

**Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used
as a Cement Replacement in Concrete**

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I. EXECUTIVE SUMMARY

This paper describes the methodology and data sources used to develop greenhouse gas (GHG) emission factors for the use of fly ash as a cement replacement in concrete. Fly ash is a fine, powdery coal combustion product (CCP) that is produced by coal-fired electricity generators.

The emission factors presented below are the latest in a series of emission factors developed by the U.S. Environmental Protection Agency (EPA). EPA's research into the link between GHG emissions and waste management began in 1994 and continues today. In 1998, EPA published *Greenhouse Gas Emissions from Selected Materials in Municipal Solid Waste*, which presented the methodology for conducting a life-cycle assessment of the GHG impacts of waste management for commonly recycled materials in the municipal solid waste stream. The key results of the report included life-cycle GHG emission factors for 12 materials and 5 waste management options: source reduction, recycling, composting, combustion, and landfilling. These emission factors were the basis for a user-friendly spreadsheet tool called the Waste Reduction Model (WARM). WARM was designed to assist waste managers in quantifying the GHG benefits of their waste management practices.

As research on life-cycle impacts of waste management practices on these and other materials progressed, it became necessary to update both the report and WARM. Both were updated to include: (1) new data on energy and recycling loss rates, (2) an improved analysis of the GHG benefits of composting, (3) emission factors for several new material types and new categories of mixed materials, (4) new energy data for the calculation of utility offsets, (5) revised carbon coefficients and fuel mixes for national average electricity generation, and (6) updated information on landfill gas recovery practices. The revised report, published in 2002, is entitled *Solid Waste Management and Greenhouse Gases: A Life Cycle Assessment of Emissions and Sinks*,¹ and covers 16 individual materials found in the municipal solid waste stream (e.g., aluminum cans, newspaper, dimensional lumber) and 7 categories of mixed materials (e.g., mixed paper, mixed plastics).²

All emission factors included in the first and second versions of the report have focused on either specific materials (e.g., steel cans) or mixed materials (e.g., mixed recyclables). This paper describes the methods EPA used to apply the life-cycle approach presented in the 1998 and 2002 reports to fly ash. The complexity of these emission factors necessitated a separate report documenting the methodology, data sources, and assumptions we used.

EPA's interest in fly ash is derived from a growing interest in green building practices, including the use of recycled building products, which represents a significant opportunity to use the large quantities of this combustion by-product that are generated each year. As a pozzolan—a siliceous material that, when in finely-divided form, reacts with lime and water to form compounds with cementitious properties³—fly ash may be used to replace a portion of the portland cement in concrete. Portland cement, a GHG-intensive material to produce, is the most common binding ingredient in concrete. When used in concrete applications, fly ash typically composes 15-35 percent by weight of all cementitious material in the concrete mix. In high-performance applications, fly ash may account for up to 70 percent.⁴

The American Coal Ash Association (ACAA) estimates that in 2001, over 68 million tons⁵ of fly ash were generated in the US, representing an area with high potential for recycling efforts. Of that, over 20 million tons were recycled into a variety of uses, most commonly as a cement replacement.⁶ Because it is generated in large amounts and has the potential to displace portland cement, fly ash is a natural candidate for inclusion in EPA's life-

¹ EPA 2002a. *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, U.S. Environmental Protection Agency, June 2002. EPA530-R-02-006.

² Report is available online at the following website: www.epa.gov/epaoswer/non-hw/muncpl/ghg/greengas.pdf.

³ ACAA 2003a. "Glossary of Terms Concerning the Management and Use of Coal Combustion Products," American Coal Ash Association. www.acaa-usa.org/PDF/ACAA%20Glossary%20of%20Terms%20-%20April%202003.pdf.

⁴ NRC 2000. *Coal Fly Ash Fact Sheet*, National Recycling Coalition—Buy Recycled Business Alliance.

⁵ In this report, the term "ton" refers to short tons. Metric tons are specifically denoted as "metric tons."

⁶ ACAA 2003b. *Coal Combustion Product Survey*, American Coal Ash Association. www.acaa-usa.org/PDF/ACAA2001CCPSurvey.pdf.

cycle GHG analysis. The research on fly ash described in this report is intended to compliment EPA’s *Characterization of Building-Related Construction and Demolition Debris in the United States*, which characterizes the generation and management of C&D debris for specific materials.

