U.S. Environmental Protection Agency
Office of Resource Conservation and Recovery

Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)

Construction Materials Chapters

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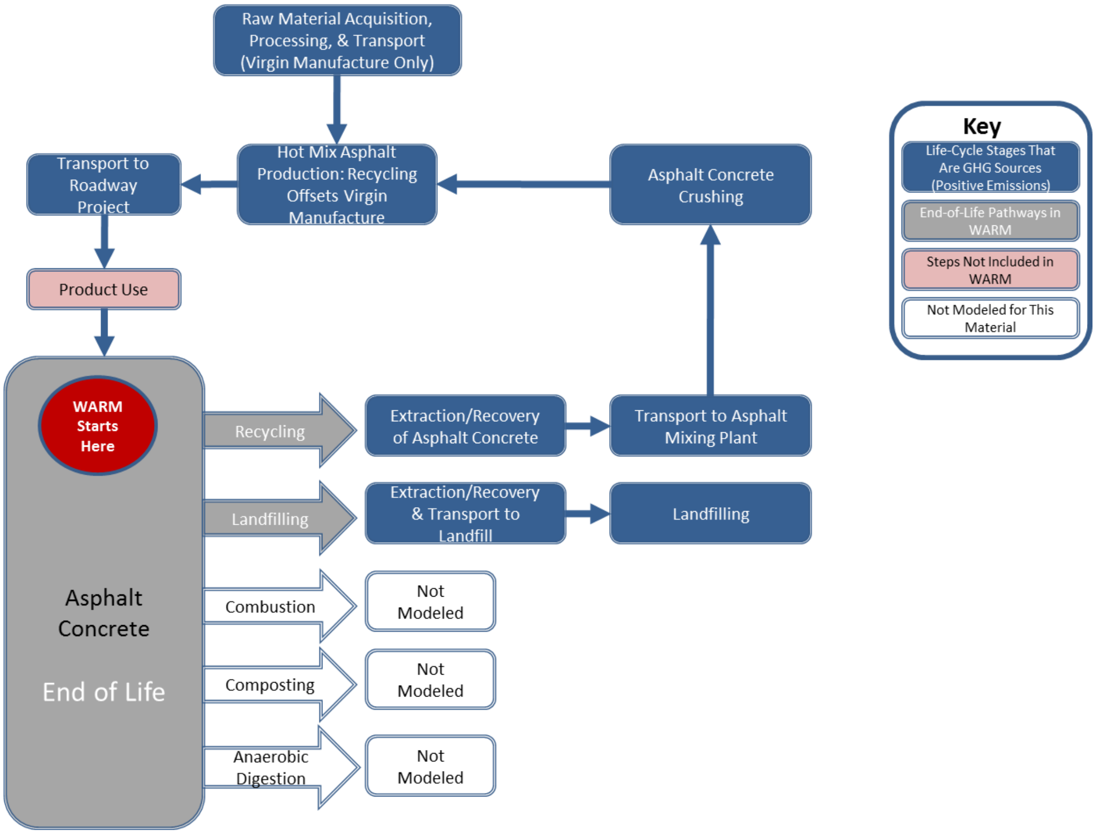
1 ASPHALT CONCRETE

1.1 INTRODUCTION TO WARM AND ASPHALT CONCRETE

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for asphalt concrete beginning at the waste generation reference point.[1] EPA uses the WARM GHG emission factors to compare the net emissions associated with asphalt concrete in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 1-1 shows the general outline of materials management pathways for asphalt concrete in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, and Landfilling, see the chapters devoted to those processes.

Exhibit 1-1: Life Cycle of Asphalt Concrete in WARM



Asphalt concrete, commonly known as asphalt, is used in the construction of highways and roads. It is produced in a variety of mixtures, including hot mix, warm mix, cold mix, cut-back, mastic, and natural, each with distinct material and energy inputs. A highway or road is built in several layers, including pavement, base, and sub-base. The pavement layer, the surface layer, is made of either asphalt concrete or portland cement concrete.

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[1] EPA would like to thank Dr. Marwa Hassan of Louisiana State University for her efforts to improve these estimates.

Several different types of asphalt include road asphalt, hot mix asphalt, and concrete pavement. Hot mix asphalt (HMA) is the industry standard for production, with more than 94 percent of U.S. roads paved with HMA; therefore, EPA calculated the WARM GHG emission factors based on HMA life-cycle data.

1.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and only consider upstream GHG emissions when the production of new materials is affected by material management decisions. Recycling and source reduction are the two materials management options that affect the upstream production of materials, and consequently, they are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not consider composting, combustion, or anaerobic digestion for asphalt concrete. As Exhibit 1-2 illustrates, all GHG sources and sinks relevant to asphalt concrete in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 1-2: Asphalt Concrete GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Asphalt Concrete	GHG Sources and Sinks Relevant to Asphalt Concrete		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Avoided process energy emissions, including aggregate production, asphalt binder production, combination of asphalt and binder • Avoided transportation for production of virgin crude oil • Avoided transportation of asphalt concrete materials to roadway project	NA	NA
Recycling	**Offsets** • Avoided virgin material extraction • Avoided process energy for aggregate and asphalt binder production • Avoided virgin material transport (especially crude oil)	NA	**Emissions** • Extraction/recovery • Transport to mixing plant • Crushing and remixing of asphalt concrete
Composting	Not applicable because asphalt concrete cannot be composted		
Combustion	Not modeled in WARM		
Landfilling	NA	NA	**Emissions** • Transport to construction and demolition landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because asphalt concrete cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all the GHG sources and sinks outlined in Exhibit 1-2 and calculates net GHG emissions per short ton of asphalt concrete inputs. For more detailed methodology on emission factors, please see the following sections on individual waste management strategies. Exhibit 1-3 outlines the net GHG emissions for asphalt concrete under each materials management option.

Exhibit 1-3: Net Emissions for Asphalt Concrete under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Asphalt Concrete	(0.11)	(0.08)	NA	NA	0.02	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
NA = Not applicable.

1.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For asphalt concrete, GHG emissions associated with RMAM are: (1) GHG emissions from energy used during the raw materials 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] Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust, or powder and road-asphalt binder, a coproduct of petroleum refining (Exhibit 1-4). The process that energy GHG emissions result from is the manufacture of these main raw materials, plus the HMA production process. The production process involves sorting and drying the aggregate, heating the asphalt binder, and heating and applying the mixture. Aggregate material can be produced from numerous sources, including natural rock, reclaimed asphalt pavement (RAP), reclaimed concrete pavement (RCP), glass, fly ash, bottom ash, steel slag, recycled asphalt shingles, and crumb rubber. The transportation GHG emissions are generated from transportation associated with raw materials during manufacture and transportation to the roadway construction site. EPA assumed that non-energy process GHG emissions from making asphalt concrete were negligible because no data were available about non-energy emissions, and the majority of the asphalt concrete is aggregate, which has no non-energy emissions associated with its production.

Exhibit 1-4: Composition of Hot Mix Asphalt

Component	Hot Mix Asphalt Composition
Asphalt Binder	5.2%
Aggregate (Fine and Coarse)	94.8%

Source: (Hassan, 2009).

1.4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction, recycling, and landfilling pathways for materials management of asphalt concrete.

Reclaimed asphalt pavement from HMA can be either recycled in an open loop as aggregate for a variety of materials or it can be recycled in a closed loop to produce new HMA, which results in lower input quantities of both new aggregate and new asphalt binder; WARM examines only the closed-loop pathway. An estimated 80–85 percent of waste HMA is recycled to produce aggregate or HMA (Levis, 2008). Asphalt concrete can also be landfilled in a construction and demolition (C&D) landfill.

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

Descriptions of life-cycle energy and GHG emissions data for virgin asphalt mixture are available from the Athena Sustainable Materials Institute (Athena, 2001) and in a technical report published by Transportation Research Board (Hassan, 2009). This analysis considers source reduction, recycling, and landfilling for materials management of asphalt concrete.

Source reduction and recycling of asphalt concrete lead to reductions in GHG emissions because both strategies avoid the energy-intensive manufacture of asphalt concrete from raw materials. Landfilling has a slightly positive emission factor resulting from the emissions from transportation to the landfill and operation of landfill equipment.

1.4.1 Source Reduction

Virgin production of HMA is generalized to be a three-step process: (1) aggregate production, (2) road asphalt binder production, and (3) HMA production. Exhibit 1-5 summarizes the avoided emissions of source reducing virgin HMA. The avoided emissions associated with process energy and transportation energy are similar in magnitude, suggesting that the transportation of raw materials to the HMA plant and to the road site is as emissions-intensive as the actual production of the HMA itself. The following paragraphs give a further explanation of the process energy and transportation energy required for HMA production and avoided by source reduction. For more information on Source Reduction, please see the chapter on Source Reduction.

Exhibit 1-5: Source Reduction Emission Factors for Asphalt Concrete ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs[a]	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Asphalt Concrete	(0.11)	(0.11)	NA	NA	(0.11)	(0.11)

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

[a]: For this material, information on the share of recycled inputs used in production is unavailable or is not a common practice; EPA assumes that the current mix is comprised of 100% virgin inputs. Consequently, the source reduction benefits of both the "current mix of inputs" and "100% virgin inputs" are the same.

– = Zero emissions.

The GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see Section 1.3) of asphalt concrete produced from a current mix of virgin and recycled inputs or from asphalt concrete produced from 100-percent virgin inputs. For asphalt concrete, the current mix is equivalent to the 100-percent virgin source reduction factor because asphalt concrete is not typically produced using recycled inputs.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end-of-life. No post-consumer emissions result from source reducing asphalt concrete because production of the material is avoided in the first place. Forest carbon storage is not applicable to asphalt concrete, and thus, does not contribute to the source reduction emission factor.

1.4.1.1 Developing the Emission Factor for Source Reduction of Asphalt Concrete

To calculate the avoided GHG emissions for asphalt concrete, EPA first looked at two components of GHG emissions from RMAM activities: (1) process energy and (2) transportation energy GHG emissions. No non-energy GHG emissions result from asphalt concrete RMAM activities. Exhibit 1-6 shows the results for each component and the total GHG emission factors for source reduction of asphalt concrete. More information on each component making up the final emission factor appears in

Section 1.4.5. A discussion of the methodology for estimating emissions from asphalt concrete manufactured from recycled materials can be found in the Recycling section.

Exhibit 1-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Asphalt Concrete (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Asphalt concrete	0.06	0.05	–	0.11

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
– = Zero emissions.

Process energy includes the requirements to produce the raw material aggregate and asphalt binder to combine the aggregate and binder in an HMA plant and to produce the hot mix asphalt. By mass, most of the HMA is composed of aggregate and the remainder consists of asphalt binder (Exhibit 1-4). By far the most energy-intensive part of this process is the production of the asphalt binder. The HMA plant operations to produce the hot mix asphalt have more modest energy requirements, and the production of aggregate (extraction and processing of limestone, granite, and other stone) is even less energy intensive.

EPA obtained all data on the energy associated with the production of aggregate from the U.S Census Bureau. EPA used the Fuels and Energy Report (Census Bureau, 1997) for data on the quantity of purchased fuels and electric energy consumed by the crushed stone industry based on North American Industry Classification System (NAICS). Also, EPA used the Mining-Subject Series Product Summary (Census Bureau, 2001) for data on the amount of crushed stone produced. Although the data are relevant to the late 1990s, this dataset represents the most updated information available from the U.S. Census.

EPA obtained energy inputs for the manufacturing process of asphalt binder from the Athena Sustainable Materials Institute’s Life Cycle Inventory for Road and Roofing Asphalt, prepared by Franklin Associates (Athena, 2001). For road asphalt binder production, EPA obtained data on virgin crude oil (which is a material input in manufacturing asphalt binder) from National Renewable Energy Laboratory’s (NREL) U.S. Life Cycle Inventory (LCI) Database (NREL, 2009). EPA also took data on limestone manufacturing from the U.S. LCI Database (NREL, 2009). Finally, EPA obtained energy inputs for the production of HMA from aggregate and asphalt binder from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). EPA then multiplied the fuel consumption estimates by the fuel-specific carbon contents. The process energy used to produce asphalt concrete and the resulting emissions appear in Exhibit 1-7.

Exhibit 1-7: Process Energy GHG Emissions Calculations for Virgin Production of Asphalt Concrete

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO$_2$E/Short Ton)
Asphalt Concrete	0.94	0.06

EPA obtained transportation energy requirements for the asphalt binder, aggregate, and HMA from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). EPA assumed that the asphalt concrete materials were transported by truck, based on the average transport distance requirements for two different types of roadway projects: Class I Roadway (rural secondary highway) and Class II Roadway (urban arterial roadway). For the production of virgin crude oil, EPA obtained transportation data from NREL (2009). The U.S. LCI Database assumes no transportation is associated with the manufacturing of limestone. The transportation energy and the resulting emissions used to produce and deliver the asphalt concrete to the roadway project appear in Exhibit 1-8.

Exhibit 1-8: Transportation Energy Emissions Calculations for Virgin Production of Asphalt Concrete

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Asphalt Concrete	0.73	0.05

Note: The transportation energy and emissions in this exhibit do not include retail transportation

1.4.2 Recycling

Asphalt concrete can be recycled into new HMA or aggregate, which can be used for several purposes. Both processes require the asphalt to be extracted and crushed before transportation to the mixing plant. EPA's analysis focused on the closed-loop recycling process, and did not consider the GHG benefits of recycling HMA into aggregate used for other purposes. For more information on Recycling, please see the chapter on Recycling.

The recycling of HMA into new HMA consists of transporting waste asphalt pavement to mixing plants, crushing it in RAP crushers, and mixing the resulting materials into new HMA. The waste pavement in this alternative replaces virgin natural aggregates, as well as asphalt binder.

To produce new HMA, the extracted asphalt concrete is transported to an HMA mixing plant, crushed, and mixed into new HMA. This process occurs at the mixing plant and uses the same energy inputs as HMA produced from virgin materials; therefore, energy savings for recycled HMA comes mainly from the avoided energy needed to obtain virgin materials (i.e., virgin aggregate) and to process the asphalt binder. Because the binder production represents the most energy-intensive part of the HMA production process, the greatest process-related savings from recycling HMA result from avoided binder production. The greatest overall savings from recycling result from the avoided transportation associated with virgin asphalt concrete manufacture, particularly because of the avoided transportation requirements for crude oil used as an input into asphalt binder production.

A recycled input credit is calculated for asphalt concrete by assuming that the recycled material avoids (or offsets) the GHG emissions associated with producing the asphalt concrete from virgin inputs. GHG emissions associated with management (i.e., collection, transportation, and processing) of recycled asphalt concrete are included in the recycling credit calculation. Each component of the recycling emission factor as shown in Exhibit 1-9 is discussed in later paragraphs. For more information on recycling in general, see the Recycling chapter.

Exhibit 1-9: Recycling Emission Factor for Asphalt Concrete ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Asphalt Concrete	–	–	(0.03)	(0.05)	–	NA	(0.08)

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
NA = Not applicable.
[a] Includes emissions from the initial production of the material being managed.
– = Zero emissions.

1.4.2.1 Developing the Emission Factor for Recycling of Asphalt Concrete

EPA calculated the GHG benefits of recycling asphalt concrete by taking the difference between producing asphalt concrete from virgin inputs and producing asphalt concrete from recycled inputs, after accounting for losses that occur during the recycling process. This difference is called the "recycled input credit" and represents the net change in GHG emissions from process energy and transportation energy in recycling asphalt concrete relative to virgin production of asphalt concrete.

The recovery and processing of the recycled asphalt concrete require additional energy inputs. These inputs include the energy required to recover, load, and crush asphalt concrete (Levis, 2008). However, the GHG emissions associated with these additional energy inputs are outweighed by the GHG savings from the avoided raw material extraction for aggregate and crude oil, as well as the avoided asphalt binder production.

To calculate each component of the recycling emission factor, EPA used the following four steps:

Step 1. *Calculate GHG emissions from virgin production of one short ton of asphalt concrete.* The GHG emissions from virgin production of asphalt concrete are provided in Exhibit 1-7 and Exhibit 1-8. EPA calculated emissions from production of virgin asphalt concrete using the data sources and methodology also used to calculate the source reduction factor. EPA applied fuel-specific carbon coefficients to the process and transportation energy use data for virgin RMAM of asphalt concrete.

Step 2. *Calculate GHG emissions from recycled production of asphalt concrete.* Exhibit 1-10 and Exhibit 1-11 provide the process and transportation emissions associated with producing recycled asphalt concrete. The same amount of energy is required to remix HMA from recycled asphalt concrete as is required to produce HMA from virgin materials (Levis, 2008). Therefore, the analysis used data on virgin HMA production from the Canadian Program for Energy Conservation as described in the source reduction section (Natural Resources Canada, 2005).

Exhibit 1-10: Process Energy GHG Emissions Calculations for Recycled Production of Asphalt Concrete

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Asphalt Concrete	0.41	0.03

EPA obtained transportation data for recycled asphalt concrete from Levis (2008). The transportation requirements include transporting the recovered asphalt concrete to the HMA mixing plant and then transporting the recycled HMA back to the road site. The largest energy benefit from recycling asphalt concrete is the avoided transport associated with the crude oil input used to produce the virgin asphalt binder.

Exhibit 1-11: Transportation Energy GHG Emissions Calculations for Recycled Production of Asphalt Concrete

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Asphalt Concrete	0.05	0.00

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

Step 3. *Calculate the difference in emissions between virgin and recycled production.* To calculate the GHG emissions implications of recycling one short ton of asphalt concrete, WARM subtracts the recycled product emissions (calculated in Step 2) from the virgin product emissions (calculated in Step 1) to calculate the GHG savings. These results appear in Exhibit 1-12.

Exhibit 1-12: Differences in Emissions between Recycled and Virgin Asphalt Concrete Manufacture ($MTCO_2E$/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Asphalt Concrete	0.06	0.05	–	0.03	0.00	–	(0.03)	(0.05)	–

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
– = Zero emissions.

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. Processors discard this portion in either the recovery stage or the remanufacturing stage; and consequently, less than one short ton of new material generally is made from one short ton of recovered material. Material losses are quantified and translated into loss rates. The recycled input credits calculated earlier are, therefore, adjusted to account for any loss of product during the recycling process. Because the recovered asphalt concrete is valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high. Therefore, EPA assumed that the loss rates for recycling asphalt concrete were less than one percent by weight (Levis, 2008) and that the recycling retention rate was 100 percent. Thus, EPA did not adjust the GHG emissions associated with recycling (i.e., the difference between virgin and recycled manufacture), as shown in Exhibit 1-12.

1.4.3 Composting

Because of the nature of asphalt concrete components, asphalt concrete cannot be composted, and thus, WARM does not include an emission factor for the composting of asphalt concrete.

