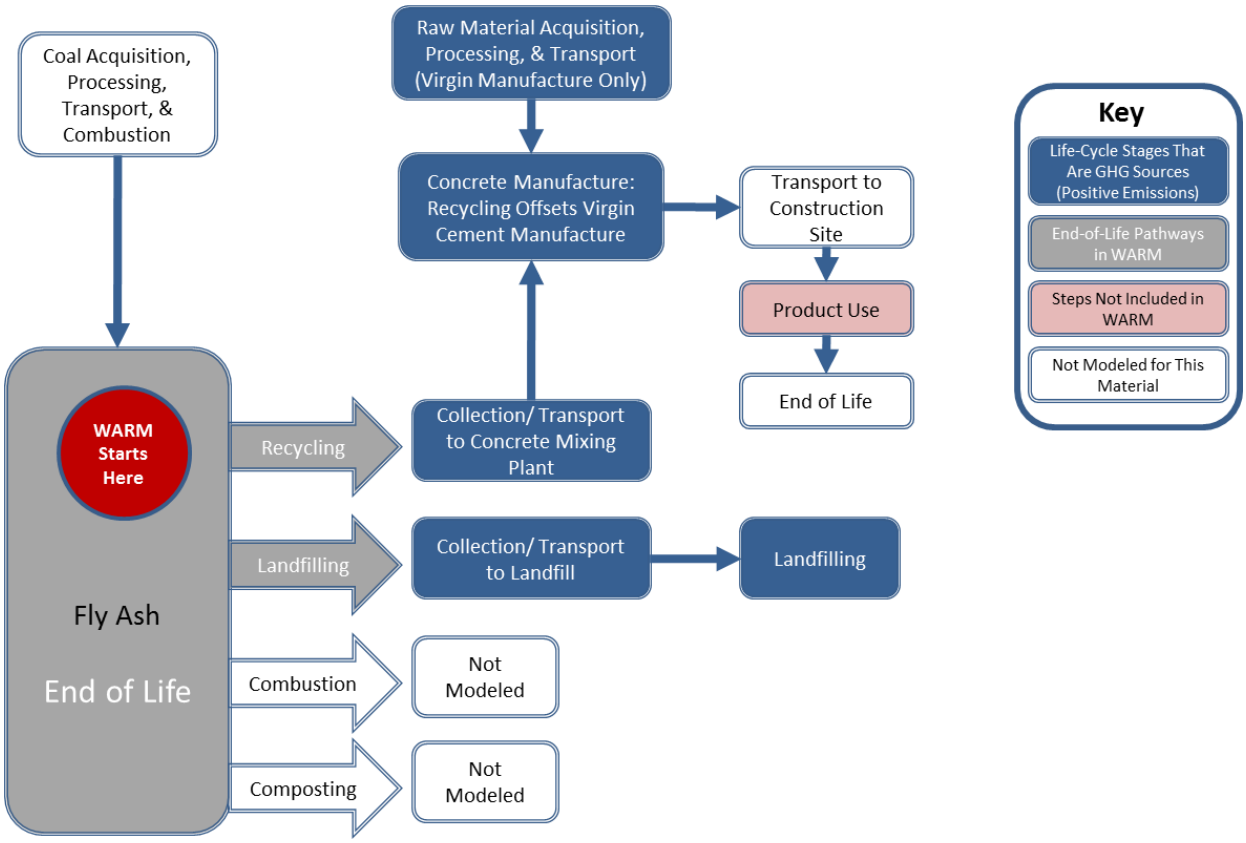
# FLY ASH

## 1. INTRODUCTION TO WARM AND FLY ASH

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for fly ash beginning at the waste generation reference point. Fly ash is generated as a byproduct of coal combustion and is used as a replacement for cement in concrete, among other uses. The WARM GHG emission factors are used to compare the net emissions associated with management of fly ash in the following two materials management alternatives: recycling and landfilling. Exhibit 1 shows the general outline of materials management pathways for fly ash in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Recycling and Landfilling, see the chapters devoted to these processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

**Exhibit 1: Life Cycle of Fly Ash in WARM**




Coal-based electricity generation results in the production of significant quantities of coal combustion products (CCP) (see Exhibit 2). Fly ash is a CCP possessing unique characteristics that allow it to be used ton-for-ton as a substitute for portland cement in making concrete. Through the reuse of fly ash, the GHG emissions associated with the production of portland cement are avoided.