We developed two emission factors for fly ash: recycling (as a substitute for Portland cement) and landfilling. The recycling emission factor represents the GHG impacts of manufacturing concrete with recycled fly ash rather than manufacturing concrete using cement. The landfilling emission factor reflects the GHG impacts of disposing fly ash in a landfill. Because fly ash does not generate methane in a landfill, the emission factor essentially reflects the emissions associated with transporting the fly ash to the landfill and operating the landfill equipment.

The primary sources of data used to derive the fly ash emission factors are the Portland Cement Association’s (PCA) *U.S. Industry Fact Sheet, 2003 Edition*, the 2000 PCA report *Environmental Life Cycle Inventory of Portland Cement Concrete* by Nisbet, et al., and the Intergovernmental Panel on Climate Change’s (IPCC) *Revised 1996 Guidelines for National Greenhouse Gas Inventories*. All the information and data that was utilized in developing the GHG emission factors for fly ash is included in this report via exhibits and appendices.

Emission factors for fly ash are presented in Exhibit 1 in units of metric tons of carbon equivalent per ton of product (MTCE/ton). These emission factors are comparable to those presented in Exhibit ES-4 of the 2002 EPA report. Although the recycling emission factors for fly ash is less than some of the other recycling emission factors, the potential for emission reductions is significant due to the high volume of fly ash produced each year. Estimates of potential emission reductions by material type are presented in Exhibit 2.

Exhibit 1. GHG Emission Factors for Fly Ash used as a Cement Replacement (MTCE/Ton)

Material	Net Source Reduction Emissions For Current Mix of Inputs	Net Recycling Emissions^a	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Fly Ash	NA	(0.24)	NA	NA	0.01

NA – Not Available.

a. These emission factors reflect the benefit of using fly ash in place of cement in the manufacture of concrete.

Source: EPA 2002a.

Exhibit 2. Potential GHG Emissions Associated with Using Fly Ash as a Cement Replacement

Material	Annual Discards (tons)	Recycling: Emission Reduction Potential (MTCE)
Fly Ash	68,100,000	(16,900,000)

Source: ACAA 2003a.

II. FLY ASH

This section presents the methodology used to estimate the life-cycle GHG impacts of waste management options for fly ash. As a coal combustion product (CCP), fly ash is unlike other materials for which EPA has developed emission factors in two respects. First, its production results from the industrial combustion of coal; therefore, there are no manufacturing emissions associated with the first generation product. Second, fly ash is unlike several of the other materials EPA has analyzed because it cannot be recycled in a closed loop. Instead, fly ash is recycled in an open loop (i.e., the second generation product is different). Once fly ash is produced, it must either be discarded or utilized in any one of several productive uses.⁷ However, this report considers only the GHG impacts of using fly ash as a replacement for cement in concrete. We did not investigate other recycling options for fly ash as we did not have sufficient data to do so, and/or the GHG impact of those options were minimal. The following sections describe how we used information on the processes associated with recycling and landfilling fly ash to develop life-cycle GHG emission factors.

Source Reduction

Because fly ash is produced as a by-product of coal combustion, source reduction (i.e., using less fly ash) is not really relevant to our analysis. That said, the quantity of fly ash generated could be reduced as a result of decreased coal consumption. However, this type of activity is beyond the scope of this analysis.

Recycling

According to the American Coal Ash Association's annual survey, in 2001, 22,004,955 tons of fly ash, or 32 percent of all fly ash generated, were recycled into new uses. Approximately 61 percent of recycled fly ash, or 13,393,626 tons, was used in concrete or cement production. Other major end-uses included structural fill, waste stabilization, and road base.⁸

Fly ash differs from the other materials for which EPA has developed GHG emission factors (e.g., aluminum cans, glass bottles) in that it is an industrial by-product suitable as a replacement for a manufactured product, i.e. cement. Therefore, the GHG benefit of concrete recycling is calculated as the emissions associated with the manufacture of the cement that is being replaced by fly ash.

For this analysis, we have assumed that neither fly ash nor virgin cement store carbon. Studies have indicated that over time, the cement portion of concrete—including both virgin cement and fly ash—is capable of absorbing carbon dioxide.⁹ The amount of carbon stored is affected by age, cement content, and the amount of exposed surface area. It is assumed that concrete made with fly ash will absorb carbon at a slower rate than concrete made only with cement. However, the difference between the carbon absorption rates of cement and fly ash are extremely difficult to quantify and are beyond the scope of this report.