1.4.4 Combustion

While asphalt concrete does contain combustible materials in the form of petroleum-based components, industry and academic experts indicate that asphalt is not combusted as an end-of-life management pathway, nor would it be logical to do so (Hassan, 2009). The combustible components of asphalt concrete make up a relatively small percentage of the material (roughly five percent), meaning that a lot of energy would be wasted to heat up the non-combustible components at the facility (Levis, 2008). The uses for recycled asphalt also provide a more valuable end-use for the material than the value of energy recovery from combustion. Finally, emissions such as volatile organic compounds generated by combustion would provide emission control burdens at the facilities that outweigh the potential energy gains (Hassan, 2009). For these reasons, EPA did not include an emission factor in WARM for combustion of asphalt concrete.

1.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, because asphalt concrete does not contain biodegradable carbon, there are zero emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling asphalt concrete. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for asphalt concrete is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. Exhibit 1-13 provides the net emission factor for landfilling asphalt concrete. For more information on landfilling, please see the Landfilling chapter.

Exhibit 1-13: Landfilling Emission Factor for Asphalt Concrete ($MTCO_2E$/Short Ton)

Material	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)
Asphalt Concrete	–	0.02	–	–	–	0.02

– = Zero emissions.

1.4.6 Anaerobic Digestion

Because of the nature of asphalt concrete components, asphalt concrete cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of asphalt concrete.

1.5 LIMITATIONS

As indicated in Section 1.1, asphalt concrete is produced in a variety of mixtures, including hot mix, warm mix, cold mix, cut-back, mastic, and natural, each with distinct material and energy inputs. EPA chose to analyze hot mix asphalt because of its widespread use in U.S. roadway projects. Recent studies indicate that warm mix asphalt may provide significant energy and GHG savings to the asphalt industry because of lower heat requirements during production (Hassan, 2009). As data become available, it will be important to estimate the life-cycle GHG emissions from the production and use of other types of asphalt concrete.

1.6 REFERENCES

Athena Sustainable Materials Institute. (2001). *A Life Cycle Inventory for Road and Roofing Asphalt.* Prepared by: Franklin Associates Ottawa, Canada. March 2001.

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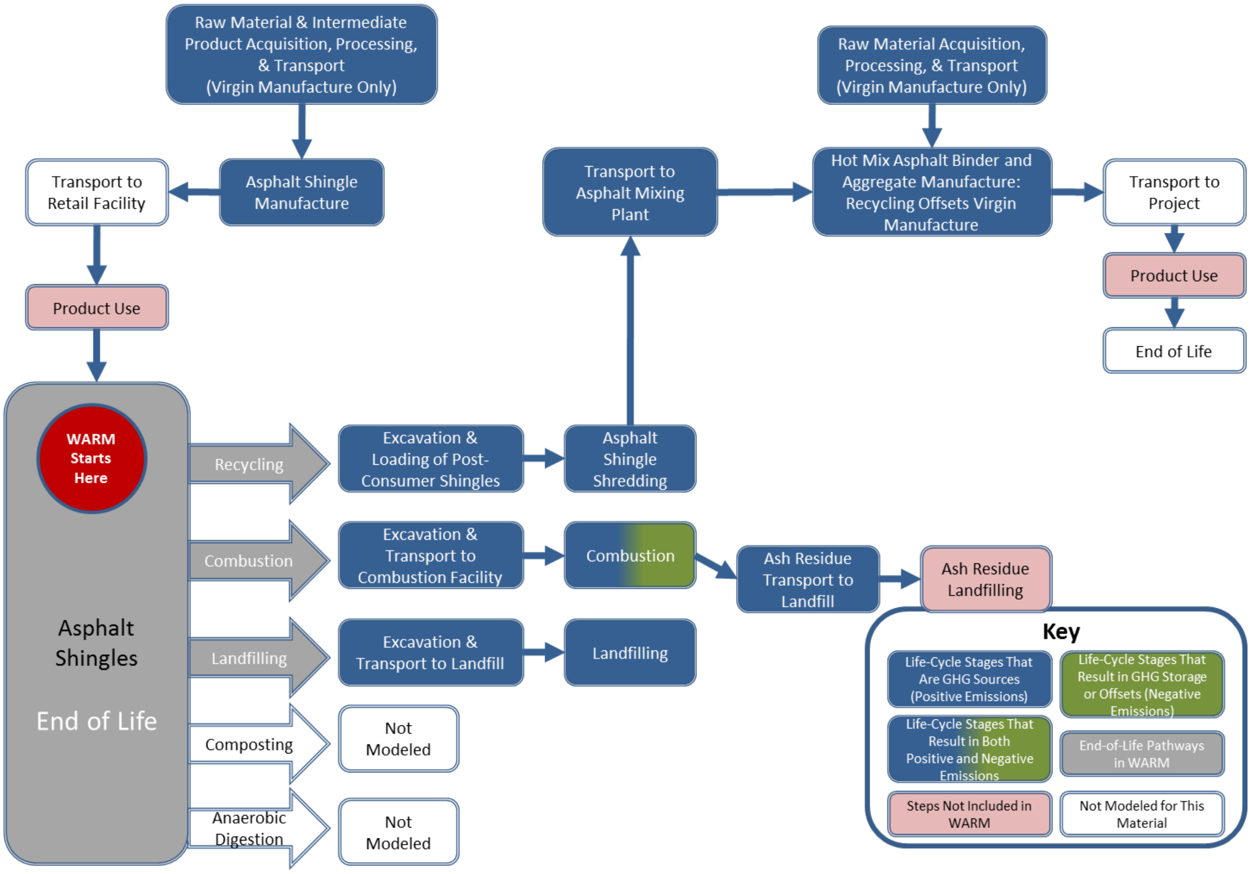
2 ASPHALT SHINGLES

2.1 INTRODUCTION TO WARM AND ASPHALT SHINGLES

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for asphalt shingles beginning at the waste generation reference point.[3] The WARM GHG emission factors are used to compare the net emissions associated with asphalt shingles in the following four waste management alternatives: source reduction, recycling, combustion, and landfilling. Exhibit 2-1 shows the general outline of materials management pathways for asphalt shingles in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, Combustion, and Landfilling, see the chapters devoted to those processes.

Exhibit 2-1: Life Cycle of Asphalt Shingles in WARM



Asphalt shingles are used as a roofing material and are typically made of a felt mat saturated with asphalt. Small rock granules are added to one side of the shingle to protect against natural elements such as sun and rain. Depending on whether the shingle base is organic or fiberglass, the granules are composed of asphalt cement (19 to 36 percent by weight, respectively), a mineral stabilizer like limestone or dolomite (eight to 40 percent), and sand-sized mineral granules (20 to 38 percent), in addition to the organic or fiberglass felt backing (two to 15 percent). The asphalt that is used in shingles

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[3] EPA would like to thank Dr. Kimberly Cochran of EPA for her efforts in improving these estimates.

is considerably harder than the asphalt used in pavement. According to the EPA, the U.S. manufactures and disposes of an estimated 11 million tons of asphalt shingles per year (NERC, 2007).

The material composition and production process is different for paper felt-based and fiberglass-based shingles. The majority of post-consumer asphalt shingle waste is generated at residential sites, while the remaining asphalt shingles waste is generated at non-residential sites (CMRA, 2007a). Additionally, our research indicates that 82 percent of the residential shingle market is fiberglass, and the market share is growing (HUD, 1999). Therefore, WARM uses the fiberglass-based asphalt shingle emission factor as the factor for asphalt shingles, rather than using two separate emission factors for fiberglass- and paper felt-based shingles.

2.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point, and only consider upstream GHG emissions when the production of new materials is affected by materials management decisions. Recycling and source reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling, and Source Reduction.

WARM does not consider composting or anaerobic digestion for asphalt shingles. As Exhibit 2-2 illustrates, all of the GHG sources and sinks relevant to asphalt shingles in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life cycle assessment.

Exhibit 2-2: Asphalt Shingles GHG Sources and Sinks from Relevant Materials Management Pathways

MSW Management Strategies for Asphalt Shingles	GHG Sources and Sinks Relevant to Asphalt Shingles		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Avoided production of primary raw materials • Avoided secondary processing to manufacture shingles • Avoided transportation of raw materials	NA	NA
Recycling	**Offsets** • Avoided production of virgin asphalt binder and aggregate • Avoided transportation for virgin asphalt binder and aggregate	NA	**Emissions** • Excavating, loading, shredding post-consumer shingles • Transport to HMA mixing plant
Composting	Not applicable since asphalt shingles cannot be composted		
Combustion	NA	NA	**Emissions** • Emissions from combustion in cement kiln • Transport to combustor **Offsets** • Avoided refinery fuel gas typically used in cement kilns
Landfilling	NA	NA	**Emissions** • Transport to C&D landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because asphalt shingles cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 2-2 and calculates net GHG emissions per short ton of asphalt shingles inputs. For more detail on the methodology on emission factors, please see the sections below on individual waste management strategies. Exhibit 2-3 outlines the net GHG emissions for asphalt shingles under each materials management option.

Exhibit 2-3: Net Emissions for Asphalt Shingles under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Asphalt Shingles	(0.19)	(0.09)	NA	(0.35)	0.02	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.

2.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For asphalt shingles, GHG emissions associated with raw materials acquisition and manufacturing are: (1) GHG emissions from energy used during the raw materials acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[4] For virgin asphalt shingles, process energy GHG emissions result from the manufacture of the main raw materials used in the manufacturing of asphalt shingles, including the fiberglass mat carrier sheet, the asphalt binder and coating, mineral surfacing and the stabilizer or filler. Process energy GHG emissions also include the actual roof shingles manufacturing process, which is a continuous process on an assembly line consisting of a dry and wet accumulator, coating, cooling/drying, shingle cutting, and roll winder that builds the shingles from the raw materials (Athena, 2000). Transportation emissions are generated from transportation associated with raw materials, during manufacture, and during transportation to the retail facility. EPA assumed that non-energy process GHG emissions from making asphalt shingles were negligible.

The RMAM calculation in WARM also incorporates “retail transportation,” which incorporates the average truck, rail, water, and other-modes transportation emissions required to transport asphalt shingles from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 2-4. Transportation emissions from the retail point to the consumer are not included. The miles travelled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 2-4: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors ($MTCO_2E$/ Short Ton)
Asphalt Shingles	356	0.39	0.03

2.4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers the source reduction, recycling, landfilling, and combustion pathways for materials management of asphalt shingles.

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

Reclaimed asphalt shingles can be used to offset the production and transport of both aggregate and binder. Greenhouse gas savings are realized for source reduction, recycling and combustion, while landfilling has a slightly positive emission factor due to the emissions from transportation to the landfill and operation of landfill equipment. It is interesting to note that the GHG savings for combustion are greater than for any other waste management alternative. This is because the asphalt shingles have significantly higher energy content (BTU per ton) relative to other materials due to the asphalt cement coating. Asphalt shingles that are combusted can displace other fuels (i.e., refinery fuel gas) used in cement kilns resulting in a reduction in combustion emissions associated with refinery fuel gas and offering potentially significant reductions in GHG emissions when considered as a waste management alternative to landfilling. This analysis considers source reduction, recycling, combustion, and landfilling for materials management of asphalt concrete.

2.4.1 Source Reduction

The type of production process used to produce asphalt shingles depends on whether the asphalt shingle is organic felt-based or fiberglass mat-based. The Athena database contains life-cycle information on both types (organic and fiberglass) of asphalt shingles (Athena, 2000). In general, the production of fiberglass mat-based asphalt shingles is less energy-intensive (and subsequently less GHG-intensive) than the production of organic paper felt-based asphalt shingles. This is because fiberglass mat does not absorb water used throughout the mat production (unlike the organic shingle counterparts). Thus, it is less energy-intensive to form glass mat since the drying of the mat is eliminated as a process step. As discussed earlier, EPA included only fiberglass shingles in WARM because they make up the majority (82 percent) of the residential shingle market (HUD, 1999). The source reduction emission factor for fiberglass asphalt shingles is summarized in Exhibit 2-5. For more information, please see the chapter on Source Reduction.

Exhibit 2-5: Source Reduction Emission Factors for Asphalt Shingles ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs[a]	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Asphalt Shingles	(0.19)	(0.19)	NA	NA	(0.19)	(0.19)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

[a]: For this material, information on the share of recycled inputs used in production is unavailable or is not a common practice; EPA assumed that the current mix is comprised of 100% virgin inputs. Consequently, the source reduction benefits of both the “current mix of inputs” and “100% virgin inputs” are the same.

– = Zero emissions.

The GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see Section 3) of asphalt shingles produced from a “current mix” of virgin and recycled inputs or from asphalt shingles produced from “100 percent virgin” inputs. For asphalt shingles, the “current mix” is equivalent to the “100 percent virgin” source reduction factor since asphalt shingles are not typically produced using recycled inputs.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end of life. When source reducing asphalt shingles, there are no post-consumer emissions because production of the material is avoided in the first place; therefore, the avoided asphalt shingles can never become post-consumer emissions. Forest carbon storage is not applicable to asphalt shingles, and thus does not contribute to the source reduction emission factor.

2.4.1.1 *Developing the Emission Factor for Source Reduction of Asphalt Shingles*

To calculate the avoided GHG emissions for asphalt shingles, EPA first looked at two components of GHG emissions from RMAM activities: process energy and transportation energy GHG emissions. There are no non-energy GHG emissions from asphalt shingles RMAM activities. Exhibit 2-6 shows the results for each component and the total GHG emission factors for source reduction of asphalt shingles. More information on each component making up the final emission factor is provided below. The methodology for estimating emissions from asphalt shingles manufactured from recycled materials is discussed below in the Recycling section.

Exhibit 2-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Asphalt Shingles (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Asphalt Shingles	0.12	0.07	–	0.19

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero Emissions.

EPA used data from the Athena Sustainable Materials Institute (2000) to develop a source reduction emission factor for fiberglass shingles. These data include the energy (by fuel type) associated with the production of the primary raw materials as well as secondary processing to manufacture the actual shingles (i.e., the energy associated with the operations at the roofing plant itself). Pre-combustion energy is not included in Athena (2000) and was subsequently added to the raw process and transportation data fuel breakdown. The process energy used to produce asphalt shingles and the resulting emissions are shown in Exhibit 2-7.

Exhibit 2-7: Process Energy GHG Emissions Calculations for Virgin Production of Asphalt Shingles

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO$_2$E/Short Ton)
Asphalt Shingles	2.15	0.12

EPA also used transportation data from the Athena Sustainable Materials Institute (2000) to develop the asphalt shingles source reduction emission factor. These data again include transportation energy associated with the primary raw materials and the manufacturing process itself. The transportation energy used to produce asphalt shingles and the resulting emissions are shown in Exhibit 2-8.

Exhibit 2-8: Transportation Energy Emissions Calculations for Virgin Production of Asphalt Shingles

Material	Transportation Energy per Ton Made from Virgin Inputs (Million Btu)	Transportation Emissions (MTCO$_2$E/Short Ton)
Asphalt Shingles	0.58	0.04

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 2-4.

2.4.2 Recycling

Used or scrap asphalt shingles can be recycled into many types of applications in hot and cold mix asphalt, as an aggregate base for road development, as mulch, as a fuel source, or into new roofing materials (CMRA, 2007a). For more information, please see the chapter on Recycling.

Using asphalt shingles as a component in hot mix asphalt (HMA) is the most common process to which recycled shingles are added. Researchers at the University of Massachusetts have determined that HMA that consists of up to seven percent recycled asphalt shingles shows no quality differences as compared to virgin HMA (Mallick, 2000). Waste shingles are ground, screened, and filtered for contaminants. They are then usually fed into and mixed with aggregate before being added to virgin asphalt binder (CMRA, 2007a). In this analysis, EPA assumed that the ground asphalt shingles displaced the production of virgin asphalt binder and aggregate, taking into account the asphalt and aggregate content of the shingles as shown in Exhibit 2-9.

Exhibit 2-9: Typical Composition of Asphalt Shingles

Component	Fiberglass Shingles
Asphalt Cement	22%
Fiberglass Felt	15%
Aggregate	38%
Stabilizer/Filler	25%
Total	100%

Source: CMRA, 2007a.

Shingle-to-shingle recycling is a relatively new concept that has not yet been fully developed into any known commercial-scale operation. The biggest challenge with closed-loop recycling of asphalt shingles is conforming to very stringent feedstock product specifications. Also, there is a lack of information and data on shingle-to-shingle recycling practices. Furthermore, there are no known facilities that produce new shingles from either manufacturers' scrap or tear-off material on a commercial basis (CMRA, 2007b). As a result, in developing the recycling emission factor, EPA assumed all recycled shingles were used to displace virgin asphalt binder and aggregate, which is used in the production of HMA.

A "recycled input credit" is calculated for asphalt shingles by assuming that the recycled material avoids (or offsets) the GHG emissions associated with producing virgin asphalt binder and aggregate, taking into account the asphalt and aggregate content of the shingles. GHG emissions associated with management (i.e., collection, transportation, and processing) of recycled asphalt shingles are included in the recycling credit calculation. Each component of the recycling emission factor as provided in Exhibit 2-10 is discussed further in section 2.4.2.1. For more information on recycling in general, see the Recycling chapter.

Exhibit 2-10: Recycling Emission Factor for Asphalt Shingles ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Asphalt Shingles	–	–	(0.11)	0.02	–	NA	(0.09)

– = Zero emissions.

[a] Includes emissions from the initial production of the material being managed.

2.4.2.1 *Developing the Emission Factor for Recycling of Asphalt Shingles*

EPA calculated the GHG benefits of recycling asphalt shingles by calculating the avoided emissions associated with virgin asphalt binder and aggregate that is subsequently used in HMA, after accounting for losses that occur during the recycling process. This difference is called the "recycled input credit" and represents the net change in GHG emissions from process energy and transportation energy in recycling asphalt shingles relative to virgin production of components used in hot mix asphalt.

To calculate each component of the recycling emission factor, EPA followed four steps, which are described in detail below:

Step 1. *Calculate emissions from the recycling of one short ton of asphalt shingles.* EPA estimated the energy associated with excavating, loading and shredding the post-consumer asphalt shingles using data from Dr. Kimberly Cochran (Cochran, 2006). EPA assumed that the machinery was operated using diesel fuel. The emissions for the process of excavating, loading and shredding the post-consumer asphalt shingles in preparation for use in hot mix asphalt are shown in Exhibit 2-11.

Exhibit 2-11: Process Energy GHG Emissions Calculations for Recycled Production of Asphalt Shingles

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Asphalt Shingles	0.04	0.00

EPA assumed that recovered asphalt shingles were transported 40 miles and trucked using diesel fuel. EPA estimated the avoided transportation energy for offsetting virgin asphalt binder using the data and methodology discussed in the Asphalt Concrete chapter. EPA obtained transportation energy requirements for the asphalt binder from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). For the production of virgin crude oil, EPA obtained transportation data from NREL (2009).