**Exhibit 2: Fly Ash Generation and Reuse in the United States, 2012**

| Material/ Product | Fly Ash Production (Short Tons) | Fly Ash Reuse (Short Tons) | Fly Ash Reuse in Cement (Short Tons) |
|---|---|---|---|
| Fly Ash | 52,100,000 | 23,205,204 | 2,281,211 |

Source: ACAA (2013).

## 2. LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The streamlined life-cycle GHG analysis in WARM focuses on the waste generation point, or the moment a material is discarded, as the reference point and only considers upstream GHG emissions when the production of new materials is affected by materials management decisions.[1]

As Exhibit 3 illustrates, most of the GHG sources relevant to fly ash in this analysis are contained in the raw materials acquisition and manufacturing and materials management sections of the life cycle. WARM does not consider source reduction, composting or combustion as life-cycle pathways for fly ash. The recycling emission factor represents the GHG impacts of manufacturing concrete with recycled fly ash in place of portland 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 reflects the emissions associated with transporting the fly ash to the landfill and operating the landfill equipment. As shown in Exhibit 3, all of the GHG sources relevant to fly ash in this analysis are contained in the materials management section of the life cycle assessment.

**Exhibit 3: Fly Ash GHG Sources and Sinks from Relevant Materials Management Pathways**

| Materials Management Strategies for Fly Ash | GHG Sources and Sinks Relevant to Fly Ash | | |
|---|---|---|---|
| | Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing | Changes in Forest or Soil Carbon Storage | End of Life |
| Source Reduction | Not modeled in WARM due to byproduct nature of fly ash | | |
| Recycling | **Offsets**<br>• Transport of cement raw materials and products<br>• Virgin cement manufacture process energy<br>• Virgin cement manufacture process non-energy | NA | **Emissions**<br>• Collection and transportation to concrete manufacturing facility |
| Composting | Not applicable because fly ash cannot be composted | | |
| Combustion | Not applicable because fly ash cannot be combusted | | |
| Landfilling | NA | NA | **Emissions**<br>• Transport to landfill<br>• Landfilling machinery |

NA = Not available.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 3 and calculates net GHG emissions per short ton of fly ash inputs (see Exhibit 4). For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

[1] The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all emissions from materials management.

**Exhibit 4: Net Emissions for Fly Ash under Each Materials Management Option ($MTCO_2E$/Short Ton)**

| Material/ Product | Net Source Reduction (Reuse) Emissions for Current Mix of Inputs | Net Recycling Emissions | Net Composting Emissions | Net Combustion Emissions | Net Landfilling Emissions |
|---|---|---|---|---|---|
| Fly Ash | NA | -0.87 | NA | NA | 0.04 |

NA = Not applicable.

## 3. RAW MATERIALS ACQUISITION AND MANUFACTURING

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[2] Because fly ash is a byproduct (waste) of the process of combusting coal for electricity, WARM considers that there are no manufacturing or combustion emissions associated with fly ash itself. In this respect, fly ash is unlike most other materials in WARM for which EPA has developed emission factors. Because the intent is not to burn coal to produce fly ash, but rather to burn coal to produce power, the fly ash would be produced in any case. Therefore, from WARM's perspective, the emissions associated with burning coal would be allocated to the power production process, and not to the production of coal ash. Hence, no RMAM emissions are considered in the life-cycle analysis of fly ash in WARM.

## 4. MATERIALS MANAGEMENT METHODOLOGIES

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 3 and calculates net GHG emissions per short ton of fly ash. Recycling fly ash leads to reductions in GHG emissions since it avoids energy-intensive manufacture of portland cement. Landfilling has a slightly positive emission factor due to the emissions from transportation of the ash and landfill operation equipment.

### 4.1 SOURCE REDUCTION

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the post-consumer waste are avoided. As a byproduct of coal combustion, source reduction, i.e., decreasing the production of fly ash, is not a materials management option that is within the scope of WARM.

For more information, please see the chapter on Source Reduction.