The GHG benefits of recycling (i.e., using fly ash as a cement replacement) are calculated by comparing the difference in emissions associated with producing and transporting a ton of virgin cement versus processing and transporting a ton of recycled inputs (i.e., fly ash). Process and transportation energy GHG emissions result from the direct combustion of fossil fuels, the upstream emissions associated with electricity use, and the combustion of upstream energy required to obtain the fuels ultimately used in cement production and transport. Also, cement production results in the release of non-energy industrial process GHG emissions. These aspects of the fly ash recycling emission factor were broken up into three components: process energy, transportation energy, and non-energy emissions. Exhibit 3 presents these emissions, as well as the net GHG emission factor for recycling. The

⁷ It should be noted that fly ash is not the only CCP that may be reused. Other CCPs, including bottom ash, boiler slag, and flue gas desulfurization material, are recycled into a variety of useful products, including wallboard, roofing granules, snow and ice control, cement replacements, etc. (ACAA 2003b).

⁸ ACAA 2003b.

⁹ Gadja, John 2001. *Absorption of Atmospheric Carbon Dioxide by Portland Cement Concrete*. Portland Cement Association, Skokie, Illinois, PCA R & D Serial No. 2255a.

remainder of this section describes the steps that were taken to calculate the GHG impacts of recycling fly ash. Appendix A presents the raw data utilized in these calculations.

Exhibit 3. Fly Ash Recycling (Used as a Cement Replacement) Emission Factor (MTCE/Ton)

(a) Process Energy Emissions	(b) Transportation Energy Emissions	(c) Process Non-Energy Emissions	(c) Net Emissions (=a + b + c)
(0.12)	-	(0.12)	(0.24)

To calculate the recycling emission factor for fly ash, the following steps were necessary:

Step 1: Calculate the emissions for virgin production of one ton of cement for each emission factor component.

Step 2: Calculate the equivalent emissions for production of one ton of recycled inputs (i.e., fly ash).

Step 3: Calculate the difference in emissions between recycled and virgin production.

These steps are described in more detail as follows:

Step 1. Calculate the emissions for virgin production of one ton of cement.

To produce cement, calcium carbonate (CaCO₃) is heated in a kiln at a temperature of approximately 1,300° C (2,400° F). This heating breaks the calcium carbonate into lime (CaO) and CO₂ in a process known as calcination. The CO₂ is emitted to the atmosphere and silica-containing materials are added to the lime to produce the intermediate product, clinker. The clinker is then allowed to cool and is mixed with a small amount of gypsum to produce portland cement.¹⁰ The large amounts of energy required to drive this process are generated by the combustion of fossil fuels, resulting in GHG process energy emissions. Fossil fuels are also required to extract and refine the fuels used in the cement manufacturing process (i.e., “pre-combustion” energy). The CO₂ emitted in the calcination step represents GHG process non-energy emissions.

To estimate process emissions, we first obtained an estimate of the total energy required to produce one ton of cement, which is reported as 4.77 million Btu.¹¹ Next, we determined the fraction of total energy associated with the various fuel types. We then multiplied each fuel’s Btu estimate by each fuel’s carbon content to obtain carbon dioxide (CO₂) emissions for each fuel. The carbon coefficients we used are presented in Exhibit 4. We then conducted a similar analysis for fugitive methane (CH₄) emissions, using fuel-specific CH₄ coefficients. Finally, total process energy GHG emissions were calculated as the sum of GHG emissions, including both CO₂ and CH₄, from all the fuel types used in the production of one ton of cement.

This process was then repeated for transportation energy. Transportation energy GHG emissions result from the combustion of fossil fuels to transport the finished cement to the concrete mixing plant. For this analysis, it was assumed that cement must be transported 60 miles to the concrete mixing plant, the same distance that was assumed for fly ash.¹² Because these distances are dependent on the local availability of cement and fly ash, we conducted a sensitivity analysis to determine how the recycling emission factor is affected by different transportation distances. The results of this analysis are discussed below (see Step 2).

¹⁰ EPA 2002b. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2000*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, April 2002. EPA 430-R-02-003.