Exhibit 2-12: Transportation Energy GHG Emissions Calculations for Recycled Production of Asphalt Shingles

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Asphalt Shingles	0.09	0.01

Step 2. *Calculate GHG emissions for production of components of hot mix asphalt.* Exhibit 2-13 and Exhibit 2-14 provide the process and transportation emissions associated with producing hot mix asphalt components.

EPA assumed that the recycled asphalt shingles would avoid the production of virgin asphalt binder and aggregate based on the relative percent virgin asphalt binder and aggregate, taking into account the asphalt and aggregate content of the shingles as shown in Exhibit 2-9 above. EPA estimated the emissions associated with the production of virgin asphalt binder using the data and methodology discussed in the Asphalt Concrete chapter. Specifically, EPA obtained energy inputs for the manufacturing process of asphalt binder from the Athena Sustainable Materials Institute's *Life Cycle Inventory for Road and Roofing Asphalt*, prepared by Franklin Associates (Athena, 2001). To estimate the emissions associated with virgin production of aggregate, EPA obtained emission factors discussed in the Concrete chapter for virgin aggregate production.

For example, since fiberglass shingles contain 22 percent "asphalt cement" per short ton, EPA assumed that each ton of recovered asphalt shingles could avoid the production-related GHG emissions of virgin asphalt binder adjusted by this percentage. The "weighted" emission factors in Exhibits 2-13 and 2-14 show the avoided GHG emissions associated with using recycled asphalt shingles in hot mix asphalt to displace virgin asphalt binder and aggregate.

Exhibit 2-13: Process Energy Emissions for Components of Hot Mix Asphalt

Material	Process Energy Emissions ($MTCO_2E$/Short Ton)	Typical Composition as Shown in Exhibit 2-9 (%)	Weighted Process Energy Emissions ($MTCO_2E$/Short Ton)
Virgin Asphalt Binder	0.54	22%	0.12
Aggregate	0.00	38%	0.00

Exhibit 2-14: Transportation Energy emissions for Components of Hot Mix Asphalt

Material	Transportation Energy Emissions ($MTCO_2E$/Short Ton)	Typical Composition as Shown in Exhibit 9 (%)	Weighted $MTCO_2E$/Short Ton
Virgin Asphalt Binder	0.05	22%	0.01
Aggregate	0.01	38%	0.00

Step 3. *Calculate the avoided hot mix asphalt emissions using recycled asphalt shingles.* To calculate the GHG emissions implications of recycling one short ton of asphalt shingles, WARM subtracts the virgin asphalt binder and aggregate avoided emissions (calculated in Step 2) from the recycling process emissions (calculated in Step 1) to obtain the GHG savings. These results are shown in Exhibit 2-15.

Exhibit 2-15: Differences in Emissions between Recycled and Virgin Asphalt Shingles Manufacture ($MTCO_2E$/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Asphalt Shingles	0.12	0.07	–	0.00	0.03	–	(0.12)	(0.04)	–

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the remanufacturing stage. Consequently, less than one short ton of new material generally is made from one short ton of recovered material. Material losses are quantified and translated into loss rates. The recycled input credits calculated above are therefore adjusted to account for any loss of product during the recycling process. Because data were unavailable for the losses associated with recovered asphalt shingles, WARM assumes a 7.2 percent loss rate for asphalt shingles recycling based on the average residue percent of throughput across all multi-material material recovery facilities (MRF) (Berenyi, 2007). The differences in emissions from virgin versus recycled process energy and transportation energy are adjusted to account for loss rates by multiplying the final three columns of Exhibit 2-15 by 92.8 percent, the amount of material retained after losses (i.e., 100 percent input – 7.2 percent lost = 92.8 percent retained).

2.4.3 Composting

Due to the nature of the components of asphalt shingles, asphalt shingles cannot be composted and thus WARM does not include an emission factor for the composting of asphalt shingles.

2.4.4 Combustion

Although the practice of combusting asphalt shingles for energy recovery is established in Europe, asphalt shingles are not usually combusted in the United States (CMRA, 2007a). However, they do contain combustible components, and therefore, EPA developed an emission factor for combustion. For more information on combustion in general, please see the chapter on Combustion.

Since C&D waste is typically not combusted in standard combustion facilities because of various impurities that are present, EPA assumed that asphalt shingles are combusted in cement kilns (CMRA, 2007a). EPA obtained data on the energy content of asphalt shingles from the Construction Materials Recycling Association (CMRA, 2007a). EPA used carbon coefficients for oil and lubricants taken from the *U.S. Inventory of Greenhouse Gas Emissions and Sinks* as a proxy to calculate combustion emissions associated with the combustion of fiberglass-based shingles (EPA, 2018). Similarly, EPA calculated offset emissions using the carbon coefficients for refinery fuel gas typically used in cement kilns, taking into account the amount of shingles needed to generate a similar amount of energy. Greenhouse gas benefits are shown in Exhibit 2-16.

Exhibit 2-16: Components of the Combustion Net Emission Factor for Asphalt Shingles ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery Offsets	Net Emissions (Post-Consumer)
Asphalt Shingles	–	0.01	0.65	0.04	(1.05)	–	-0.36

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.

2.4.4.1 Developing the Emission Factor for Combustion of Asphalt Shingles

Raw Material Acquisition and Manufacturing: Because WARM takes a materials-management perspective (i.e., starting at end-of-life disposal of a material), RMAM emissions are not included for this materials management pathway.

Transportation to Combustion: GHG emissions from transportation energy use were estimated to be 0.04 $MTCO_2E$ for one short ton of asphalt shingles (FAL, 1994).

CO_2 from Combustion and N_2O from Combustion: Carbon coefficients for oil and lubricants are based on the *U.S. Inventory of Greenhouse Gas Emissions and Sinks* as a proxy to calculate combustion emissions associated with the combustion of fiberglass-based shingles in cement kilns (EPA, 2018). Emissions of N_2O are also included in the combustion factor.

Avoided Utility Emissions: Because asphalt shingles are not typically combusted in waste-to-energy (WTE) combustion facilities, EPA modeled the combustion of asphalt shingles as avoiding the combustion of refinery fuel gas typically combusted in cement kilns. The energy content and carbon content of refinery fuel gas are based on data from the American Petroleum Institute and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, respectively (API, 2004; EPA, 2018). Using the energy content per ton of fiberglass shingles in comparison to the energy and carbon content of refinery fuel gas, EPA calculated the avoided GHG emissions associated with combusting fiberglass shingles instead of refinery fuel gas in cement kilns, as shown in Exhibit 2-17.

Exhibit 2-17: Avoided Emissions from Combustion of Asphalt Shingles in Cement Kilns

(a)	(b) Energy Content (Million Btu/Short Ton)	(c) Carbon Content (kg C/Million Btu)[a]	(d) Short Tons of Shingles Required/Short Ton Refinery Fuel Gas	(e) Avoided Emissions ($MTCO_2E$/Short Ton Asphalt Shingles) (e = c adjusted per ton/d)
Refinery Fuel Gas	37.5	32.65	NA	NA
Fiberglass Shingles	8.8	20.24	4.26	1.05

Source: New Mexico Environment Department Solid Waste Bureau, 2010.
NA = Not applicable.
[a] The carbon content for refinery fuel gas is adjusted to mass based on the assumption that 250 gallons of refinery fuel gas weigh one ton.

Steel Recovery: There are no steel recovery emissions associated with asphalt shingles because they do not contain steel.

Because transportation and avoided utility emissions are positive emission factors, net GHG emissions for combustion are positive for asphalt shingles.

2.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage and avoided utility emissions from landfill gas-to-energy recovery. However, because asphalt shingles do not biodegrade, there are zero emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling asphalt shingles. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for asphalt shingles is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. For further information, please refer to the chapter on Landfilling. Exhibit 2-18 provides the net emission factor for landfilling asphalt shingles.

Exhibit 2-18: Landfilling Emission Factor for Asphalt Shingles ($MTCO_2E$/Short Ton)

Material	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)
Asphalt Shingles	–	0.02	–	–	–	0.02

– = Zero emissions.

2.4.6 Anaerobic Digestion

Because of the nature of asphalt shingles components, asphalt shingles cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of asphalt shingles.

2.5 LIMITATIONS

Although currently EPA does not consider the closed-loop recycling of asphalt shingles (i.e., using recovered asphalt shingles to produce new asphalt shingles), this process is technically feasible. However, many manufacturers have difficulty meeting product specifications when recycled shingles are used as inputs into the production of new asphalt shingles. EPA will consider including closed-loop shingle recycling when data become available for facilities producing new shingles from either manufacturers' scrap or tear-off material on a commercial basis.

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3 CARPET

3.1 INTRODUCTION TO WARM AND CARPET

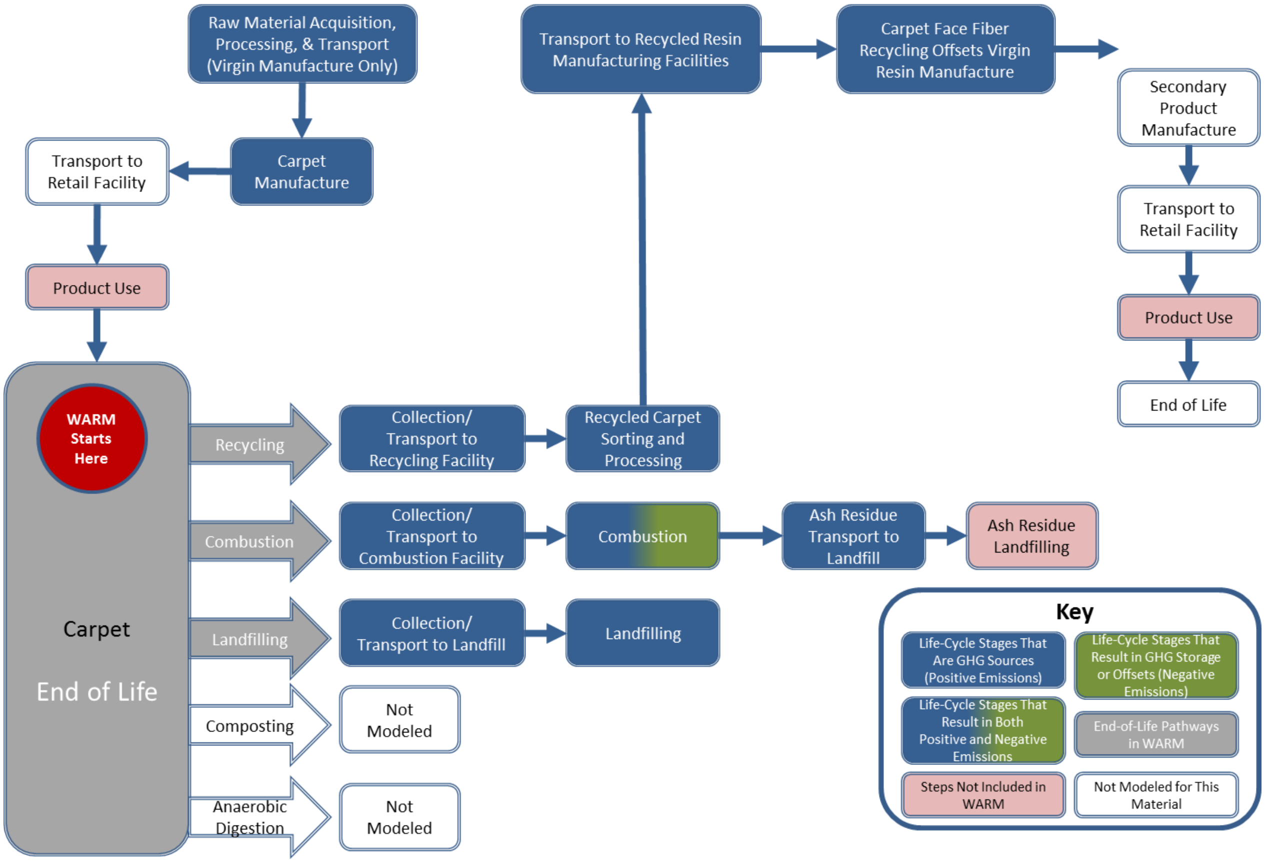
This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for carpet beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with carpet in the following four materials management alternatives: source reduction, recycling, landfilling, and combustion. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, Landfilling, and Combustion, see the chapters devoted to those 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.

At the end of its useful life, carpet can be recovered for recycling, sent to a landfill, or combusted. Landfilling is the most commonly selected waste management option for carpet. According to EPA (2011), nine percent of carpet is recycled annually. Efforts by industry, EPA, and other organizations over the past few years have increased the fraction of waste carpet that is recycled.

WARM accounts for the four predominant materials constituting face fibers in residential carpeting: Nylon 6, Nylon 6-6, Polyethylene terephthalate (PET) and Polypropylene (PET). Because the composition of commercial carpet is different than that of residential carpet, the emission factors presented in this chapter and in WARM only apply to broadloom residential carpet. The components of nylon broadloom residential carpet in this analysis include: face fiber, primary and secondary backing, and latex used for attaching the backings.

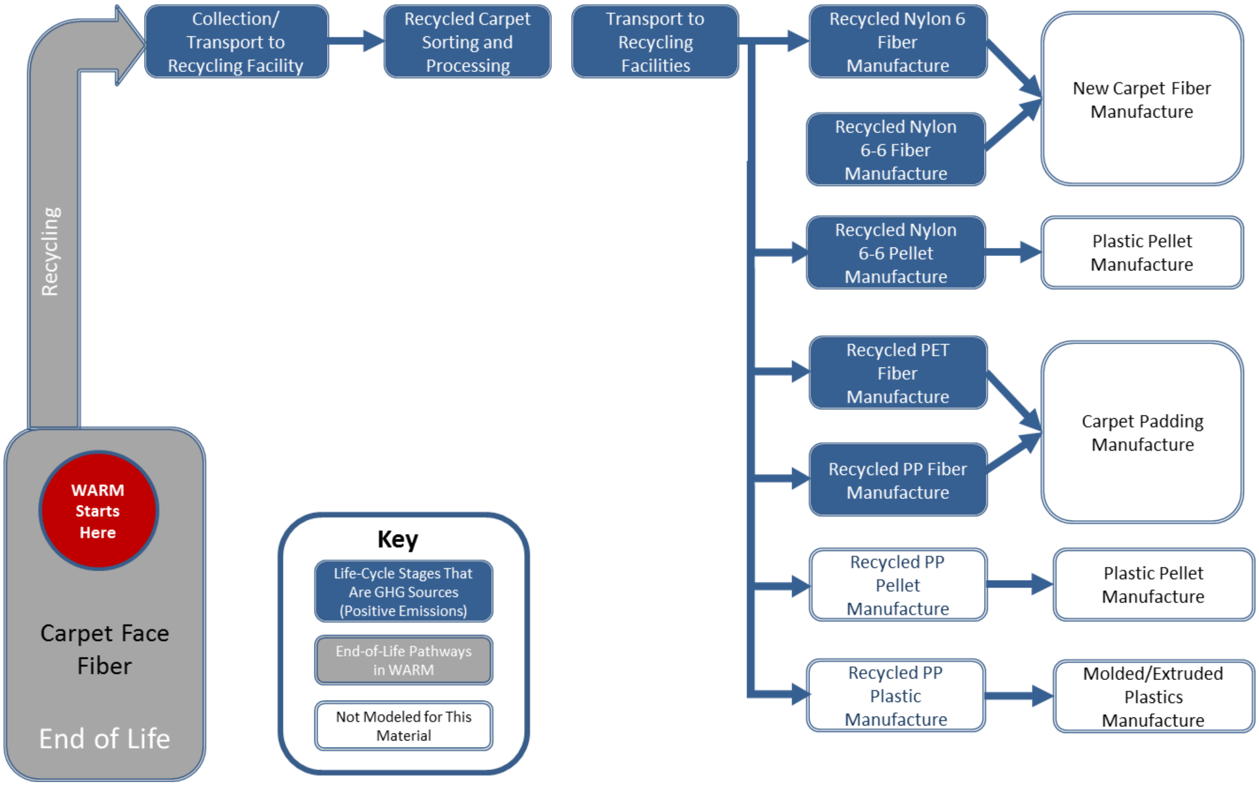
Exhibit 3-1 shows the general outline of materials management pathways in WARM and how they are modeled for carpet. Recycling carpet is an open-loop process, meaning that components are recycled into secondary materials such as carpet pad, molded products, and carpet backing. The life-cycle energy and material requirements for converting recycled carpet into these various secondary end products were unavailable (Realff, 2010a) and therefore not included in WARM. Therefore, in the recycling pathway, the recycling benefits for carpet incorporate the avoided manufacture of the various virgin plastic resins only. Carpet is collected curbside and at special recovery events, or individuals can bring it to designated drop-off sites. Once carpet has been collected for recycling, it is sent to material recovery facilities that specialize in separating and recovering materials from carpet. Building on Exhibit 3-1, a more detailed flow diagram of the recycling pathway for carpet is provided in Exhibit 3-2.

Exhibit 3-1: Life Cycle of Carpet in WARM



Since the original development of the carpet material type energy and GHG emission factors for WARM in 2004, updated life-cycle data for the recycling pathway which more accurately reflect carpet composition and recycling input energy have become available (Realff, 2011b). The updates include revisions to include two additional types of plastics found in the face fibers of residential broadloom carpets as well as the incorporation of the loss rates within the carpet recycling process. Updated information on the source reduction and landfilling life-cycle pathways for carpet was not available. Therefore, this update to the carpet factors in WARM includes changes only to the recycling and combustion pathways.

Exhibit 3-2: Detailed Recycling Flows for Carpet in WARM



3.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, and only consider upstream emissions when the production of materials is affected by end-of-life materials management decisions. Recycling and source reduction are the two materials management options that impact the upstream production of materials and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM includes source reduction, recycling, landfilling, and combustion pathways for materials management of carpet. Composting and anaerobic digestion are not included as pathways for materials management of carpet. As Exhibit 3-3 illustrates, most of the GHG emissions from end-of-life management of carpet occur from waste management of this product, while most of the GHG savings occur from offsetting upstream raw materials acquisition and the manufacturing of other secondary materials that are recovered from carpet.

Exhibit 3-3: Carpet GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Carpet	GHG Sources and Sinks Relevant to Carpet		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End-of-Life**
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Virgin process non-energy • Transport of carpet to point of sale	NA	NA
Composting	Not applicable because carpet cannot be anaerobically digested		
Recycling	**Emissions** • Transport of recycled materials • Recycled process energy • Recycled process non-energy **Offsets** • Emissions from producing Nylon 6, Nylon 6-6, PET and PP plastic resins from virgin material	NA	**Emissions** • Collection of carpet and transportation to recycling center • De-manufacturing and reprocessing recovered carpet
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related CO_2 **Offsets** • Avoided electric utility emissions
Anaerobic Digestion	Not applicable because carpet cannot be anaerobically digested		

NA = Not applicable.