### 4.2 RECYCLING

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Given its byproduct nature, fly ash cannot be recycled in a closed loop and is thus different from most of the other materials considered in the WARM emission factor analysis. Instead, it is recycled in an open loop, replacing cement in the production of concrete.[3] Therefore, the GHG benefits of using fly ash are equivalent to the emissions associated with the manufacture of the quantity of cement that is replaced by fly ash, minus emissions associated with transporting the ash to a concrete manufacturing facility.

[2] Process non-energy GHG emissions are emissions that occur during the manufacture of certain materials and are not associated with energy consumption.

[3] While fly ash can be recycled into a number of productive uses, this study only considers one use, given the lack of useful data for other processes and/or the small GHG impact of those options relative to the use as a cement replacement in concrete.

Portland cement, a material with GHG-intensive production, is the most common binding ingredient in concrete. As a pozzolan—a siliceous material that in a finely divided form reacts with lime and water to form compounds with cementitious properties (ACAA, 2003)—fly ash may be used to replace a portion of the portland cement 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 (NRC, 2000).

The calculation of the fly ash emission factor involves estimating the emissions associated with production of one ton of virgin cement and one ton of recycled inputs (i.e., fly ash) individually, and then determining the difference in emissions between recycled and virgin production. The fly ash recycling emission factor is made up of three components: process energy, transportation energy and non-energy emissions. Exhibit 5 presents a summary of these components. The following sections contain descriptions of how each component is calculated.

**Exhibit 5: Components of the Fly Ash Recycling Emission Factor ($MTCO_2E$/Short Ton)**

| (a)<br>Material/Product | (b)<br>Process Energy | (c)<br>Transportation Energy | (d)<br>Process Non-Energy | (e)<br>Net Emissions (e = b + c + d) |
|---|---|---|---|---|
| Cement (Virgin Production) | 0.42 | 0.01 | 0.45 | 0.88 |
| Fly Ash | – | 0.01 | – | 0.01 |

– = Zero emissions.

### 4.2.1 Developing the Emission Factor for the Recycling of Fly Ash

Process energy GHG emissions from production of portland cement result from the direct combustion of fossil fuels, the upstream emissions associated with electricity use, and the combustion of upstream energy required for obtaining the fuels ultimately used in material production and transport. As mentioned above, WARM considers the emissions associated with virgin production of cement to arrive at the relevant emission factors for recycling of fly ash.

*Cement Production.* To produce cement, calcium carbonate ($CaCO_3$) is heated in a kiln at a temperature of approximately 1,300° C (2,400° F), thus breaking the calcium carbonate into lime (CaO) and carbon dioxide ($CO_2$) in a process known as calcination. This $CO_2$ 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 (EPA, 2014). The large amounts of energy required to drive this process are generated by the combustion of fossil fuels, which result in GHG process energy emissions. Additionally, fossil fuels are also required to extract and refine the fuels used in the cement manufacturing process (i.e., "pre-combustion" energy).

To estimate process emissions, we first obtain an estimate of the total energy required to produce one ton of cement, which is reported as 4.77 million Btu (PCA, 2003).[4] Next, WARM determines the fraction of this total energy that is associated with the various fuel types. Each fuel's share of energy is then multiplied by that fuel's carbon content to obtain $CO_2$ emissions for each fuel. EPA then conducts a similar analysis for fugitive methane ($CH_4$) emissions, using fuel-specific $CH_4$ coefficients. Finally, total process energy GHG emissions are calculated as the sum of GHG emissions, including both $CO_2$ and $CH_4$, from all of the fuel types used in the production of one ton of cement.

*Fly Ash Production.* Because fly ash is the byproduct of coal combusted for electricity generation, no process energy and non-energy emissions are attributed to fly ash. In general, fly ash with a low (less

[4] This total represents the sum of pre-combustion and combustion process energy.

than 3–4 percent) carbon content 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 or that inject activated carbon to control mercury emissions, the carbon content (5–9 percent) may be too high for the fly ash to be used without further processing. However, this analysis does not include energy associated with fly ash processing because this process currently takes place on a limited scale. Therefore, the process energy and non-energy emissions for manufacturing fly ash are assumed to be zero.

Hence, the benefits from using fly ash as a recycled product instead of virgin cement in concrete result in negative emissions. Exhibit 6 provides the process energy emissions from production of cement and fly ash as calculated in WARM.