¹¹ This total represents the sum of pre-combustion and combustion process energy.

¹² Nisbet, M.A., M.G. VanGeem, J. Gajda, and M.L. Marceau 2000. *Environmental Life Cycle Inventory of Portland Cement Concrete*. Portland Cement Association, PCA R&D Serial No. 2137.

The calculations for virgin process and transportation emissions for cement are shown in Exhibits 4 and 5. As the exhibits show, the process and transportation energy for cement result in 0.12¹³ and 0.0021 MTCE per ton of cement produced, respectively.

The process non-energy emissions were calculated based on the methods outlined in the IPCC's *Revised 1996 Guidelines for National Greenhouse Gas Inventories* and *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. As mentioned above, when calcium carbonate (CaCO₃) is heated in a cement kiln, it breaks down into lime (CaO) and CO₂, which is emitted. To calculate the process non-energy emissions, the molecular weight of CO₂ is divided by the molecular weight of CaO to determine the ratio of CO₂ emitted to lime produced. This ratio is then multiplied by the lime content of cement to determine the ratio of CO₂ emitted to concrete produced. It was assumed that the average lime content of clinker is 65 percent and the average clinker content of portland cement is 95 percent.¹⁴ Finally the results were adjusted by a 2 percent cement kiln dust (CKD) correction factor, in accordance with the IPCC's *Good Practice Guidance*.¹⁵ This calculation, demonstrated in greater detail in Appendix A, Exhibit A-3, resulted in a process non-energy emission factor of 0.49 tons CO₂ per ton portland cement. As shown in Exhibit 6, this value was then converted into MTCE, resulting in 0.12 MTCE per ton of cement.

Exhibit 4. Process Energy Emissions Calculations for Virgin Cement

Fuel Type	(a) Percent of Total Btu^a	(b) Million Btu used for Cement Production (=4.7667 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)^b	(d) Fugitive CH₄ Emissions (MTCE/Million Btu^b)	(e) Process Energy CO₂ Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH₄ Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.11%	0.0050	0.0192	0.0001	0.0001	<0.0001	0.0001
Distillate Fuel	0.89%	0.0424	0.0199	0.0001	0.0008	<0.0001	0.0008
Residual Fuel	0.09%	0.0041	0.0214	0.0001	0.0001	<0.0001	0.0001
LPG	0.01%	0.0003	0.0169	0.0001	<0.0001	<0.0001	<0.0001
National Average Fuel Mix for Electricity	9.98%	0.4759	0.0158	0.0006	0.0075	0.0003	0.0078
Coal Used by Industry (Non- Coking Coal)	58.24%	2.7762	0.0251	0.0009	0.0697	0.0026	0.0722
Petroleum Coke	17.45%	0.8316	0.0279	-	0.0232	-	0.0232
Natural Gas	5.58%	0.2660	0.0138	0.0007	0.0037	0.0002	0.0039
Waste Fuel	7.66%	0.3651	0.0194	<0.0001	0.0071	<0.0001	0.0071
Total	100%	4.7667	n/a	n/a	0.1122	0.0030	0.1152

n/a – not applicable.

Note: Totals may not sum due to independent rounding.

a. Calculated using fuel-specific Btu data provided in Appendix A.

b. The electricity emission factor was calculated from a weighted average of fuels used in energy production in the US. Source: EIA 2001. *Annual Energy Review: 2000*. U.S. Department of Energy, EIA.

¹³ All emission estimates are presented with two significant figures in the text.

¹⁴ IPCC/UNEP/OECD/IEA 1997. *Revised 1996 Guidelines for National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, United Nations Environment Programme, Organization for Economic Cooperation and Development, International Energy Agency.

¹⁵ IPCC 2000. *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme.

Exhibit 5. Transportation Energy Emissions Calculations for Virgin Cement

	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Fuel Type	Percent of Total Btu^a	Million Btu used for Cement Transport (=0.1042 x a)	Fuel-specific Carbon Coefficient (MTCE/Million Btu)	Fugitive CH₄ Emissions (MTCE/Million Btu)	Transport Energy CO₂ Emissions (MTCE/Ton) (=b x c)	Transport Energy CH₄ Emissions (MTCE/Ton) (=b x d)	Total Transport Energy Emissions (MTCE/Ton) (=e + f)
Diesel Fuel	100	0.1042	0.0199	0.0001	0.0021	<0.0001	0.0021
Total	100	0.1042	n/a	n/a	0.0021	<0.0000	0.0021

n/a – not applicable.

a. Calculated using fuel-specific Btu data provided in Appendix A.