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

Exhibit 3-4: Net Emissions for Carpet under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) GHG Emissions For Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Landfilling Emissions	Net Combustion Emissions	Net Anaerobic Digestion Emissions
Carpet	(3.68)	(2.38)	NA	0.02	1.10	NA

[a] The current mix of inputs for carpet is considered to be 100% virgin material.

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

NA = Not applicable.

3.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

The components of nylon broadloom residential carpet in this analysis include: face fiber, primary and secondary backing, and latex used for attaching the backings. The face fiber used for nylon carpet is typically made of a combination of Nylon 6, Nylon 6-6, Polyethylene terephthalate (PET) and Polypropylene (PP). For the purpose of developing an emission factor that represents “typical” broadloom residential carpet, WARM reflects the market share of each material in the carpet industry.

Carpet backing for broadloom carpet typically consists of polypropylene (PP). For latex used to adhere carpet backings, EPA modeled styrene butadiene, the most common latex used for this purpose. Styrene butadiene latex is commonly compounded with a filler such as calcium carbonate (limestone). Inputs to the manufacture of nylon, PP, and styrene butadiene are crude oil and/or natural gas. Exhibit 3-5 provides the assumed material composition of the typical carpet used for this analysis (FAL, 2002; Realff, 2011b).

Exhibit 3-5: Material Composition of One Short Ton of Carpet

Material	Application	% of Total Weight	Weight (lbs) (Assuming 2,000 lbs of Carpet)
Nylon, PET, PP mix	Face fiber	45%	910
PP	Woven for backing	15%	304
Styrene butadiene latex	Carpet backing adhesive	8%	164
Limestone	Filler in latex adhesive	32%	648
Total		**100%**	**2,026 lbs[a]**

[a] Note that these values total 2,026 pounds, which is greater than one short ton. This is because 26 pounds of the raw materials used to manufacture carpet are assumed to be "lost" during the manufacturing process. In other words, producing one short ton of carpet actually requires slightly more than one short ton of raw materials (FAL, 2002).

The main polymers that are used for the face fiber are Nylon 6-6, Nylon 6, PET, and PP with very small amounts of wool and a growing interest in the use of bio-based fibers. The average proportion of each of these plastic resins in carpet face fibers is provided in Exhibit 3-6. These components are recovered and recycled in different ways, each consuming different amounts of energy. For example, Nylon 6 face fiber is recycled mostly through depolymerization, whereas Nylon 6-6 face fiber is recycled mainly through shaving the fiber followed by remelting and extrusion.

Exhibit 3-6: Residential Face Fiber Mix 1995-2000

Plastic Resin	% of Total Weight
Nylon 6	25%
Nylon 6-6	40%
PET	15%
PP	20%
Total Face Fiber	**100%**

Source: Realff, 2011b.

The process used to turn the components in Exhibit 3-5 into a finished carpet may include weaving, tufting, needlepunching, and/or knitting. According to the Carpet and Rug Institute, 95 percent of carpet produced in the United States is tufted (CRI, 2010). During tufting, face pile yarns are rapidly sewn into a primary backing by a wide multineedled machine. After the face pile yarns are sewn into the primary backing, a layer of latex is used to secure a secondary backing, which adds strength and dimensional stability to the carpet.

3.4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction, recycling, landfilling, and combustion of carpet. It is important to note that carpet is not recycled into new carpet; instead, it is recycled in an open-loop process. The life-cycle assessment of carpet disposal must take into account the variety of second-generation products made from recycled carpet. Information on carpet recycling and the resulting second-generation products is sparse; however, EPA has modeled pathways for which consistent data are available for recycled carpet components. As described previously, due to the lack of available life-cycle data on the manufacture of second-generation products from recycled carpet, EPA modeled only the remanufacture of the various virgin plastic resins (i.e., one step before the resins are used to manufacture the second-generation products such as carpet pad, molded products, and carpet backing). Please see Exhibit 3-2 for the process flow diagram that illustrates these boundaries.

The data source used to develop the emissions factor for source reduction is a 2002 report published by Franklin Associates Limited (FAL) on energy and GHG emission factors for the manufacture and end-of-life management of carpet (FAL, 2002). These data were based on a number of industry and academic data sources dating from the 1990s and 2000s. The background data for the development of the source reduction carpet emission factors are available in an EPA background document associated with the FAL 2002 report (EPA, 2003). The data source used to develop the open-loop recycling emission factor for carpet is based on updated data from Dr. Matthew Realff of Georgia Institute of Technology (Georgia Tech). His findings were informed by the 2009 Carpet America Recovery Effort (CARE) 2009 annual report, which provided a breakdown of the components of carpet face fiber polymer (CARE, 2009). In 2011, Dr. Realff collected data in collaboration with the carpet industry that provided the energy inputs used to recycle carpet face fiber into plastic constituents (Realff, 2011b). Dr. Realff provided the life-cycle data for recycling carpet in a spreadsheet designed for incorporation into WARM (Realff, 2011c).

3.4.1 Source Reduction

Source reduction activities reduce the amount of carpet that is produced, thereby reducing GHG emissions from carpet production. Source reduction of carpet can be achieved through using less carpeting material per square foot (i.e., thinner carpet) or by finding a way to make existing carpet last longer through cleaning or repair. For more information on this practice, see the Source Reduction chapter.

Exhibit 3-7 outlines the GHG emission factor for source reducing carpet. GHG benefits of source reduction are calculated as the avoided emissions from raw materials acquisition and manufacturing (RMAM) of new carpet.

Exhibit 3-7: Source Reduction Emission Factor for Carpet (MTCO$_2$E/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Carpet	(3.68)	(3.68)	NA	NA	(3.68)	(3.68)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
Information on the share of recycled inputs used in production is unavailable or is not a common practice; EPA assumed that the current mix is comprised of 100% virgin inputs. Consequently, the source reduction benefits of both the "current mix of inputs" and "100% virgin inputs" are the same.
NA = Not applicable.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end-of-life. Source reducing carpet does not involve post-consumer emissions because production of the material is avoided in the first place. Forest products are not used in the production of carpet; therefore, forest carbon storage is not applicable to carpet and thus does not contribute to the source reduction emission factor.

3.4.1.1 Developing the Emission Factor for Source Reduction of Carpet

To calculate the avoided GHG emissions for carpet, EPA looked at three components of GHG emissions from RMAM activities: process energy, transportation energy, and process non-energy GHG emissions. Exhibit 3-8 shows the results for each component and the total GHG emission factor for source reduction. More information on each component making up the final emission factor is provided in the remainder of this section.

Exhibit 3-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Carpet ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Carpet	3.08	0.10	0.50	3.68

FAL (2002) reports the amount of energy required to produce one short ton of carpet as 60.32 million Btu. FAL (2002) also provided the fuel mix that makes up this energy estimate. To estimate GHG emissions, EPA multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. Summing the resulting GHG emissions by fuel type, gives the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in carpet manufacture (Exhibit 3-9).

Exhibit 3-9: Process Energy GHG Emissions Calculations for Virgin Production of Carpet

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Carpet	60.32	3.08

Transportation energy emissions come from fossil fuels used to transport carpet raw materials and intermediate products. The methodology for estimating these emissions is the same as that for process energy emissions. Based upon estimated total carpet transportation energy in Btu, EPA calculated the total emissions using fuel-specific carbon coefficients (Exhibit 3-10).

Exhibit 3-10: Transportation Energy Emissions Calculations for Virgin Production of Carpet

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Carpet	1.36	0.10

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

Process non-energy GHG emissions occur during manufacture but are not related to combusting fuel for energy. For carpet, non-energy GHGs are emitted in the use of solvents or chemical treatments. FAL provided data on GHG emissions from non-energy-related processes in units of pounds of native gas (2002). EPA converted pounds of gas per 1,000 lbs of carpet to metric tons of gas per short ton of carpet, and then multiplied that by the ratio of carbon to gas to produce the emission factor in $MTCO_2E$ per short ton of carpet, as detailed in the example below, showing the calculation of CH_4 process non-energy emissions for carpet. Exhibit 3-11 shows the components for estimating process non-energy GHG emissions for carpet.

$$2.72 \text{ lbs } CH_4/1{,}000 \text{ lbs carpet} \times 2{,}000 \text{ lbs carpet}/1 \text{ short ton carpet} \times 1 \text{ metric ton } CH_4/2{,}205 \text{ lbs } CH_4 = 0.0025 \text{ MT } CH_4/\text{short ton carpet}$$

$$0.0025 \text{ MT } CH_4/\text{short ton carpet} \times 25 \text{ MTCO2E/metric ton } CH_4 = 0.06 \text{ } MTCO_2E/\text{short ton carpet}$$

Exhibit 3-11: Process Non-Energy Emissions Calculations for Virgin Production of Carpet

Material	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)
Carpet	0.01	0.00	–	–	0.00	0.50

– = Zero emissions.

3.4.2 Recycling

This section describes the development of the recycling emission factor, which is shown in the final column of Exhibit 3-12. For more information on recycling in general, please see the Recycling chapter. As mentioned previously, updated life-cycle data for recycling carpet were available from Dr. Matthew Realff of Georgia Tech. His findings were informed by the 2009 Carpet America Recovery Effort (CARE) 2009 annual report, which provided a breakdown of the components of carpet face fiber polymers in conjunction with the collaboration with the carpet industry to collect data that provided the energy inputs used to recycle carpet face fiber plastic constituents.

Exhibit 3-12: Recycling Emission Factor for Carpet (MTCO$_2$E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Sequestration	Net Emissions (Post-Consumer)
Carpet	–	–	(1.43)	(0.01)	(0.94)	–	(2.38)

[a] Includes emissions from the virgin production of secondary materials.

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

NA = Not applicable.

In WARM, EPA models open-loop recycling of carpet into a mixture of following plastic resins: Nylon 6, Nylon 6-6, PET, and PP. The resulting plastic resins produced from the open-loop recycling process will then be converted into a number of products including new carpet fiber, molded or extruded plastics, and plastic pellets. The additional energy and resultant GHG emissions from the conversion of the recycled plastic resins into these final secondary products were not available. Therefore, the recycling benefits for carpet are limited to the avoided energy and GHG emissions associated with virgin plastic resin manufacture.

The recycled input credits shown in Exhibit 3-12 include all the GHG emissions associated with collecting, transporting, processing, and recycling or remanufacturing carpet into secondary materials. None of the upstream GHG emissions from manufacturing the carpet in the first place are included; instead, WARM calculates a “recycled input credit” by assuming that the recycled material avoids (or offsets) the GHG emissions associated with producing the same amount of secondary resins from virgin inputs. The eventual secondary products those resins are then used to manufacture are not factored into WARM’s calculations. Consequently, GHG emissions associated with management (i.e., collection, transportation, and processing) of end-of-life carpet are included in the recycling credit calculation. Because carpet does not contain any wood products, there are no recycling benefits associated with forest carbon storage. The GHG benefits from the recycled input credits are discussed further below.

EPA calculated the GHG benefits of recycling carpet by comparing the difference between the emissions associated with manufacturing a short ton of each of the four resins derived from recycled carpet and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. WARM assumes that both recycled Nylon 6-6 fiber and Nylon 6-6 pellets displace the virgin production of Nylon 6-6 resin. These results are then weighted by the distribution shown in Exhibit 3-13 to obtain a composite emission factor for recycling one short ton of carpet. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy.

Exhibit 3-13: Secondary Resins Produced from Recycled Carpet Fibers

Material	Percent of Recovered Carpet Face Fiber
Nylon 6 Fiber	54.02%
Nylon 6-6 Fiber	6.72%
Nylon 6-6 Pellet	23.07%
PET Fiber	7.71%
PP Fiber	8.62%

Source: Realff, 2011b.

To calculate each component of the recycling emission factor, EPA followed five steps, which are described in detail below.

Step 1. *Calculate emissions from virgin production of one short ton of secondary resin.*

EPA applied fuel-specific carbon coefficients to the life-cycle data for virgin RMAM of each secondary resin (FAL, 2010; Plastics Europe, 2005). The life-cycle data for virgin production of Nylon 6 and Nylon 6-6 were unavailable for production of these resins in the United States. Thus, life-cycle data for the production of these resins in the European context were used as a proxy (Plastics Europe, 2005). Life-cycle data for the production of PET and PP resins are the same as used in the development of the PET and PP emission factors in WARM (FAL, 2011). The upstream life-cycle data also incorporated transportation and process non-energy data. The calculations for virgin process, transportation, and process non-energy emissions for the secondary resins are presented in Exhibit 3-14, Exhibit 3-15, and Exhibit 3-16, respectively.

Exhibit 3-14: Process Energy GHG Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Energy Emissions (MTCO$_2$E/Short Ton Carpet)
Nylon 6	112.16	6.70
Nylon 6-6	122.40	7.55
PET	28.06	1.72
PP	23.52	1.15

Exhibit 3-15: Transportation Energy Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Emissions (MTCO$_2$E/Short Ton Carpet)
Nylon 6	1.05	0.07
Nylon 6-6	0.82	0.05
PET	1.00	0.07
PP	2.36	0.14

Exhibit 3-16: Process Non-Energy Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material	CO$_2$ Emissions (MT/Short Ton Carpet)	CH$_4$ Emissions (MT/Short Ton Carpet)	CF$_4$ Emissions (MT/Short Ton Carpet)	C$_2$F$_6$ Emissions (MT/Short Ton Carpet)	N$_2$O Emissions (MT/Short Ton Carpet)	Non-Energy Carbon Emissions (MTCO$_2$E/Short Ton)
Nylon 6	1.04	0.00	–	–	0.01	3.43
Nylon 6-6	0.84	0.00	–	–	0.00	1.08
PET	0.27	0.00	–	–	–	0.39
PP	0.07	0.01	–	–	0.00	0.21

– = Zero emissions.

Step 2. *Calculate emissions from recycled production of one short ton of the secondary resin.*

EPA then applied the same carbon coefficients to the energy data for the production of the secondary resin production from recycled carpet. Personal correspondence with Dr. Matthew Realff (2011a) indicated that no non-energy process emissions occur in recycled production of secondary resins from carpet. The same amount of energy is required to remix HMA from recycled asphalt concrete as is required to produce HMA from virgin materials (Levis, 2008). Therefore, the analysis used data on virgin HMA production from the Canadian Program for Energy Conservation as described in the source reduction section (Natural Resources Canada, 2005)

Exhibit 3-17 and Exhibit 3-18 present the emission calculation components for recycled secondary product process energy emissions and transportation energy emissions, respectively.

Exhibit 3-17: Process Energy GHG Emissions Calculations for Recycled Production of Carpet Secondary Resins

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO$_2$E/Short Ton)
Nylon 6 Fiber	74.24	3.99
Nylon 6-6 Fiber	3.13	0.15
Nylon 6-6 Pellet	13.39	0.66
PET Fiber	1.24	0.06
PP Fiber	10.55	0.53

Exhibit 3-18: Transportation Energy GHG Emissions Calculations for Recycled Production of Carpet Secondary Resins

Material	Transportation Energy per Short Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO$_2$E/Short Ton)
Nylon 6 Fiber	0.97	0.07
Nylon 6-6 Fiber	2.83	0.21
Nylon 6-6 Pellet	4.16	0.00
PET Fiber	3.61	0.00
PP Fiber	0.95	0.00

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

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

To calculate the GHG reductions associated with replacing virgin production with recycled production of secondary products, EPA then subtracted the emissions from recycled production (Step 2) from the emissions from virgin production (Step 1). These results are shown in Exhibit 3-19.

Exhibit 3-19: Differences in Emissions between Recycled and Virgin Carpet Manufacture (MTCO$_2$E/Short Ton)

Material/ Product	Product Manufacture Using 100% Virgin Inputs (MTCO$_2$E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO$_2$E/Short Ton)			Difference Between Virgin and Recycled Manufacture (MTCO$_2$E/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Nylon 6 Fiber	6.70	0.07	3.43	3.99	0.07	–	(2.71)	(0.01)	(3.43)
Nylon 6-6 Fiber	7.55	0.05	1.08	0.15	0.21	–	(7.40)	0.16	(1.08)
Nylon 6-6 Pellet	7.55	0.05	1.08	0.66	0.00	–	(6.89)	(0.05)	(1.08)
PET Fiber	1.72	0.07	0.39	0.06	0.00	–	(1.66)	(0.07)	(0.39)
PP Fiber	1.15	0.14	0.21	0.53	0.00	–	(0.64)	(0.14)	(0.21)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions

Step 4. *Adjust the emissions differences to account for recycling losses.*

For almost every material that gets recycled, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the manufacturing stage. Consequently, less than one ton of new material is typically made from one ton of recovered materials. Material losses are quantified and translated into loss rates. Exhibit 3-20 shows the relative amounts of each plastic resin recovered from a given ton of recycled carpet and their end uses. Associated with each of these end uses are different recycling routes. For example, Nylon 6 face fiber is recycled mostly through depolymerization, whereas Nylon 6-6 face fiber is recycled mainly through shaving the fiber followed by remelting and extrusion.

The distribution of end uses for carpet material is shown in Exhibit 3-20 and illustrates the total amount of plastic resins recovered and ultimately remanufactured per 1000 kg of recycled carpet. Note that the recovery and remanufacture of plastic resins per 1000 kg of incoming carpet material is less than 50 percent by mass indicating a high loss rate for recycling carpet. Furthermore, due to the lack of data, EPA did not factor in the recovery of plastic pellets and molded plastics made from recovered PP resin. Exhibit 3-21 shows the recovery rates for each plastic resin recovered from carpet face fiber. The recovery rates add up to less than 100 percent due to the low overall recovery rate outlined in Exhibit 3-20.

Exhibit 3-20: End Uses for Recycled Carpet based on 1000 kg of Incoming Carpet Material

	Per 1000 kg Recycled Carpet				
Material	**Nylon 6 (kg)**	**Nylon 6-6 (kg)**	**PET (kg)**	**PP (kg)**	**Total Recovery in WARM (kg)**
New Carpet	207.5	25.8	–	–-	233.3
Plastic Pellets	–	88.6	–	82.5*	88.6
Molded or Extruded Plastics	–	–	–	25.9*	0.00
Carpet Padding	–	–	29.6	33.1	62.7
Total Polymer Weight	**207.5**	**114.4**	**29.6**	**141.5**	**384.6**

Note: The recycled flows indicated by an asterisk (*) are not accounted in the recycling pathway in WARM because the life-cycle data associated with recovering these flows in the recycling process were not available.
Source: Realff, 2011b.