**Exhibit 6: Process Energy GHG Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash**

| Material/Product | Process Energy per Short Ton Made from Virgin Inputs (Million Btu) | Process Energy GHG Emissions ($MTCO_2E$/Short Ton) |
|---|---|---|
| Cement | 4.77 | 0.42 |
| Fly ash | – | – |

– = Zero emissions.

GHG emissions associated with transportation energy result from the direct combustion of fossil fuels for transportation: the upstream energy required for obtaining the fuels ultimately used in transportation, transport of raw materials and transport of the final product. Transportation energy GHG emissions result from the combustion of fossil fuels to transport the finished cement and the fly ash byproduct to the concrete mixing plant.

Because the transportation energy emissions for virgin cement and recycled fly ash are calculated to be identical (see Exhibit 7), the transportation energy emissions associated with fly ash recycling are estimated to be zero.

**Exhibit 7: Transportation Energy Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash**

| Material/Product | Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu) | Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton) |
|---|---|---|
| Cement | 0.10 | 0.01 |
| Fly Ash | 0.10 | 0.01 |

Cement production results in non-energy industrial process GHG emissions in the form of $CO_2$ emitted during the calcination step. To calculate the process non-energy emissions, the molecular weight of $CO_2$ is divided by the molecular weight of CaO to determine the ratio of $CO_2$ emitted to lime produced. This ratio is then multiplied by the lime content of cement to determine the ratio of $CO_2$ emitted to concrete produced. It is assumed that the average lime content of clinker is 65 percent and the average clinker content of portland cement is 95 percent (IPCC/UNEP/OECD/IEA, 1997). The results are adjusted by a 2-percent cement kiln dust (CKD) correction factor, in accordance with the IPCC's Good Practice Guidance (IPCC, 2000). This calculation resulted in a process non-energy emission factor of 0.45 $MTCO_2E$ per ton portland cement.

Exhibit 8 provides the calculations for each source of emissions from non-energy processes. Exhibit 9 shows the calculation of the emission factor for use of recycled fly ash in place of virgin cement.

**Exhibit 8: Process Non-Energy Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash**

| Material/Product | $CO_2$ Emissions (MT/Short Ton) | $CH_4$ Emissions (MT/Short Ton) | $CF_4$ Emissions (MT/Short Ton) | $C_2F_6$ Emissions (MT/Short Ton) | $N_2O$ Emissions (MT/Short Ton) | Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton) |
|---|---|---|---|---|---|---|
| Cement | 0.45 | – | – | – | – | 0.45 |
| Fly ash | – | – | – | – | – | – |

– = Zero emissions.

**Exhibit 9: Difference in Emissions between Virgin Cement Production and Recycled Fly Ash Use ($MTCO_2E$/Short Ton)**

| Material/ Product | Virgin Cement Production ($MTCO_2E$/Short Ton) | | | Recycled Fly Ash Use ($MTCO_2E$/Short Ton) | | | Difference Between Virgin Cement Production and Recycled Fly Ash Use ($MTCO_2E$/Short Ton) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Process Energy | Transpor-tation Energy | Process Non-Energy | Process Energy | Transpor-tation Energy | Process Non-Energy | Process Energy | Transpor-tation Energy | Process Non-Energy |
| Fly Ash/ Cement | 0.42 | 0.01 | 0.45 | – | 0.01 | – | -0.42 | – | -0.45 |

– = Zero emissions.

For more information about all of these calculations, please refer to the *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete (*EPA, 2003).

## 4.3 COMPOSTING

Fly ash is not subject to aerobic bacterial degradation, and therefore, cannot be composted. Therefore, EPA does not include an emission factor in WARM for the composting of fly ash.

## 4.4 COMBUSTION

Fly ash cannot be combusted; therefore, WARM does not include and an emission factor for combustion.

## 4.5 LANDFILLING

Landfilling is the most common waste management option for fly ash and a majority of the fly ash generated in the United States each year is disposed of in landfills (see Exhibit 2). Fly ash is typically placed in specialized fly ash landfills situated and built to prevent trace elements in the fly ash from leaching into drinking water supplies (EPRI, 1998). Although the construction of these specialized landfills requires energy and thus results in GHG emissions, the emissions from landfill construction are considered to be beyond the scope of this analysis; thus, the WARM landfill emission factor excludes these emissions.