Exhibit 6. Process Non-Energy Emissions Calculations for Virgin Cement

	(a)	(b)	(c)	(d)
Fuel Type	Tons of Gas per Ton of Cement^a	Metric Tons of Gas per Ton of Cement (=a * 0.9072 Metric Tons per Ton)	MTCE/Metric Ton of Gas	MTCE/Ton of Cement (=b x c)
Diesel Fuel	0.4943	0.4484	0.2727	0.1223
Total	0.4943	0.4484	0.2727	0.1223

a. Calculated using data provided in Appendix A.

Step 2. Calculate the emissions for recycled production of one of ton fly ash. Because fly ash is the by-product of coal combusted for electricity generation, the process energy and non-energy emissions are not attributed to fly ash. In general, fly ash with a low carbon content (less than 3-4 percent) may be used in concrete without any additional processing. In the past, most U.S. fly ash has fallen into this category. However, at power plants that have instituted new NO_x emissions controls, the carbon content is often too high to be used without further processing (5-9 percent). We did not include energy associated with fly ash processing in this analysis because this process is currently taking place on a limited scale. Therefore, the process energy and non-energy emissions for fly ash are zero.

As with cement, transportation energy emissions are calculated by applying fuel-specific carbon and fugitive CH₄ emissions coefficients to energy data for fly ash transportation. For the calculation of this emission factor, we assumed that fly ash must be transported 60 miles¹⁶ to the concrete mixing plant. As mentioned above, these distances are dependent on the local availability of cement and fly ash and may vary. To determine how the recycling emission factor is affected by different transportation distances, we conducted a sensitivity analysis. The results of this analysis, as shown in detail in Appendix B, indicate that even in an extreme situation where fly ash transport distance is 500 miles (versus 60 miles for cement), using recycled fly ash would still represent a significant GHG savings. In such a situation, the amount of GHG emissions avoided would be only 7 percent less than under default transportation assumptions. As shown in Exhibit 7, the transportation energy is estimated at 0.0021 MTCE per ton of fly ash recycled.

¹⁶ This assumption is discussed in greater detail in Appendix B.

Exhibit 7. Transportation Energy Emissions Calculations for Fly Ash Used as a Cement Replacement

	(a)	(b)	(c)	(d)	(e)	(f)	(g)
Fuel Type	Percent of Total Btu ^a	Million Btu used for Fly Ash Transport (=0.1042 x a)	Fuel-specific Carbon Coefficient (MTCE/Million Btu) ^b	Fugitive CH ₄ Emissions (MTCE/Million Btu ^b)	Transport Energy CO ₂ Emissions (MTCE/Ton) (=b x c)	Transport Energy CH ₄ Emissions (MTCE/Ton) (=b x d)	Total Transport Energy Emissions (MTCE/Ton) (=e + f)
Diesel	100	0.1042	0.0199	0.0001	0.0021	<0.0001	0.0021
Total	100	0.1042	n/a	n/a	0.0021	<0.0000	0.0021

n/a – not applicable.

Note: Totals may not sum due to independent rounding.

a. Calculated using fuel-specific Btu data provided in Appendix A.

b. Source: The electricity emission factor was calculated from a weighted average of fuels used in energy production in the US.

Source: EIA 2001.

Step 3. Calculate the difference in emissions between virgin and recycled production. The GHG savings associated with recycling were then calculated by subtracting the virgin emissions estimate from the recycled emissions estimate using the results from Steps 1 and 2. It was assumed that one ton of fly ash is used to replace one ton of cement.¹⁷ It should be noted, however, that the ratio of cement replacement is dependent on many factors. Therefore, in addition to the default assumption that fly ash replaces cement on an equal mass basis, we have also calculated the fly ash recycling emission factor for several other plausible replacement ratios. The results of the default calculation are presented in Exhibit 8; the results of the sensitivity analysis on other replacement ratios are presented in Appendix B.