Each product's process energy, transportation energy, and process non-energy emissions are weighted by the percentages in Exhibit 3-21 and then they are summed as shown in the final column of Exhibit 3-22.

Exhibit 3-21: Calculation of Adjusted GHG Savings for Carpet Recycled into Secondary Products

Material	**Rate of Recovery per Short Ton Carpet Collected**
Nylon 6 Fiber	20.7%
Nylon 6-6 Fiber	2.58%
Nylon 6-6 Pellet	8.85%
PET Fiber	2.96%
PP Fiber	3.31%

Source: The WARM Model – Analysis and Suggested Action (Realff, 2011b).

Step 5. *Weight the results by the percentage of recycled carpet that the secondary products comprise.*

Exhibit 3-22: Carpet Recycling Emission Factors ($MTCO_2E$/Short Ton)

Material	Recycled Input Credit for Recycling One Short Ton of Carpet			
	Weighted Process Energy ($MTCO_2E$/Short Ton Product)	Weighted Transport Energy ($MTCO_2E$/Short Ton Product)	Weighted Process Non-Energy ($MTCO_2E$/Short Ton Product)	Total ($MTCO_2E$/Short Ton Product)
Nylon 6 Fiber	(0.56)	(0.00)	(0.80)	(1.36)
Nylon 6-6 Fiber	(0.19)	0.00	(0.03)	(0.22)
Nylon 6-6 Pellet	(0.61)	(0.01)	(0.10)	(0.71)
PET Fiber	(0.05)	(0.00)	(0.01)	(0.06)
PP Fiber	(0.02)	(0.00)	(0.01)	(0.03)
Carpet Total	**(1.43)**	**(0.01)**	**(0.94)**	**(2.38)**

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

3.4.3 Composting

Carpet is not subject to aerobic bacterial degradation and therefore cannot be composted. As a result, WARM does not consider GHG emissions or storage associated with composting carpet.

3.4.4 Combustion

Combustion results in both direct and indirect emissions: direct emissions from the combustion process itself and indirect emissions associated with transportation to the combustor. To the extent that carpet combusted at waste-to-energy (WTE) facilities produces electricity, combustion offsets GHG emissions that would have otherwise been produced from non-baseload power plants feeding into the national electricity grid. These components make up the combustion factor calculated for carpet. The tables presented here are based on the national average grid mix, rather than on any of the regional grid mixes also available in the Excel version of WARM.

For further information on combustion, see the Combustion chapter. Because WARM's analysis begins with materials at end-of-life, emissions from RMAM are zero. Exhibit 3-23 shows the components of the emission factor for combustion of carpet. Further discussion on the development of each piece of the emission factor is discussed below.

Exhibit 3-23: Components of the Combustion Net Emission Factor for Carpet ($MTCO_2E$/Short Ton)

Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery Offsets	Net Emissions (Post-Consumer)
–	0.01	1.67	–	(0.58)	–	1.10

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

3.4.4.1 Developing the Emission Factor for Combustion of Carpet

EPA estimated that carpet has a weighted carbon content of 51 percent and that 98 percent of that carbon is converted to CO_2 during combustion. These estimates are based on the carbon that is contained within the various plastics and the limestone in carpet. These carbon contents and resulting direct CO_2 emissions from combustion of carbon in carpet are presented in Exhibit 3-24.

Exhibit 3-24: Carpet Combustion Emission Factor Calculation

Components	% of Total Weight	Carbon Content	Carbon Content % of Total Weight	Carbon Converted to CO_2 during Combustion	Total $MTCO_2E$/Short Ton
Styrene-butadiene (latex)	10%	90%	9%	98%	0.29
Limestone	37%	12%	4%	98%	0.13

Components	% of Total Weight	Carbon Content	Carbon Content % of Total Weight	Carbon Converted to CO_2 during Combustion	Total $MTCO_2E$/Short Ton
Backing Fiber (PP)	11%	86%	9%	98%	0.29
Face Fibers:					
Nylon 6 and Nylon 6-6	28%	64%	18%	98%	0.59
PP	8%	86%	7%	98%	0.23
PET	6%	63%	4%	98%	0.13
Carpet (Sum)	**NA**	**NA**	**51%**	**98%**	**1.67**

Sources: Styrene-butadiene carbon content calculated from chemical formula; limestone carbon content (Kantamaneni, 2002); polypropylene and nylon carbon contents (EPA, 2001, Ch. 7). Face fiber plastic component distribution from personal communication with Matthew Realff (Realff 2011a).
Totals may not sum due to independent rounding.
NA = Not applicable.

EPA estimated CO_2 emissions from transporting carpet to the WTE plant and transporting ash from the WTE plant to the landfill using data provided by FAL (2002). Transportation-related CO_2 emissions were estimated to be 0.03 $MTCO_2E$ per short ton of carpet combusted.

Most utility power plants use fossil fuels to produce electricity, and the electricity produced at a WTE plant reduces the demand for fossil-derived electricity. As a result, the combustion emission factor for carpet includes avoided GHG emissions from utilities. EPA calculated the avoided utility CO_2 emissions based on the energy content of carpet, the combustion efficiency of the WTE plant including transmission and distribution losses, and the national average carbon-intensity of electricity produced by non-baseload power plants. EPA utilized the energy content from recent analysis, which presents the energy content that is more representative of the current carpet composition (Realff, 2010b). Exhibit 3-25 shows the estimated utility offset from combustion of carpet.

Exhibit 3-25: Utility GHG Emissions Offset from Combustion of Carpet

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
Carpet	15.2*	17.8%	0.21	0.58

* Calculated from the "Carpet 1" architecture in Table 2 of Realff 2010b using the heat of combustion (20% solid) value.

3.4.5 Landfilling

Typically, the emission factor for landfilling is composed of four parts: landfill CH_4; CO_2 emissions from transportation and landfill equipment; landfill carbon storage; and avoided electric utility emissions. However, as with other non-biodegradable materials in WARM, there are zero landfill methane emissions, landfill carbon storage, or avoided utility emissions associated with landfilling carpet, as shown in Exhibit 3-26. GHG emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling carpet represents only the transportation emissions associated with collecting the waste and operating the landfill equipment. For more information on landfilling, refer to the Landfilling chapter.

Exhibit 3-26: Landfilling Emission Factor for Carpet ($MTCO_2E$/Short Ton)

Material	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)
Carpet	–	0.02	NA	NA	NA	0.02

NA = Not applicable.
– = Zero emissions.

3.4.6 Anaerobic Digestion

Because of the nature of carpet components, carpet cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of carpet.

3.5 LIMITATIONS

As discussed in the Recycling section (3.4.2), the open-loop recycling process is a complicated end-of-life process for carpet. There are some limitations associated with modeling the GHG emissions from open-loop carpet recycling, including limited availability of representative life-cycle inventory (LCI) data for carpet and the materials recovered from them. Therefore, the recycling factor for carpet is subject to important limitations, described below.

A primary data gap is the availability of representative LCI data for carpet in the closed-loop recycling process, and the materials recovered from them in the open-loop recycling process. For this analysis, EPA used life-cycle data to represent the recovery of various plastic resins from recycled carpet but did not incorporate the additional energy and material requirements for converting these plastic resins into secondary products. Since the WARM carpet emission factor was initially developed, manufacturers have increased their capacity to recycle carpet into different end products including new carpet, plastic pellets, molded plastics and carpet padding. According to the CARE Annual Report for 2009, 47 percent of carpet recovered for recycling is used to manufacture new carpet, 35 percent was used to manufacture plastic pellets, 13 percent was used to manufacture carpet padding, and five percent was used to manufacture molded or extruded plastics (CARE, 2009). EPA is investigating the availability of data necessary to develop a more representative open-loop recycling emission factor for carpet, including updated LCI data on the conversion of plastic resins into final secondary products for carpet. This additional information could affect the results for the recycling benefits associated with carpet.

The open-loop recycling pathways for each carpet type vary significantly (Realff, 2010a). WARM currently assumes that the same average mix of carpet types is recycled by each of the three open-loop recycling pathways, since at the time the emission factors were created, no further information was available. However, more recent data show that some carpet types are rarely or never recycled into some open-loop products. For example, Nylon 6 carpet is exclusively recycled into new Nylon 6 carpet, PET carpet is exclusively recycled into new carpet padding, and Nylon 6-6 carpet is only recycled into new Nylon 6-6 carpet and plastic pellets (CARE, 2009).

Emissions associated with retail transport of carpet from manufacturing to point of sale were not developed in the original WARM analysis as the representative transportation mode/distance data were not available. EPA is investigating the availability of these data through the U.S. Census and will likely incorporate emissions from retail transport in the next version of the carpet emission factor in WARM.

For the source reduction pathway, the LCI data to estimate GHG emissions from the manufacture of carpet from virgin materials are slightly outdated. EPA is investigating the availability of updated life-cycle data and will revise the source reduction emission factor accordingly in WARM.

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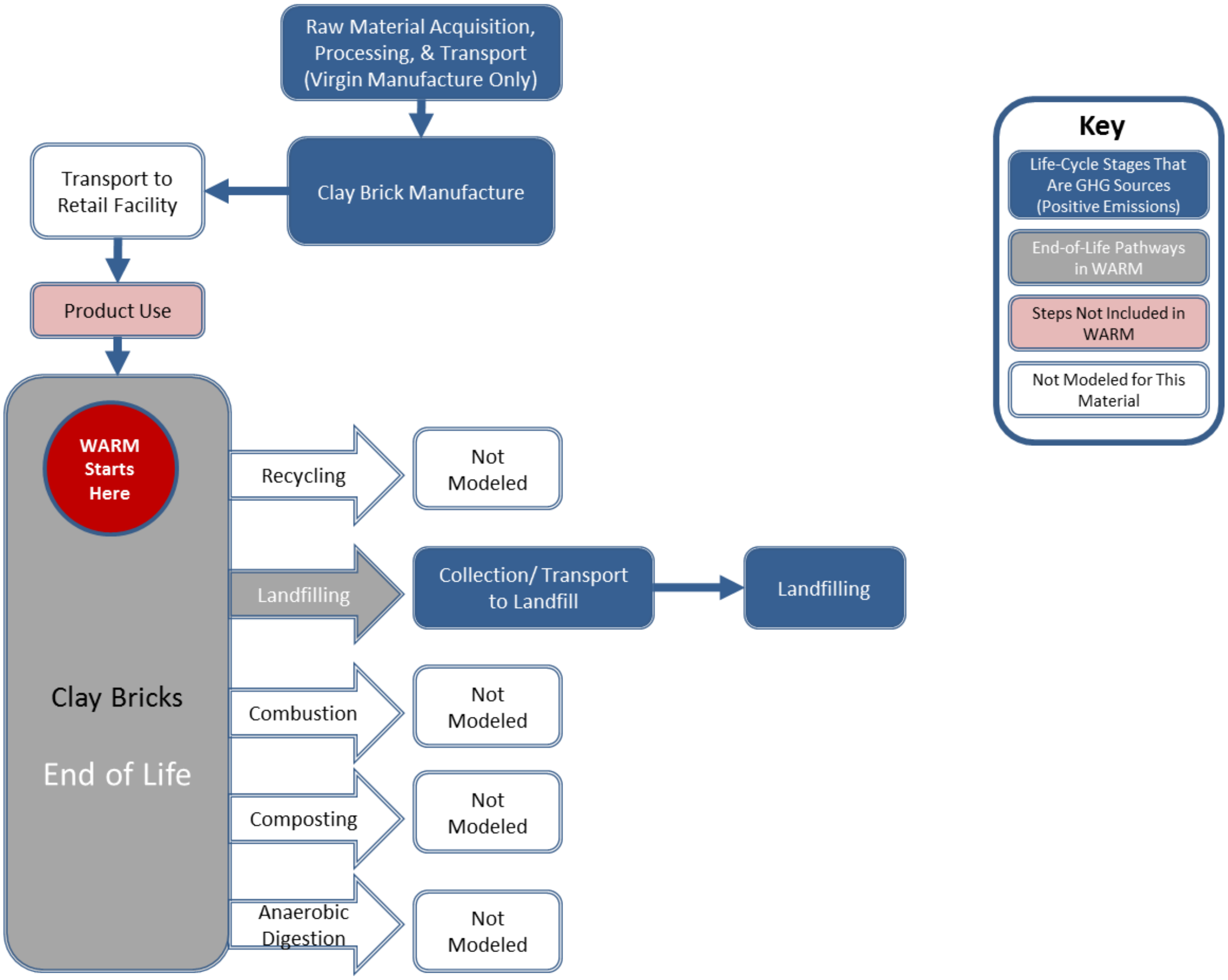
4 CLAY BRICKS

4.1 INTRODUCTION TO WARM AND CLAY BRICKS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for clay bricks beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with clay bricks in the following waste management alternatives: source reduction and landfilling. Exhibit 4-1 shows the general outline of materials management pathways for clay bricks in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction 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 4-1: Life Cycle of Clay Bricks in WARM



Most clay bricks are produced by firing common clay and shale in a kiln, although other types of clay, such as kaolin and fire clay, are also sometimes used (Virta, 2009). Of the 5.4 billion bricks produced in the U.S. in 2008, the majority were clay, accounting for 60 percent of annual production, or approximately 3.3 billion bricks (U.S. Census Bureau, 2010).

Clay bricks can be salvaged and reused, enabling source reduction of virgin clay bricks. It may also be possible to recycle broken or damaged clay bricks during the manufacturing process, although EPA did not locate sufficient data to model a recycling pathway for management of clay bricks. Because clay bricks are inert and non-combustible, they cannot be composted or incinerated for energy recovery.

4.2 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.[5] For most materials, recycling and source reduction are the two materials management options that impact their upstream production and consequently are the only pathways that include upstream GHG emissions. Since WARM does not evaluate a recycling pathway for management of clay bricks, source reduction is the only pathway that affects upstream GHG emissions from clay bricks. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

As Exhibit 4-2 illustrates, the GHG sources relevant to clay bricks in this analysis are contained in the raw materials acquisition and manufacturing portion and end of life portions of the life cycle. WARM does not evaluate recycling, composting, combustion, or anaerobic digestion as life-cycle pathways for clay bricks because recycling is not a common practice and the data on recycling of clay bricks are limited, and clay bricks cannot be combusted, composted, or anaerobically digested.

Exhibit 4-2: Clay Bricks GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Clay Bricks	GHG Sources and Sinks Relevant to Clay Bricks		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy	NA	NA
Recycling	Not applicable because clay bricks are not commonly recycled		
Composting	Not applicable because clay bricks cannot be composted		
Combustion	Not applicable because clay bricks cannot be combusted		
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because clay bricks cannot be anaerobically digested		

NA = Not applicable.

4.3 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

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[5] 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.

from manufacturing processes.[6] For clay bricks, process energy GHG emissions result from acquiring the raw clay used in manufacture and the firing process used to produce clay bricks. Transportation emissions are generated from transporting raw materials to the brick manufacturing facility. EPA assumed that non-energy process GHG emissions are negligible because no data source consulted indicated the presence of these emissions.

In general, RMAM calculations in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport a material or product from the manufacturing facility to the retail or distribution point. However, the emissions associated with retail transport of clay bricks are assumed to be zero/not modeled in WARM because no suitable data on retail transportation of clay bricks was available at the time of creating this emission factor.

4.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM evaluates GHG sources and sinks from source reduction and landfilling of clay bricks. Exhibit 4-3 provides the net GHG emissions per short ton of clay bricks for each of these materials management pathways. Source reduction avoids GHG emissions because it offsets emissions from manufacturing processes and transportation of raw materials. Landfilling results in GHG emissions from transporting clay bricks to the landfill and operation of landfill equipment. More details on the methodologies for developing these emission factors are provided in sections 4.4.1 through 4.4.5.

Exhibit 4-3: Net Emissions for Clay Bricks under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Clay Bricks	(0.27)	NA	NA	NA	0.02	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not available.

4.4.1 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 postconsumer waste are avoided. In WARM, source reduction of clay bricks involves reusing old bricks that have been salvaged at end of life. Because reused bricks may lack the strength and durability of new bricks, the reuse of bricks is not appropriate for all brick structures. This is why the U.S. Green Building Council (USGBC) recommends that reused bricks not be used in exterior structures in cold climates, as cold temperatures can exacerbate existing weaknesses in reused bricks (Webster, 2002). Clay bricks are sometimes reused in such decorative or non-structural applications as brick fireplaces, hearths, patios, etc.[7]

As discussed previously, under the measurement convention used in this analysis, source reduction for clay bricks has negative raw material and manufacturing GHG emissions (i.e., it avoids emissions attributable to production) and zero end-of-life management GHG emissions. The overall source reduction emission factors for clay bricks are shown in Exhibit 4-4.

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

[7] The qualities of reused bricks are therefore not necessarily "functionally equivalent" to those of new bricks, because they cannot be used in all the same applications. WARM does not account for this in the source reduction emission factor because the model assumes that reusing clay bricks for non-structural purposes would still offset the production of new virgin bricks.

Exhibit 4-4: Source Reduction Emission Factor for Clay Bricks ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs[a]	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Clay Bricks	(0.27)	(0.27)	NA	NA	(0.27)	(0.27)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

[a] For this material, information on the share of recycled inputs used in production is unavailable or is not a common practice; EPA assumes that the current mix is comprised of 100% virgin inputs. Consequently, the source reduction benefits of both the "current mix of inputs" and "100% virgin inputs" are the same.

NA = Not applicable.

Because EPA assumed that clay bricks were always produced from 100 percent virgin materials, the GHG emission factor for "100 percent virgin inputs" is equal to the factor for the "current mix" of virgin and recycled inputs. Post-consumer emissions are the emissions associated with materials management pathways that could occur at end-of-life. When source reducing clay bricks, there are no post-consumer emissions because production of the material is avoided in the first place. There are no changes in forest carbon storage because clay bricks contain no paper or wood and therefore do not influence forest carbon stocks. For more information on this topic, please see the chapter on Source Reduction.

4.4.1.1 Developing the Emission Factor for Source Reduction of Clay Bricks

The approach and data sources used to calculate the emission factor for source reduction of clay bricks are summarized below for each of the three categories of GHG emissions: process energy (pre-combustion and combustion), transportation energy, and process non-energy emissions.

Avoided Process Energy Emissions: Process energy GHG emissions result from both the direct combustion of fossil fuels and the upstream emissions associated with the production of fuels and electricity (i.e., "pre-combustion" energy).[8] An estimated 5.1 million Btu of total energy are required to produce one ton of clay bricks (Athena, 1998).[9] To calculate process energy emissions, EPA determined the national-average mix of fuels used to manufacture clay bricks. EPA then multiplied the amount of each fuel consumed by the fuel's GHG emissions intensity (i.e., GHG emissions per Btu of fuel) to obtain CO_2 and CH_4 emissions for each fuel (EPA, 2018). 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 clay bricks. Results of these calculations are provided in Exhibit 4-5.