Fly ash does not biodegrade measurably in anaerobic conditions, and therefore does not generate any $CH_4$ emissions in the landfill environment, store carbon in the landfill, or generate any avoided utility emissions because of landfill storage. However, transportation of fly ash to a landfill and operation of landfill equipment result in anthropogenic $CO_2$ emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes. As a result, the landfilling emission factor is equal to the GHG emissions generated by transportation to the landfill. WARM assumes the standard landfill transportation factor. This information is summarized in Exhibit 10.

**Exhibit 10: Landfilling Emission Factor for Fly Ash ($MTCO_2E$/Short Ton)**

| Material/ Product | Raw Material Acquisition and Manufacturing (Current Mix of Inputs) | Transportation to Landfill | Landfill $CH_4$ | Avoided $CO_2$ Emissions from Energy Recovery | Landfill Carbon Storage | Net Emissions (Post-Consumer) |
|---|---|---|---|---|---|---|
| Fly Ash | – | 0.04 | – | – | – | 0.04 |

– = Zero emissions.

For more information, please see the chapter on Landfilling.

## 5. LIMITATIONS

Although this analysis is based upon the best available life-cycle data, it suffers from certain limitations:

- It does not consider emissions from construction of special leak-proof landfills for fly ash.
- It does not include energy associated with the processing of fly ash with high carbon content (5–9 percent) because this process currently takes place on a limited scale.
- 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.

## 6. REFERENCES

ACAA. (2013). *2012 Coal Combustion Product (CCP) Production & Use Survey Report*. Aurora, CO: American Coal Ash Association. Retrieved from: http://www.acaa-usa.org/Portals/9/Files/PDFs/revisedFINAL2012CCPSurveyReport.pdf.

ACAA. (2009b). *Coal Combustion Products: Not a Hazardous Waste*. *Coal Ash Facts.* Aurora, CO: American Coal Ash Association Educational Foundation, March 10, 2009. Retrieved July 16, 2010 from: http://www.coalashfacts.org/documents/CCP%20Fact%20Sheet%202%20-%20Not%20a%20Hazardous%20Waste_FINAL.pdf.

ACAA. (2003). *Fly Ash Facts for Highway Engineers*. Aurora, CO, and Washington, DC: American Coal Ash Association, supported by the Federal Highway Administration, December 1995. (Report No. FHWA-SA-94-081.) Retrieved from: http://www.fhwa.dot.gov/pavement/recycling/fafacts.pdf.

EPA (2014). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2012.* (EPA publication no. EPA 430-R-11-005.) Washington, DC: U.S. Environmental Protection Agency, Office of Atmospheric Programs, April. Retrieved from: http://epa.gov/climatechange/emissions/usinventoryreport.html

EPA. (2003). *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete*. Washington, DC: U.S. Environmental Protection Agency, November 7, 2003. (EPA publication no. EPA530-R-03-016.) Retrieved from: http://www.epa.gov/climatechange/wycd/waste/downloads/FlyAsh_11_07.pdf.

EPRI. (1998). Coal Ash: Its origin, disposal, use, and potential health issues. *Environmental Focus*. Palo Alto, CA: Electric Power Research Institute.

FAL. (1994). *The Role of Recycling in Integrated Solid Waste Management for the Year 2000.* Franklin Associates, Ltd. (Stamford, CT: Keep America Beautiful, Inc.), September, pp. I–16.

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

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. Available at: http://www.ipcc-nggip.iges.or.jp/public/gl/invs1.html.

Nisbet, M. A., VanGeem, M. G., Gajda, J., & Marceau, M. L. (2000). E*nvironmental Life Cycle Inventory of Portland Cement Concrete*. PCA R&D Serial No. 2137. Skokie, IL: Portland Cement Association.

NRC. (2000). *Coal Fly Ash Fact Sheet.* Washington, DC: National Recycling Coalition—Buy Recycled Business Alliance.

PCA. (2003). *U.S. Industry Fact Sheet, 2003 Edition.* Skokie, IL: Portland Cement Association.