Exhibit 8. Fly Ash Recycling Emission Factor (MTCE/Ton)

	(a)	(b)	(c)	(d)
	Process Energy Emissions	Transportation Energy Emissions	Process Non-Energy Emissions	Net Emissions (a + b + c)
Recycled Manufacture	-	0.0021	-	0.0021
Virgin Manufacture	0.1152	0.0021	0.1223	0.2396
Total (Recycled - Virgin)	(0.1152)	-	(0.1223)	(0.2375)

Combustion

As combustion is not a disposal option for fly ash, we did not develop a GHG emission factor for this waste management option.

Landfilling

Currently, more than two-thirds of the fly ash generated in the US each year is disposed of in landfills. Although EPA determined in 1993 that fly ash is non-hazardous, fly ash is typically placed in specialized fly ash landfills built to prevent trace elements in the fly ash from leeching into drinking water supplies.¹⁸ Although the construction of these specialized landfills requires energy and thus results in GHG emissions, the emissions from landfill construction are beyond the scope of this analysis.

Typically, the emission factor for landfilling is comprised of four parts: landfill CH₄, CO₂ emissions from transportation and landfill equipment, landfill carbon storage, and avoided utility emissions. However, as with

¹⁷ Nisbet, et al. 2000.

¹⁸ EPRI 1998. "Coal Ash: Its origin, disposal, use, and potential health issues," *Environmental Focus*. EPRI, Palo Alto, CA.

other inorganic materials for which EPA has developed emission factors, there are no landfill CH₄ emissions, landfill carbon storage, or avoided utility emissions associated with landfilling fly ash. As a result, the emission factor for landfilling represents the CO₂ emissions associated with transporting the waste to the landfill and operating the landfill equipment. These emissions were estimated at 0.01 MTCE per ton of fly ash landfilled.¹⁹

¹⁹ Landfill data obtained from Franklin Associates, Ltd., *The Role of Recycling in Integrated Solid Waste Management for the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.) September 1994, p. I-5.

III. SUMMARY

The emission factors in this report are designed to help waste managers and others quantify the GHG benefits using fly ash as a cement replacement in concrete. These factors build on the life-cycle GHG emission factor research described in the report, *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*, available online at www.epa.gov/mswclimate/greengas.pdf. Readers are encouraged to consult this report for more background on how life-cycle analysis is used to develop emission factors.

In addition, these factors are now part of EPA's WARM model, which provides a user-friendly way of assessing the GHG impacts of alternative waste management practices. Users simply need to enter tonnage data for the baseline and alternative waste management options, and WARM will provide the emissions results. WARM also allows users to specify some of the assumptions driving the emission factors, such as the miles of travel required to transport discarded fly ash to the landfill. WARM is available online at www.epa.gov/globalwarming/actions/waste/w-online.htm.

To apply these emission factors one needs to compare the GHG results using a baseline and alternative waste management scenario. For each scenario, the GHG impact is calculated by multiplying the tonnage of fly ash by the appropriate emission factor. For example, suppose a company is considering selling its waste fly ash to concrete mixers instead of its current (baseline) practice of landfilling the fly ash. If the company generated 100 tons of fly ash, the GHG benefits of recycling versus landfilling could be calculated as follows:

$$[100 \text{ tons} \times -0.24 \text{ MTCE/Ton}_{\text{recycling}}] - [100 \text{ tons} \times 0.01 \text{ MTCE/Ton}_{\text{landfilling}}] = -25 \text{ MTCE}$$

As the above equation shows, this one company could save 25 MTCE by recycling 100 tons of fly ash that would otherwise have gone to the landfill. This savings is equivalent to reducing gasoline use by approximately 10,440 gallons.²⁰

When applying the emission factors at the national level, we can see the tremendous potential for GHG emission reductions. Exhibit 9 shows the current estimated concrete life-cycle GHG emissions assuming the current waste disposal scenario, as well as the potential reductions if all of the waste was recycled. As the exhibit shows, if all fly ash was recycled as a cement substitute, 16 million MTCE would be avoided, equivalent to removing nearly 13 million cars from the road for a year.²¹

Finally, we close by noting that although this analysis is based upon the best available life-cycle data, uncertainties do exist in the final emission factors. It is important that we continue to assess the assumptions and data used to develop the emission factors. As the combustion processes, manufacturing processes, and recycling processes change in the future, these changes will be incorporated into revised emission factors. In addition, it should be noted that these results are designed to represent national average data. The actual GHG impacts of recycling or landfilling fly ash will vary depending on individual circumstances.