Exhibit 4-5: Process Energy GHG Emissions Calculations for Virgin Production of Clay Bricks

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Clay Bricks	5.10	0.27

Avoided Transportation Energy Emissions: Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for clay brick production. The methodology for estimating these emissions is the same as the one used for process energy emissions. Total transportation energy emissions are calculated based upon an estimate of total clay brick transportation energy and the corresponding fuel mix (Athena, 1998) and using fuel-specific coefficients for CO_2 and CH_4 (EPA, 2018). The related GHG emissions are provided in Exhibit 4-6.

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[8] "Pre-combustion" emissions refer to the GHG emissions that are produced by extracting, transporting, and processing fuels that are in turn consumed in the manufacture of products and materials.

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

Exhibit 4-6: Transportation Energy Emissions Calculations for Virgin Production of Clay Bricks

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Clay Bricks	0.03	0.00

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

Avoided Process Non-Energy Emissions: No process non-energy emissions take place during the manufacture of clay bricks. Hence, there are no avoided emissions.

4.4.2 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. Research indicates that there is very little postconsumer recycling of bricks (Athena, 1998). Likewise, almost all bricks in the United States are made from virgin materials, so EPA has not analyzed the impacts of using recycled material in brick manufacture.[10]

4.4.3 Composting

Clay bricks are not subject to aerobic bacterial degradation and cannot be composted. Consequently, WARM does not include an emission factor for the composting of clay bricks.

4.4.4 Combustion

Clay bricks cannot be combusted; consequently, WARM does not include an emission factor for the combustion of clay bricks.

4.4.5 Landfilling

In general, GHG impacts from landfilling consist of landfill CH_4 emissions; CO_2 emissions from transportation and landfill equipment operation; landfill carbon storage; and avoided utility emissions that are offset by landfill gas energy recovery. However, because clay bricks do not contain carbon-based materials or degrade in landfills, they do not produce CH_4 emissions or result in carbon storage in landfills. Therefore, the landfilling emission factor only accounts for transportation emissions: transportation of clay bricks 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. This information is summarized in

Exhibit 4-7. For more information on this topic, please see the chapter on Landfilling.

Exhibit 4-7: Landfilling Emission Factor for Clay Bricks ($MTCO_2E$/Short Ton)

Material	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)
Clay Bricks	–	0.02	–	–	–	0.02

– = Zero emissions.

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[10] Athena (1998) describes the recycling of old clay bricks as feasible but not widely practiced at this time. Athena also notes that four to eight percent of the volume of raw materials used in brick production is made up of damaged, finished ware that has been recycled back into raw materials. Because these inputs reflect pre-consumer recycling, not post-consumer recycling, the energy associated with manufacturing brick with these inputs would still be considered "virgin" in our nomenclature. Based on the information provided by Athena, it appears that there is very little (if any) recycled-content brick being produced. Therefore, this analysis assumes that virgin production is the same as production using the current mix (nearly 100 percent virgin inputs).

4.4.6 Anaerobic Digestion

Because of the nature of clay bricks components, clay bricks cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of clay bricks.

4.5 LIMITATIONS

Although this analysis is based upon best available life-cycle data, uncertainties exist in the final emission factors. Certain limitations to this analysis are outlined below:

- This life-cycle analysis does not evaluate recycling as a possible pathway because of a lack of information about this infrequent practice. Data and information about recycling processes for clay bricks, energy use, and GHG emissions would be extremely helpful in analyzing and developing an emission factor for recycling as a materials management strategy.
- The source reduction emission factor could be improved through better information regarding potential reuses of clay bricks.
- Retail transport emissions for clay bricks are not currently included in the RMAM emissions factor. They could be added in the future if a suitable proxy were found.
- The data used to develop the emission factors are more than a decade old. The emission factors have the potential for improvement if EPA were to find more recent life-cycle data for clay bricks.

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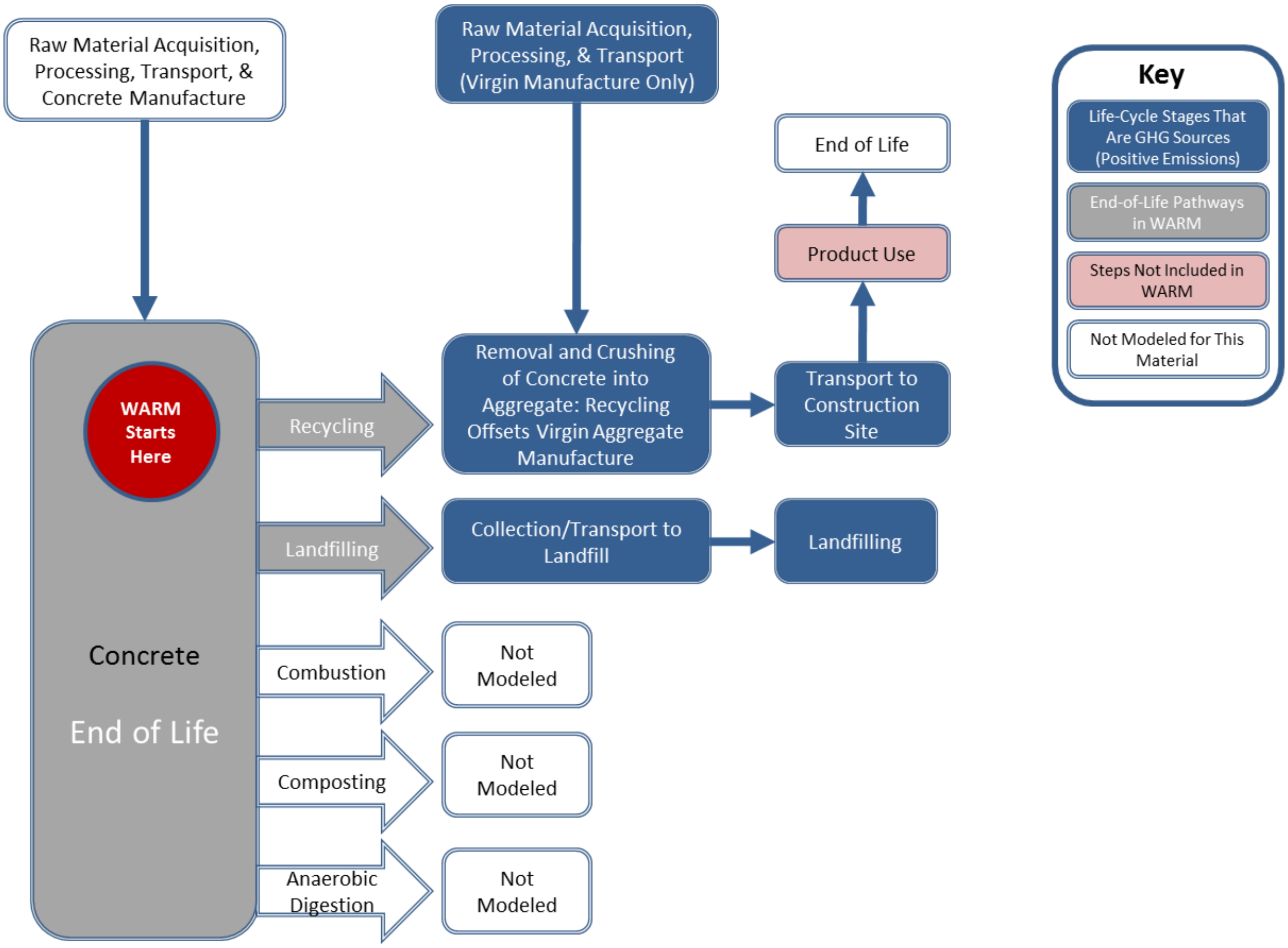
5 CONCRETE

5.1 INTRODUCTION TO WARM AND CONCRETE

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for concrete beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with concrete in the following two waste management alternatives: recycling and landfilling. Exhibit 5-1 shows the general outline of materials management pathways for concrete in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & 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 5-1: Life-cycle of Concrete in WARM



Concrete is a high-volume, low-cost building material produced by mixing cement, water, and coarse and fine aggregates. Its use is nearly universal in modern construction, as it is an essential component of roads, foundations, high-rises, dams, and other staples of the developed landscape.

Approximately 578 million tons of concrete[11] were produced in 2011 and approximately 200 million tons of waste concrete are generated annually from construction and demolition (C&D) and public works projects (Turley, 2002; Wilburn and Goonan, 1998). According to Turley (2002) and Wilburn and Goonan (1998), an estimated 50 to 60 percent of waste concrete is recycled, while the remainder is landfilled.

5.2 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.[12]

As Exhibit 5-2 illustrates, most of the GHG sources relevant to concrete in this analysis are contained in the raw materials acquisition and manufacturing and end of life sections of the life cycle assessment. WARM does not consider source reduction, composting, combustion, or anaerobic digestion as life-cycle pathways for concrete. Of note, the recycling emission factor represents the GHG impacts of manufacturing concrete using recycled concrete in place of the virgin aggregate component. The landfilling emission factor reflects the GHG impacts of disposing of concrete in a landfill. Because concrete does not generate methane in a landfill, the emission factor is the emissions from transporting the concrete to the landfill and operating the landfill equipment.

Exhibit 5-2: Concrete GHG Sources and Sinks from Relevant Materials Management Pathways

MSW Management Strategies for Concrete	GHG Sources and Sinks Relevant to Concrete		
	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		
Recycling	**Offsets** • Transport of raw materials and products • Virgin aggregate mining and production process energy	NA	**Emissions** • Collection and transportation to processing facility • Sorting and processing energy
Composting	Not applicable because concrete cannot be composted		
Combustion	Not applicable because concrete cannot be combusted		
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because concrete cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all the GHG sources and sinks outlined in Exhibit 5-2 and calculates net GHG emissions per short ton of concrete inputs for each materials management alternative (see Exhibit 5-3). For additional discussion on the detailed methodology used to develop these emission factors, please see sections 5.3 and 5.4 on individual waste management strategies.

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[11] The total consumption of cement in 2011 was 72,200,000 tons (USGS, 2013). It was assumed that 100 percent of this cement was used to make concrete and the concrete contained 12.5 percent cement by weight (Collins, 2002), resulting in a calculated concrete production of about 578 million tons.

[12] 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 5-3: Net Emissions for Concrete under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Concrete	NA	(0.01)	NA	NA	0.02	NA

NA = Not applicable.

[a] The current mix of inputs for carpet is considered to be 100% virgin material.

5.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

In general, 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.[13] For the recycling emission factor, WARM compares the impact of producing aggregate from recycled concrete to the impact of producing virgin aggregate. In WARM, concrete is considered to be essentially a byproduct of the demolition of buildings and other concrete structures. Because the structures were created for themselves, and not for the purpose of being turned into aggregate, WARM considers that there are no manufacturing or combustion emissions associated with concrete before end of life. Hence, no RMAM emissions are considered in the life-cycle analysis of concrete in WARM. However, EPA noted that the production of concrete is a greenhouse-gas- and energy-intensive process.

5.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM analyzes all the GHG sources and sinks outlined in Exhibit 5-2 and calculates net GHG emissions per short ton of concrete. This analysis considers recycling and landfilling as possible materials management options for concrete. Recycling of concrete leads to reductions in GHG emissions because it avoids manufacture of virgin aggregate. Landfilling has a slightly positive emission factor due to the emissions from landfill operation equipment.

5.4.1 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 postconsumer waste are avoided. Although concrete may be reused or used in ways that could reduce the overall demand for new concrete structures, the benefits of this type of activity have not yet been quantified. Therefore, WARM does not include an emission factor for source reduction.

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

5.4.2 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. The Construction Materials Recycling Association (CMRA) indicates that approximately 140 million tons of concrete are recycled annually in the United States (CMRA, 2010). WARM investigates the GHG impacts associated with reusing crushed concrete in place of virgin aggregate, an open-loop recycling process.[14] Virgin aggregates, which include crushed

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

[14] Concrete may be recycled in a “closed-loop” by being crushed and reused as aggregate in new concrete. The recycling process is believed to rehydrate some cement in the used concrete, thus reducing the need for cement in

stone, gravel, and sand, are used in a wide variety of construction applications, such as road base and fill, and as an ingredient in concrete and asphalt pavement. When structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate, reducing the GHG emissions associated with producing concrete using virgin aggregate material. Therefore, the GHG benefit of using recycled concrete results from the avoided emissions associated with mining and processing aggregate that concrete is replacing.[15]

More than two billion tons of aggregates are consumed each year in the United States, with an estimated five percent coming from recycled sources such as asphalt pavement and concrete (USGS, 2000). The U.S. Geological Survey (USGS) estimates that, of the concrete recycled in 1997, at least 83 percent was used in applications that typically employ virgin aggregate: 68 percent of all recycled product was used as road base, nine percent in asphalt hot mixes, and six percent in new concrete mixes. Non-aggregate uses of recycled concrete included seven percent as general fill, three percent as high-value riprap, and seven percent as other (USGS, 2000). As tipping fees at landfills increase in many urban areas and recycling techniques continue to improve, concrete recycling is expected to become even more popular.

The calculation of the concrete emission factor involves estimating the emissions associated with production and transportation of one ton of virgin input (aggregate) versus one ton of recycled input (i.e., crushed concrete) individually, and then determining the difference in emissions between recycled and virgin production. The GHG emissions associated with these steps result from the consumption of fossil fuels used in the production and transport of aggregate (combustion energy), as well as the upstream energy (pre-combustion energy) required to obtain these fuels. The concrete recycling emission factor is made up of two components: process energy and transportation energy. No process non-energy emissions occur. Exhibit 5-4 presents a summary of these components. The following sections contain descriptions of how each component is calculated.

Exhibit 5-4: Recycling Emission Factor for Concrete ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Concrete	–	–	(0.00)	(0.01)	–	–	(0.01)

NA = Not applicable.
– = Zero emissions.
[a] Includes emissions from the initial production of the material being managed.

5.4.2.1 *Developing the Emission Factor for Recycling Concrete*

EPA calculated the benefits of recycling by comparing the difference between the emissions associated with producing one short ton of recycled concrete aggregate and the emissions from producing one short ton of virgin aggregate. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy. Because process non-energy

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the new concrete, resulting in additional GHG benefits. However, sufficient data to quantify this additional benefit are not available at this point.

[15] There is evidence that recycled concrete would also have the benefit of increased carbon storage. Studies have shown that, over time, the cement portion of concrete can absorb CO_2. Factors such as age, cement content, and the amount of exposed surface area affect the rate of carbon absorption. While it is likely that the increase in surface area due to crushing would increase the rate of CO_2 absorption, insufficient data exist at this time to quantify this benefit (Gadja, 2001).

emissions for production of both virgin aggregate and recycled concrete are considered to be zero, this component is not considered in the discussion below.

To calculate the benefit of recycling concrete to displace virgin aggregate, EPA followed three steps, described here in detail.

Step 1. *Calculate emissions from virgin production of aggregate.* GHG emissions from the combustion of fossil fuels are attributed to both process energy (required to extract and process raw materials such as coarse aggregate and sand) and transportation energy (required to transport virgin aggregate to the job site where it is used.) Emissions associated with transporting the virgin or recycled materials to the consumer, in the case of aggregates, were a driving factor in the GHG impacts of end-of-life concrete management options. EPA estimated the total energy required to produce one short ton of aggregate as 0.0429 million Btu.[16] WARM applied fuel-specific carbon content and fugitive CH_4 emissions coefficients to the energy data for production of (one ton of) virgin aggregate, in order to obtain total process energy GHG emissions, including CO_2 and CH_4. This estimate was then summed with the emissions from transportation energy to calculate the total emissions from virgin production of aggregate. Both process and transportation energy estimates for virgin aggregate production were calculated from data in U.S. Census Bureau (1997), as detailed in EPA (2003).

Step 2. *Calculate GHG emissions from production of recycled aggregate (i.e., crushed concrete).* Recycling of concrete involves crushing, sizing, and blending to provide suitable aggregates for various purposes. Concrete may also contain metals (such as rebar) and waste materials that need to be removed. As above, WARM calculates emissions from both process and transportation energy by applying fuel-specific carbon and fugitive CH_4 emissions coefficients to energy data for recycled aggregate production and transportation. Both process and transportation energy estimates for recycled aggregate production were taken from Wilburn and Goonan (1998).

Exhibit 5-5 and Exhibit 5-6 present the process and transportation energy and associated emissions for virgin and recycled manufacture of aggregate.

Exhibit 5-5: Process Energy GHG Emission Calculations for Concrete

Material	Process Energy per Short Ton Aggregate (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Virgin Aggregate	0.05	0.00
Recycled Aggregate (Crushed Concrete)	0.04	0.00

Source: Wilburn and Goonan (1998).

Exhibit 5-6: Transportation Energy GHG Emission Calculations for Concrete

Material	Transportation Energy per Short Ton Aggregate (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Virgin Aggregate	0.19	0.01
Recycled Aggregate (Crushed Concrete)	0.09	0.01

Note: The transportation energy and emissions in this exhibit do not include retail transportation.

Step 3. *Calculate the difference in emissions between virgin and recycled aggregate production.* EPA then subtracted the recycled product emissions (Step 2) from the virgin product emissions (Step 1) to get the GHG savings for using recycled concrete in place of virgin aggregate. These results are shown in Exhibit 5-7.

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[16] This total represents the sum of pre-combustion and combustion process energy. Please refer to Appendix B of *Background Document for Life-Cycle Greenhouse Gas Emission Factors Clay Brick Reuse and Concrete Recycling* (EPA, 2003) for more details on how the total energy per ton of aggregate was calculated.

Exhibit 5-7: Differences in Emissions between Recycled and Virgin Concrete Manufacture (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Total (d = b + c)
Recycled Aggregate (Crushed Concrete)	0.00	0.01	0.01
Virgin Aggregate	0.00	0.01	0.02
Total (Recycled - Virgin)	0.00	(0.01)	(0.01)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

Because no material losses occur during the recovery and manufacturing stages of recycling concrete, the recycling factor obtained above does not need to be adjusted for loss rates. For more information on this topic, please see the chapter on Recycling. For more information about all of these calculations, please refer to the *Background Document for Life-Cycle Greenhouse Gas Emission Factors Clay Brick Reuse and Concrete Recycling* (EPA, 2003).

5.4.3 Composting

Concrete is not subject to aerobic bacterial degradation and cannot be composted. Consequently, WARM does not include an emission factor for the composting of concrete.

