,500	0.167
Iowa	Boone	2011	17,000	3,300	0.194
Iowa	Indianola	2011	13,000	600	0.046
Iowa	Pella	2011	10,000	1,600	0.162
Kansas	Topeka	1997	161,000	14,162	0.088
Kansas	Kaw River	1997	82,000	3,468	0.042
Kansas	Clinton	1997	82,000	1,004	0.012
Kansas	Johnson County	1997	355,000	28,580	0.081
Total	—	—	1,371,000	111,684	0.081

^aLime sludge generation data was obtained from van Leeuwen et al.² and Shannon.¹²

Table 2.
Estimation of Overall Savings from Replacing 3.2 Million Tons of Limestone with Lime Sludge

cost item	unit cost (2018 \$)	total cost
Lime sludge disposal	28.26 (\$/ton)	+\$89,512,428
Limestone material	6.39 (\$/ton)	+\$20,255,019
Limestone grinding	1.60 (\$/ton)	+\$5,063,755
Lime sludge transportation (7 miles)	1.28 (\$/ton-mile, 80 wt % solid)	−\$35,446,284
Limestone transportation (30 miles)	0.19 (\$/ton)	+\$18,054,858
Total savings		+\$97,439,777