²⁰ EPA 2003. Greenhouse Gas Equivalencies Calculator. Draft version.

²¹ Please note that this estimate is for demonstration purposes only. Not all fly ash produced in the US may be readily used as a cement substitute. Furthermore, there are other valuable uses for fly ash for which the GHG emission factor was not calculated.

Exhibit 9. Current Baseline GHG Emissions and Reduction Potential for Fly Ash

	Baseline Disposal				Assume 100% Recycling		
	(a) EF (MTCE/ Ton)	(b) End of Life Fate (%)	(c) End of Life Fate (Tons)	(d) Net GHG Emissions (MTCE) (=a x c)	(e) End of Life Fate (%)	(f) End of Life Fate (Tons)	(g) Net GHG Emissions (MTCE) (=a x f)
Disposal Option							
Recycling as cement replacement	(0.24)	20%	13,393,626	(3,180,706)	100%	68,123,551	(16,177,919)
Landfilling ^a	0.01	68%	46,118,596	483,289	0%	0	0
Other Recycling ^b	NA	13%	8,611,329	NA	0%	0	NA
Total				(2,697,417)			(16,177,919)

NA – Not available.

a. All fly ash not reported as reused by ACAA 2003a was assumed to be landfilled.

b. “Other recycling” includes use as structural fill, waste stabilization, road base, mining applications, and other applications. Emission factors for these other recycling options were not calculated in this report.

Appendix A. Data Used to Derive Fly Ash Emission Factor

Exhibit A-1: Process Energy Data for the Production of One Ton of Portland Cement

Fuel	(a) Combustion Process Energy (million Btu/ton cement)^a	(b) Precombustion Process Energy (million Btu/ton cement)^b	(c) Total Process Energy per (million Btu/ton cement) (=a + b)
Electricity	0.4759	-	0.4759
Natural Gas	0.2373	0.0287	0.2660
LPG	0.0003	<0.0001	0.0003
Coke	0.6901	0.1415	0.8316
Coal	2.7071	0.0690	2.7762
Distillate Oil	0.0357	0.0066	0.0424
Residual Oil	0.0035	0.0006	0.0041
Gasoline	0.0042	0.0009	0.0050
Waste Fuel	0.3651	-	0.3651
Total	4.5193	0.2473	4.7667

a. Source: PCA 2003. "U.S. Industry Fact Sheet," 2003 Edition, Portland Cement Association.

b. "Precombustion" energy is calculated by multiplying the combustion energy by a fuel-specific scaling factor from EPA 1998 to account for upstream combustion energy required to obtain the fuels. Source: EPA 1998. *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, U.S. Environmental Protection Agency, Office of Solid Waste.

Exhibit A-2: Transportation Energy Consumption

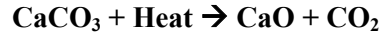
Material	(a) Transportation Combustion Energy, Diesel Fuel¹ (million Btu/ton-mile)	(b) Transportation Distance^a (miles)	(c) Transportation Combustion Energy (million Btu/ton) (=a x b)	(d) Transportation Precombustion Energy^b (million Btu/ton)	(e) Total Transportation Energy (million Btu/ton) (=c + d)
Cement	0.0015	60	0.0879	0.0163	0.1042
Fly Ash	0.0015	60	0.0879	0.0163	0.1042

a. Source: Nisbet, et al. 2000.

b. "Precombustion" energy is calculated by multiplying the combustion energy by a fuel-specific scaling factor from EPA 1998 to account for upstream combustion energy required to obtain the fuels. Source: EPA 1998.

Exhibit A-3: Calculation of Cement Process Non-Energy Emissions

As discussed above, during the production of cement, calcium carbonate (CaCO₃) is heated in a kiln at a temperature of approximately 1,300° C (2,400° F). This heating breaks the calcium carbonate into lime (CaO) and CO₂ in a process known as calcination. This process is described in the following equation:



The lime (CaO) is combined with silica-containing materials to produce clinker, an intermediate cement product, while the CO₂ is emitted to the atmosphere. This CO₂ represents the industrial non-energy process emissions associated with cement production. The calculation of these emissions requires three steps:

- Step 1: Stoichiometrically calculate the ratio of CO₂ emitted to lime produced.
- Step 2: Determine the lime content of cement based on the average lime content of clinker and the average clinker content of cement.
- Step 3: Multiply the lime content by the ratio of CO₂ emitted to lime produced and correct for cement kiln dust (CKD), in accordance with the IPCC *Good Practice Guidance*.