5.4.4 Combustion

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

5.4.5 Landfilling

In general, GHG emissions from landfilling consist of landfill CH$_4$; CO$_2$ emissions from transportation and landfill equipment operation; landfill carbon storage; and avoided utility emissions that are offset by landfill gas energy recovery. However, because concrete is not subject to aerobic bacterial degradation and does not degrade in landfills, it does not produce any CH$_4$ emissions associated with landfilling concrete. Studies have indicated that, over time, the cement portion of concrete is capable of absorbing CO$_2$ (Gadja, 2001). The amount of carbon stored is affected by age, cement content, and the amount of exposed surface area. While this effect would represent landfill carbon storage when concrete is deposited in a landfill, the results of this with respect to the emission factor are difficult to quantify and are considered to be beyond the scope of WARM. Therefore, WARM only counts transportation emissions: transportation of concrete 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 and move the wastes. This information is summarized in Exhibit 5-8. For more information on this topic, please see the chapter on Landfilling.

Exhibit 5-8: Landfilling Emission Factor for Concrete (MTCO$_2$E/Short Ton)

Material	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)
Concrete	–	0.02	–	–	–	0.02

– = Zero emissions.

5.4.6 Anaerobic Digestion

Because of the nature of concrete components, concrete cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of concrete.

5.5 LIMITATIONS

Although this analysis is based upon the best available life-cycle data, uncertainties do exist in the final emission factors. This life cycle assessment has the following limitations:

- Landfill carbon storage by the cement component of concrete deposited in a landfill is difficult to quantify and considered to be beyond the scope of WARM. Better data and more information on this storage process could help improve the landfill emission factor.
- Current there is a lack of sufficient data to quantify the GHG benefits of “closed-loop” recycling of concrete. Concrete may be recycled and reused as aggregate in new concrete such that it rehydrates some cement in the used concrete, thus reducing the need for cement in the new concrete, and resulting in additional GHG benefits. More information related to a decrease in need for virgin cement due to this kind of recycling could help improve the recycling emission factor.

If updated information could be obtained to address these limitations, the life-cycle emission factor for concrete could be further refined. EPA is continuing 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 concrete will vary, depending on individual circumstances.

5.6 REFERENCES

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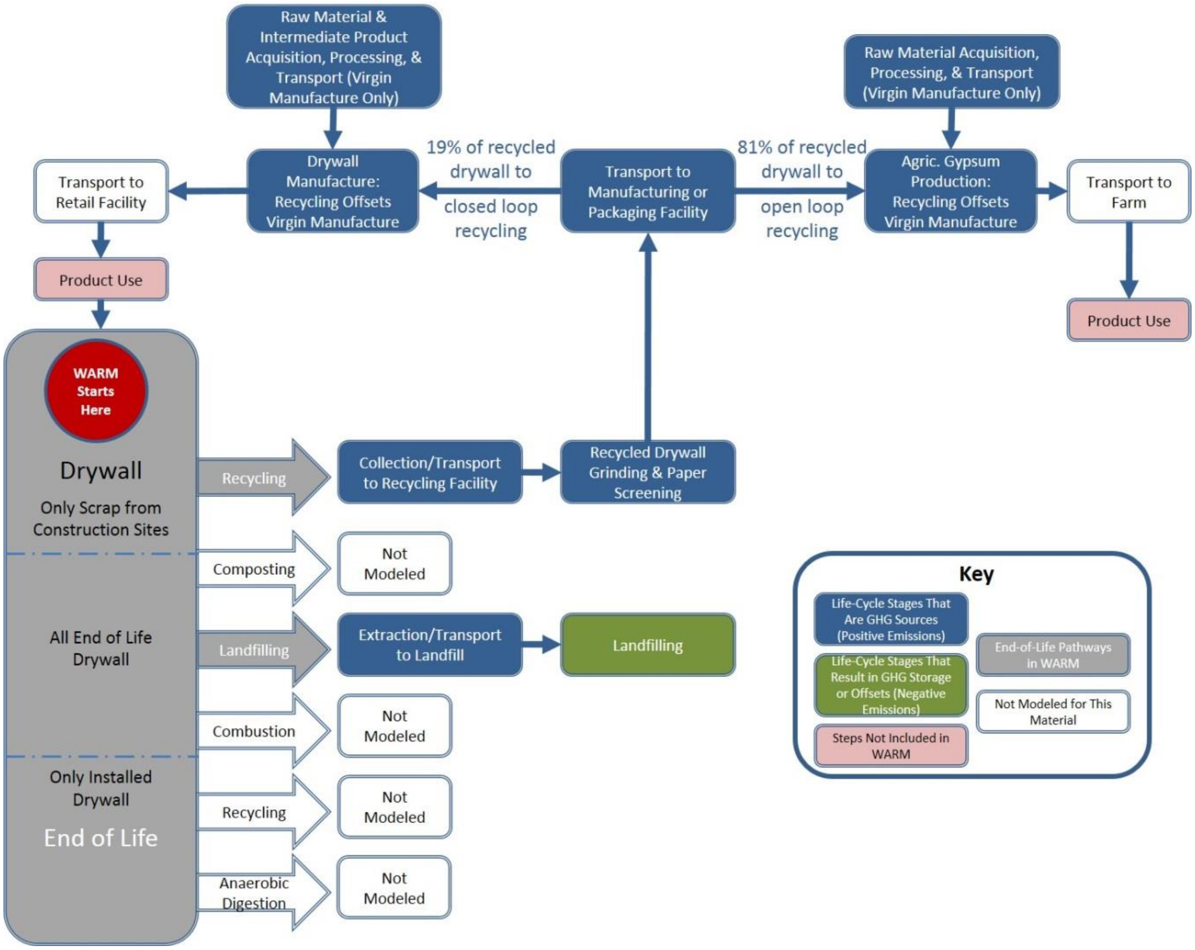
6 DRYWALL

6.1 INTRODUCTION TO WARM AND DRYWALL

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for drywall beginning at the waste generation reference point.[17] The WARM GHG emission factors are used to compare the net emissions associated with drywall in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 6-1 shows the general outline of materials management pathways for drywall in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, and Landfilling, see the chapters devoted to those 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 6-1: Life Cycle of Drywall in WARM



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[17] EPA would like to thank Rik Master of USG Corporation for his efforts to improve these estimates.

Drywall, also known as wallboard, gypsum board, or plaster board, is manufactured from gypsum plaster and a paper covering. Exhibit 6-2 presents the sources of drywall entering the waste stream.

Exhibit 6-2: Composition of the Drywall Waste Stream

Source of Waste Drywall	% of Total
New Construction	64%
Demolition	14%
Manufacturing	12%
Renovation	10%

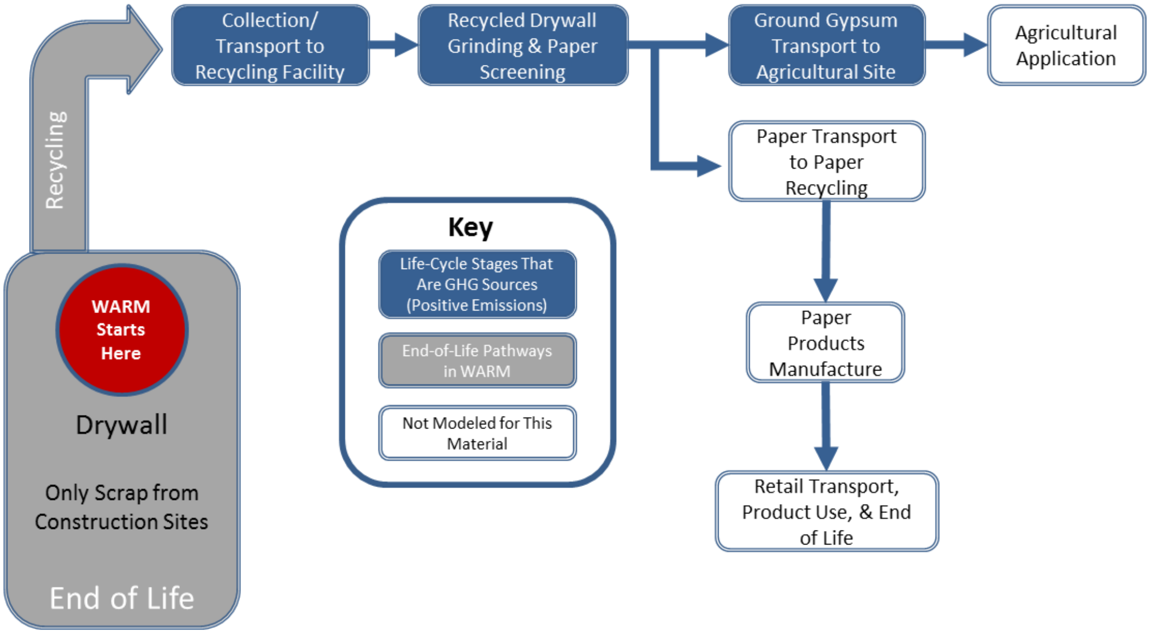
Source: CIWMB (2009b).

There are several different types of drywall products, including fire-resistant types (generally known as Type X drywall), water-resistant types, and others. Additionally, drywall can be produced in a range of thicknesses. EPA's analysis examined the life-cycle emissions of the most common type of drywall, half-inch-thick regular gypsum board.

Most drywall is currently disposed of in landfills (Master, 2009). This disposal pathway can be problematic; if water is admitted to the landfill, under certain conditions the drywall may produce hydrogen sulfide gas. Additionally, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by communications with Dr. Morton Barlaz. Incineration can produce sulfur dioxide gas, and is banned in some states (CIWMB, 2009b). Drywall is sometimes accepted at composting facilities, but it is used as an additive to compost, rather than a true compost input (please see section 6.4.3). For this reason, WARM does not include a composting emission factor for drywall. However, users interested in the GHG implications of sending drywall to a composting facility can use the recycling factor as a proxy (again, see section 6.4.3).

Drywall, however, is sometimes recycled into agricultural products, new drywall, as a component of cement, and some other uses. Sometimes the gypsum and paper are disposed of together, but they are also sometimes separated out during the recycling process, creating a somewhat more complicated life-cycle pathway (refer to Exhibit 6-1 for the primary lifecycle pathways of the gypsum and paper used in drywall). Recycling drywall is an open-loop process, meaning that components are recycled into secondary materials such as agricultural amendments and paper products. Building on Exhibit 6-1, a more detailed flow diagram showing the open-loop recycling pathways of drywall is provided in Exhibit 6-3.

Exhibit 6-3: Detailed Recycling Flows for Drywall in WARM



6.2 LIFECYCLE 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.[18] Recycling and Source Reduction are the two materials management options that impact the upstream production of materials and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not consider composting, combustion, or anaerobic digestion for drywall. As Exhibit 6-4 illustrates, the GHG sources and sinks relevant to drywall in this analysis are contained in all three sections of the life cycle assessment: raw materials acquisition and manufacturing (RMAM), changes in forest or soil carbon storage, and materials management.

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[18] The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all environmental impacts from municipal solid waste management options.

Exhibit 6-4: Drywall GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Drywall	GHG Sources and Sinks Relevant to Drywall		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Avoided raw material acquisition of gypsum • Avoided manufacturing of wallboard, including paper facing • Avoided transportation of raw gypsum	NA	NA
Recycling	**Emissions** • Transport of recycled materials to drywall recycling facility , and then to drywall manufacturing facility and retail site • Recycled manufacture process energy **Offsets** • Avoided gypsum extraction and initial processing • Avoided manufacturing of wallboard • Avoided transport of virgin gypsum to drywall manufacturing facility and site	NA	**Emissions** • Drywall extraction • Grinding of drywall • Transport to recycling facility
Composting	Not modeled in WARM		
Combustion	Not modeled in WARM		
Landfilling	NA	**Offsets** • Landfill carbon storage by paper facing	**Emissions** • Transport to construction and demolition landfill • Landfilling machinery
Anaerobic Digestion	Not modeled in WARM		

NA = Not applicable.

WARM analyzes all the GHG sources and sinks outlined in Exhibit 6-4 and calculates net GHG emissions per short ton of drywall inputs. For more detailed methodology on emission factors, please see sections 4.1 through 4.5. Exhibit 6-5 outlines the net GHG emissions for drywall under each materials management option.

Exhibit 6-5: Net Emissions for Drywall under Each Materials Management Option (MTCO$_2$E/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Drywall	(0.22)	0.03	NA	NA	(0.06)	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.

6.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

GHG emissions associated with raw materials acquisition and manufacturing 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.[19] For drywall, process energy GHG emissions result from acquiring the virgin gypsum used in manufacture, as well as the manufacturing processes used to prepare the stucco and paper facings, and to produce the actual wallboards. Transportation emissions are generated from transporting raw materials to the drywall manufacturing facility. Due to the nature of the processes and materials used to manufacture drywall, there are no non-energy process emissions.

Gypsum products use a combination of virgin, recycled, and synthetic gypsum. Virgin gypsum is synonymous with mined gypsum. Recycled gypsum comes mainly from drywall, and synthetic gypsum is the product of various industrial processes, mainly from pollution-control equipment at coal-fired power plants. The proportion of each type of gypsum used varies by product and by manufacturer. However, virgin gypsum comprises the vast majority (85 percent) of "new" (non-recycled) gypsum consumption in the United States (Olson, 2000). The contribution of recycled gypsum is not known, but is likely much smaller than new gypsum, given the fact that most drywall is landfilled at present.

To manufacture drywall, the gypsum is first heated and partially dehydrated (calcined), resulting in a material known as stucco. Next, the stucco is mixed with water and some additives to create a gypsum slurry. This slurry is spread onto a layer of facing paper, then covered by another layer of facing paper so that the slurry is sandwiched between two layers of paper. When the slurry has hardened, the resulting boards are cut to the desired length, sent to a drying kiln, and then readied for shipment.

Installed drywall also requires the use of finishing products (e.g., nails and joints). While these products are closely linked to the use of drywall, they represent a relatively small portion of installed drywall. EPA did not have sufficient data to assess the impacts these components would have on the different end-of-life pathways, and therefore excluded these products from the analysis.

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport drywall from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 6-6. Transportation emissions from the retail point to the consumer are not included. The miles traveled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and greenhouse gas emissions from the Management of Selected Materials (EPA, 1998).

Exhibit 6-6: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy per Short Ton of Product (Million Btu)	Retail Transportation Emissions ($MTCO_2E$/ Short Ton)
Drywall	356	0.39	0.03

6.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM evaluates GHG sources and sinks from source reduction, recycling, and landfilling of drywall. Exhibit 6-7 provides the net GHG emissions per short ton of drywall for each of these materials

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

management pathways. Source reduction avoids GHG emissions because it offsets emissions from manufacturing processes and transportation of raw materials. Landfilling results in GHG emissions from the transport of drywall to the landfill and operation of landfill equipment. Recycling drywall into new drywall or using it for agricultural purposes results in positive net emissions, but fewer emissions than would be obtained from landfilling the material. More details on the methodologies for developing these emission factors are provided in sections 4.1 through 4.5.

EPA used data on drywall manufacturing from the Athena Sustainable Materials Institute (Venta, 1997), which assumes that drywall is manufactured with 85 percent virgin gypsum, six percent synthetic gypsum, five percent gypsum recycled from manufacturing waste (internal recycling) and four percent recycled gypsum from construction sites (Venta, 1997, Table 9.3). Because EPA was unable to disaggregate the energy data for each source of gypsum, the 100 percent "virgin" drywall estimates in fact represent this composition. However, since most drywall likely contains at least some synthetic and/or recycled gypsum, this composition likely approximates an upper bound for virgin gypsum in drywall. Also, the paper facing used in drywall is made from recycled paper. The "virgin" drywall estimates therefore reflect the use of recycled paper rather than virgin paper. The "current mix" of drywall production reflects these same percentages.

6.4.1 Source Reduction

Reducing the amount of drywall wasted at construction sites, or the amount of drywall and other wall finishing products needed, results in emission reductions. The benefits of source-reducing drywall come primarily from avoided emissions from the manufacturing process, and also from avoided transportation emissions. Avoided raw material acquisition presents some small additional savings. The avoided emissions are summarized in Exhibit 6-7. For more information on this topic, please see the chapter on Source Reduction.

Exhibit 6-7: Source Reduction Emission Factors for Drywall ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs[a]	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Drywall	(0.22)	(0.22)	NA	NA	(0.22)	(0.22)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

[a] For this material, information on the share of recycled inputs used in production is unavailable or is not a common practice; EPA assumed that the current mix is comprised of 100% virgin inputs. Consequently, the source reduction benefits of both the "current mix of inputs" and "100% virgin inputs" are the same.

NA = Not applicable.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end of life. When source-reducing drywall, there are no post-consumer emissions because production of the material is avoided in the first place. Forest carbon storage is not applicable to drywall, and thus does not contribute to the source reduction emission factor.

6.4.1.1 Developing the Emission Factor for Source Reduction of Drywall

The approach and data sources used to calculate the emission factor for source reduction of drywall are summarized in the following paragraphs for each of the three categories of GHG emissions: process energy (pre-combustion and combustion), transportation energy, and process non-energy emissions. Exhibit 6-8 shows the results for each component and the total GHG emission factors for source reduction of drywall.

Exhibit 6-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Drywall ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Drywall	0.18	0.04	–	0.22

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.

Avoided Process Energy. Process energy GHG emissions result from the direct combustion of fossil fuels used to extract raw materials and to manufacture the stucco, the paper facing and the drywall boards themselves. Process energy also includes the upstream emissions associated with the production of fuels and electricity (i.e., "pre-combustion" energy).[20] EPA obtained data on raw material extraction, and drywall and paper manufacturing from Venta (1997). While these data are several years old, they represent the most complete dataset available at the time these emissions factors were developed.

During the expert review process, EPA received feedback that indicated that, while the overall estimates for energy needs for wallboard production were reasonable, the breakdown of the estimates across the various production stages were not quite consistent with current industry experience. The discrepancies are possibly due to process changes since the Venta (1997) report was published, and to production differences in Canada versus the United States. EPA was unable to obtain more specific estimates of energy needs, as the data were proprietary, and therefore scaled the Venta (1997) energy estimates so that each stage contributed similar proportional amounts of energy usage as the more recent industry estimates. When excluding wallboard distribution (which is included elsewhere in the calculations), the energy breakdown of the drywall production stage is approximately:

- Raw material creation—13 percent
- Raw material transportation—three percent
- Wallboard manufacturing—85 percent[21]

Because the Venta (1997) estimates do not include the pre-combustion energy of the fuels, EPA added pre-combustion values based on pre-combustion estimates by fuel types cited in FAL (2007). 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 drywall. Results of these calculations are provided in Exhibit 6-9.