The calculation of non-energy emissions is demonstrated in Exhibit A-3.

Step 1: Ratio of CO₂ Emitted to Lime in Clinker

(a)	(b)	(c)
Molecular Weight of CO ₂ (g/mole)	Molecular Weight of CaO	Ratio of CO ₂ Emitted to CaO in Clinker (=a / b)
44.01	56.08	0.78

Step 2: Determine Lime Content of Cement

(a)	(b)	(c)
Average Lime Content of Clinker ^a	Clinker fraction in portland cement ^a	Lime Content of Cement (=a x b)
0.65	95%	0.62

a. Source: IPCC/UNEP/OECD/IEA 1997.

Step 3: Calculate Total Process Non-Energy CO₂ Emissions

(a)	(b)	(c)	(d)
Lime Content of Cement	Ratio of CO ₂ Emitted to CaO in Clinker	CKD Correction Factor ^a	Ton CO ₂ Emitted/Ton Portland Cement = a x b x (1 + c)
0.62	0.78	2%	0.49

a. Source: IPCC 2000.

Appendix B. Transportation Distance and Cement Replacement Ratio Sensitivity Analyses

For the calculation of the emission factor for fly ash recycling (as a cement substitute), it was assumed that both cement and fly ash are transported an average of 60 miles to the concrete mixing plant. This assumption was provided by Nisbet, et al., 2000. However, these distances are dependent on the local availability of materials and therefore are not representative of all markets. In order to determine the effect that different transport distances have on the overall recycling emission factor, we recalculated the emission factor using a variety of transport distance scenarios. The results are presented in Exhibit B-1.

Exhibit B-1: Effect of Distance on the Fly Ash Recycling Emission Factor

	MTCE/ton	Cement Transportation Distance (miles)	Fly Ash Transportation Distance (miles)	% Difference
Default Emission Factor	-0.24	60	60	-
Emission Factors for Alternative Transportation Scenarios	-0.25	500	60	-6
	-0.24	200	60	-2
	-0.24	150	60	-1
	-0.24	100	60	-1
	-0.24	60	30	0
	-0.24	30	60	0
	-0.24	60	100	1
	-0.23	60	150	1
	-0.23	60	200	2
-0.22	60	500	7	

For the calculation of the emission factor for fly ash recycling, it was assumed that fly ash was used to replace cement on a one-to-one basis by weight. This assumption was provided by Nisbet, et al., 2000. In practice, replacement ratios vary. We have calculated the recycling emission factor using several different replacement ratios. The results are presented in Exhibit B-2.

Exhibit B-2: Effect of Replacement Ratio on Fly Ash Recycling Emission Factor

	Fly Ash:Cement Ratio	MTCE/ton	% Difference
Default Emission Factor	1:1	-0.24	-
Emission Factors for Alternative Ratio Scenarios	1.2:1	-0.20	17
	1.1:1	-0.22	9
	1:1.1	-0.26	-10
	1:1.2	-0.29	-20

Appendix C. Conversion Factors Used in Calculations

Exhibit C-1. Conversions

Unit Conversions		
1 ton	=	0.9072 metric tons
1 metric ton	=	2,204.6226 pounds
1 ton	=	907.1847 kilograms
1 MTCO ₂	=	44/12 MTCE
Global Warming Potentials (GWPs)		
1 metric ton CH ₄	=	1/21 MTCO ₂

Exhibit C-2. Carbon Coefficients

Fuel	Metric Tons Carbon Equivalent (MTCE) from Combustion Per Million Btu	MTCE from Fugitive CH₄ Emissions Per Million Btu
Gasoline	0.01925	0.00010
LPG	0.01691	0.00010
Distillate Fuel	0.01987	0.00010
Residual Fuel	0.02141	0.00010
Diesel	0.01987	0.00010
National Average Fuel Mix for Electricity	0.01579	0.00059
Coal Used by Industry (Non-Coking Coal)	0.02510	0.00092
Petroleum Coke	0.02785	-
Natural Gas	0.01378	0.00070
Wastes	0.01942	0.00001