Exhibit 6-9: Process Energy GHG Emissions Calculations for Virgin Production of Drywall

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Drywall	3.08	0.18

Avoided Transportation Energy. Transportation energy emissions occur when fossil fuels are used to transport raw materials, intermediate products for drywall production, and the finished drywall to the retail location. Transportation energy also includes the upstream emissions associated with the production of fuels and electricity (i.e., "pre-combustion" energy).

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[20] Pre-combustion emissions refer to the GHG emissions that are produced by extracting, transporting, and processing fuels that are in turn consumed in the manufacture of products and materials.

[21] Derived from Master (2010).

While the U.S. Census Bureau (2004) provides transportation data on the transport of raw gypsum, WARM uses transportation data from use estimates provided by R. Master (2010) for raw gypsum because, among the estimates currently available, these appear to be the most recent and most relevant to the United States. EPA obtained transportation data on finished products from the Census Bureau (2004). The related GHG emissions are provided in Exhibit 6-10.

Exhibit 6-10: Transportation Energy Emissions Calculations for Virgin Production of Drywall

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Drywall	0.10	0.01

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 6-6.

6.4.2 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. Drywall is modeled as being recycled in a semi-open loop, because some drywall is recycled back into drywall (closed-loop), and some is recycled into agricultural gypsum (open-loop). This section describes the development of the recycling emission factor for drywall, which is shown in the final column of Exhibit 6-11. For more information about this topic, please refer to the Recycling chapter.

Exhibit 6-11: Recycling Emission Factor for Drywall ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Drywall	–	–	0.00	0.02	–	–	0.03

[a] Includes emissions from the virgin production of secondary materials.
NA = Not applicable.
– = Zero emissions.

6.4.2.1 Developing the Emission Factor for Recycling of Drywall

EPA calculated the GHG benefits of recycling drywall by comparing the difference between the emissions associated with manufacturing drywall and agricultural gypsum from virgin materials versus manufacturing them using recycled drywall.

While a relatively small number of U.S. recyclers now accept post-construction drywall waste, almost all recycled drywall still comes from new drywall scrap (i.e., clean, uninstalled drywall scraps from construction sites). Concerns over lead and asbestos contamination can make recyclers wary of recycling drywall from renovation and demolition, and make some states reluctant to issue permits to allow this recycling (Manning, 2009). Therefore, the recycling estimates in WARM represent the recycling of new drywall scrap from construction sites.

To recycle drywall, the drywall is first ground, resulting in about 93 percent gypsum powder, 6.8 percent shredded paper, and 0.2 percent waste (which is landfilled), by weight (WRAP, 2008). The paper can be left in, if it is used as an agricultural amendment, or screened out and recycled.

Most recycled drywall is used for a variety of agricultural purposes. For example, the gypsum can be used as a soil conditioner, as it helps increase soil water infiltration and adds calcium and sulfur to the soil. The paper backing, meanwhile, can be recovered and used as animal bedding. Drywall is also recycled back into new wallboard and is possibly used in concrete manufacture. WARM assumes that 19 percent of recycled drywall is recycled into new drywall (closed-loop recycling), and 81 percent is recycled for agricultural purposes (open-loop recycling) (derived from Master, 2009) as illustrated in Exhibit 6-12. There is conflicting evidence about the extent to which recycled gypsum is used in cement manufacture. Due to a lack of information, EPA has not included cement manufacture as a recycling pathway for drywall in WARM. However, as the recycled gypsum would likely displace virgin gypsum, savings from avoided raw material extraction and transportation and avoided landfilling emissions would likely be similar to those raw material and landfilling savings experienced when recycling gypsum into agricultural products and new drywall.

Exhibit 6-12: Assumed End-Uses of Recycled Drywall

End Use	% of Recycled Drywall Going to this End Use
Drywall	19%
Agricultural Uses	81%

Source: Derived from Master (2009).

Because wallboard facing is always made from recycled paper, recycling the drywall paper facing into new drywall paper facing does *not* displace virgin paper production. Rather, it represents another source of recycled paper for the drywall manufacturing process. The calculations therefore focus on recycling of the gypsum. In reality, some of the recycled gypsum used for agricultural purposes may contain paper, which may eventually be applied to fields. While this process may result in some form of soil carbon sequestration, EPA is not able to accurately estimate the sequestration values and therefore did not include this in the analysis.

To calculate the recycling factor for drywall, EPA followed five steps, which are described in detail.

Step 1: *Calculate emissions from virgin production of one short ton of drywall, and one short ton of agricultural gypsum.* As noted above, “virgin” drywall in fact includes some recycled material. Emissions from production of virgin drywall were calculated using the data sources and methodology similar to those used for calculating the source reduction factor. EPA applied fuel-specific carbon coefficients to the process and transportation energy use data for virgin RMAM of drywall (using data from Venta (1997) and Master (2010)).

Because the analysis models both an open- and a closed-loop pathway, EPA also calculated the emissions associated with virgin agricultural gypsum. EPA used the same raw material extraction and initial processing energy data used by Venta (1997). Because the more energy-intensive processing of wallboard manufacturing is not necessary, the energy needs of agricultural gypsum are notably less than those of drywall. Transportation estimates of the virgin gypsum were calculated using information from Master (2010).

Exhibit 6-13: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Agricultural Gypsum (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Agricultural Gypsum	0.00	0.01	–	0.01

– = Zero emissions.

Step 2: *Calculate emissions for recycled production of drywall and agricultural gypsum.* EPA applied the same fuel-specific carbon coefficients to the process energy required to recycle drywall. EPA obtained information on gypsum recycling from WRAP (2008), which estimates that recycling one metric ton of waste wallboard requires 9.9 kWh of electricity and 0.09 liters of diesel. Because these estimates represent data from the United Kingdom, where renovation/demolition waste drywall is more commonly recycled than in the United States, these estimates reflect a small amount of post-construction wallboard recycling. Because this type of recycling would require additional processing, these estimates may slightly overstate the energy requirements to recycle construction waste drywall. Process energy emissions are shown in Exhibit 6-14.

While Venta (1997) does include a small amount of recycled gypsum in its calculations, EPA could not disaggregate the data into recycled gypsum and non-recycled gypsum components. Therefore, EPA assumed that recycling displaces all raw material acquisition of gypsum as estimated by Venta (1997), which includes acquisition of some recycled and synthetic gypsum.

EPA did not locate published estimates on transportation distances for transporting reclaimed wallboard to a recycling facility or transporting the recycled gypsum to either the drywall manufacturing facility or the agricultural site. However, recycling facilities tend to deal more locally in terms of both their supply of recycled drywall and also their end-use customers; thus, recycled gypsum generally travels less distance than mined gypsum. EPA used the U.S. Census Bureau's (2004) estimate on finished drywall transportation for both transporting the waste wallboard to the recycling facility as well as transporting the recycled gypsum to the wallboard manufacturers; the latter seems generally consistent with information provided by Manning (2009) on where one recycler tends to ship its gypsum. EPA also used Census Bureau (2004) estimates to represent the distance that recycled gypsum is shipped for agricultural purposes. Process energy emissions are shown in Exhibit 6-15.

Exhibit 6-14: Process Energy GHG Emissions Calculations for Recycled Production

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Drywall	3.19	0.18
Agricultural Gypsum	0.11	0.01

Exhibit 6-15: Transportation Energy GHG Emissions Calculations for Recycled Production

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Drywall	0.02	0.00
Agricultural Gypsum	–	–

– = Zero emissions.

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 6-6.

Step 3: *Calculate the difference in emissions between virgin and recycled production of drywall, and virgin and recycled production of agricultural gypsum.* To calculate the GHG emissions savings from recycling one short ton of drywall, WARM subtracts the recycled product emissions (from Step 2) from the virgin product emissions (from Step 1) for drywall, and for agricultural gypsum.

Step 4: Adjust the emissions differences to account for recycling losses. Material losses occur in both the recovery and manufacturing stages of recycling. The loss rate represents the percentage of end-of-life drywall collected for recycling that is lost during the recycling process, and ultimately disposed of. WARM assumes a 0.2 percent loss rate for drywall recycling (WRAP, 2008). The differences in emissions from virgin versus recycled process energy and transportation energy are adjusted to account for loss rates by multiplying the final three columns of Exhibit 6-16 by 99.8 percent, the amount of material retained after losses (i.e., 100 percent input – 0.2 percent lost = 99.8 percent retained).

Exhibit 6-16: Differences in Emissions between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Drywall	0.18	0.04	–	0.18	0.00	–	0.01	(0.04)	–
Agricultural Gypsum	0.00	0.02	–	0.00	0.04	–	0.00	(0.02)	–

– = Zero emissions.

Step 5: *Develop a weighted recycling factor to reflect the end-use products' respective share of the recycled gypsum market.* The differences in emissions from virgin versus recycled manufacturing of drywall are combined with the differences in emissions from virgin versus recycled manufacturing of agricultural gypsum, weighting the two end uses by their market share. WARM assumes that 19 percent of recycled drywall is recycled into new drywall, and 81 percent is recycled for agricultural purposes (derived from Master, 2009).

6.4.3 Composting

Some composting facilities accept clean (e.g., construction scrap) drywall, although most do not accept demolition or renovation waste drywall due to contamination concerns. However, although drywall is accepted at composting facilities, it is misleading to say that it is actually composted.

Drywall is composed primarily of gypsum, which is an inorganic substance and therefore cannot become compost. Instead, drywall is generally added to the compost mix *after* the compost has been created. It is added to compost because gypsum can supply important nutrients to plants. When drywall is sent to a composting facility, therefore, it is actually used as an *additive to* compost, rather than turned *into* compost.[22]

For these reasons, WARM does not include a composting emission factor for drywall. However, users interested in the GHG implications of sending drywall to a composting facility rather than a landfill may use the drywall recycling factor as a reasonable proxy. The recycling factor is based on the assumption that nearly 81 percent of drywall is recycled into agricultural gypsum, much of which is used as a soil amendment (the other 19 percent is assumed to be recycled into new drywall). Therefore, the recycling factor captures many of the same GHG emissions, and avoided GHG emissions, that would occur if the drywall were sent to a composting facility rather than landfilled. Please note that inherent in the recycling factor is the assumption that the recycled drywall replaces virgin gypsum used as a soil amendment; WARM does not estimate the GHG implications of using recycled drywall instead of other non-gypsum alternatives.

6.4.4 Combustion

Drywall is generally not combusted, and is even banned from combustion facilities in some states. EPA therefore did not develop an emission factor for combustion.

6.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage and avoided utility emissions

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[22] More information about drywall recycling can be found at http://www.cdrecycling.org/drywall-recycling.

from landfill gas-to-energy recovery. Because gypsum is inorganic and does not contain biogenic carbon, there are zero emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling gypsum. However, the paper facing on drywall is organic, resulting in some carbon sequestration. While the paper facing would separately generate landfill methane emissions, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by Dr. Morton Barlaz. As such, methane yield from gypsum board is likely to be negligible and is therefore assumed to be zero in WARM. EPA obtained data on the moisture content and carbon storage factor for drywall from Barlaz and Staley (2009). In addition to those emissions, EPA assumed the standard WARM landfilling emissions related to transportation and equipment use. The carbon sequestration benefits outweigh the transportation emissions, resulting in net carbon storage in the landfill, as illustrated in Exhibit 6-17. For more information, please see the chapter on Landfilling.

Exhibit 6-17: Landfilling Emission Factor for Drywall (MTCO$_2$E/Short Ton)

Material	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)
Drywall	–	0.02	–	–	(0.08)	(0.06)

– = Zero emissions.

6.4.6 Anaerobic Digestion

Because of the nature of drywall components, drywall cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of drywall.

6.5 LIMITATIONS

Although this analysis is based upon best available life-cycle data, the primary data source for this material (Venta) was published in 1997. Although EPA made some updates to the dataset, most of the calculations rely on data that are now more than 10 years old, and reflect the Canadian drywall industry. The data on energy needs for recycling came from WRAP (2008), which relies on an analysis of the drywall industry in the United Kingdom. Advancements in production processes, and industry differences among nations, could affect the resulting emission factors.

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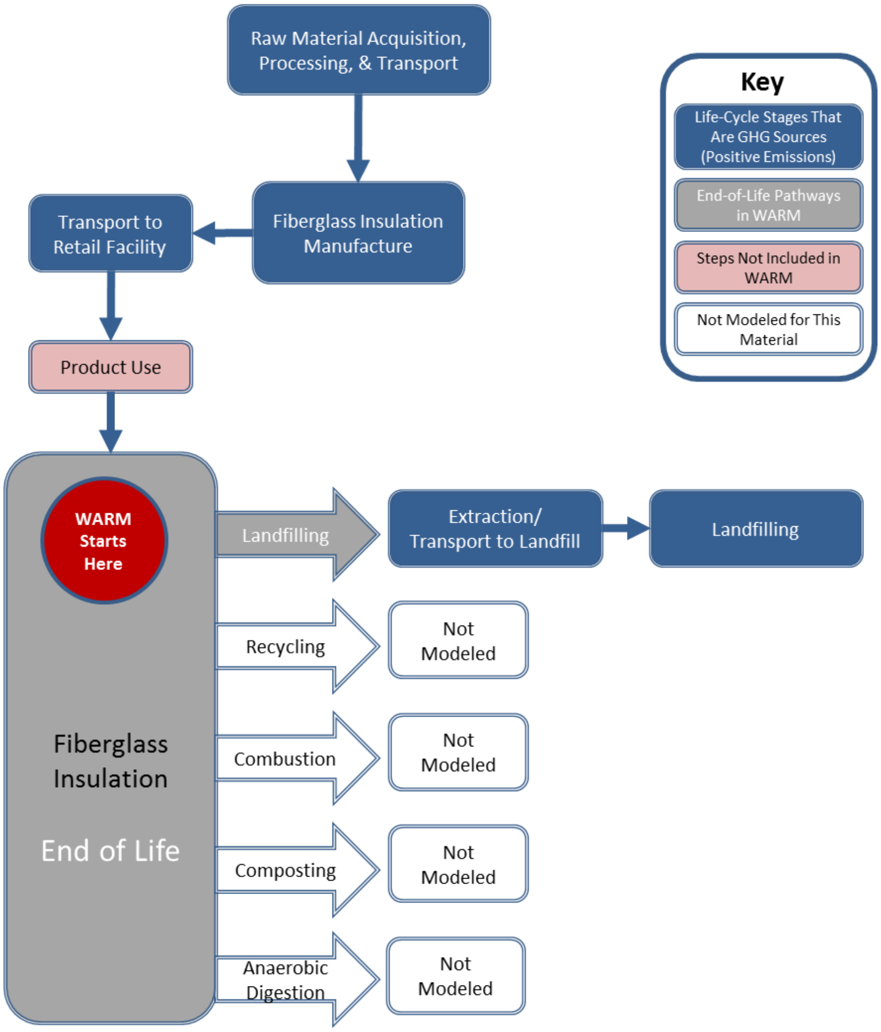
7 FIBERGLASS INSULATION

7.1 INTRODUCTION TO WARM AND FIBERGLASS INSULATION

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for fiberglass insulation beginning at the waste generation reference point.[23] The WARM GHG emission factors are used to compare the net emissions associated with fiberglass insulation in the following two waste management alternatives: source reduction and landfilling. Exhibit 7-1 shows the general outline of materials management pathways for fiberglass insulation in WARM. For background information on the general purpose and function of WARM emission factors, see the General Guidance chapter. For more information on Source Reduction and Landfilling, see the chapters devoted to those 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 7-1: Life Cycle of Fiberglass Insulation in WARM



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[23] EPA would like to thank Mr. Scott Miller of Knauf Insulation for his efforts to improve these estimates.

WARM models fiberglass batt insulation, which is often used in building walls and ceilings for its thermal insulating properties. Fiberglass batt insulation is sold under a variety of thicknesses and densities, which offer different thermal resistance values (R-values). The WARM factors are based on weight (short tons), rather than thickness or square foot, of insulation and therefore are not specific to any particular R-value type of insulation.

7.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and only consider upstream GHG emissions when the production of new materials is affected by materials management decisions. Recycling and Source Reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM only has emission factors for landfilling and source reduction for fiberglass insulation. Fiberglass insulation is neither combusted, composted, nor anaerobically digested. It *is* reusable in that it can be easily removed and re-installed (NAIMA, 2007); the extent to which this is actually done, however, is not known. As Exhibit 7-2 illustrates, all the GHG sources and sinks relevant to fiberglass insulation in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life cycle.

Exhibit 7-2: Fiberglass Insulation GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Fiberglass Insulation	**GHG Sources and Sinks Relevant to Fiberglass Insulation**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Acquisition of raw materials • Transport of raw materials and products • Manufacture process energy • Manufacture process non-energy	NA	NA
Recycling	Not modeled in WARM		
Composting	Not applicable because fiberglass insulation cannot be composted		
Combustion	Not modeled in WARM		
Landfilling	NA	NA	**Emissions** • Transport to construction & demolition landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because fiberglass insulation cannot be anaerobically digested		

NA =Not applicable.

WARM analyzes all the GHG sources and sinks outlined in Exhibit 7-2 and calculates the net GHG emissions per short ton of fiberglass insulation. For more detailed methodology on emission factors, please see the sections below on individual waste management strategies. Exhibit 7-3 outlines the net GHG emissions for fiberglass insulation under each materials management option.

Exhibit 7-3: Net Emissions for Fiberglass Insulation under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Fiberglass Insulation	(0.38)	NA	NA	NA	0.02	NA

NA =Not applicable.

7.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For fiberglass insulation, the GHG emissions associated with raw materials acquisition and manufacturing are: (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes. Process non-energy GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption.

Fiberglass insulation is produced using recycled glass cullet, sand, soda ash, limestone, borax, and binder coatings. Exact proportions of these materials can vary. Fiberglass can be made using 100 percent virgin inputs (i.e., no recycled glass cullet), although most manufacturers do include recycled cullet in their manufacturing processes.

Exhibit 7-4 shows the proportion of materials assumed in WARM; this calculation was derived using Lippiatt (2007) and Miller (2010). Fiberglass generally uses cullet from recycled plate glass, but the Glass Packaging Institute (cited in NAIMA, 2007, p. 5) notes that "fiberglass insulation is the largest secondary market for recycled glass containers."

Exhibit 7-4: Material Composition of Fiberglass, by Weight

Material	% Composition of Fiberglass
Recycled Glass Cullet	40%
Sand	28%
Soda Ash	11%
Limestone	8%
Borax	8%
Binder Coatings	5%

Source: Derived from Lippiatt (2007) and Miller (2010).

The fiberglass insulation production process is similar to the production process for glass containers described in the Glass chapter. However, instead of being formed into molds, the molten glass is spun into fibers, and glass coatings are added. The product is then sent through a curing oven and cut to the appropriate size. Making fiberglass insulation from recycled cullet requires less energy than making it from sand and other raw materials, since it avoids the energy needed to fuse the raw materials into glass. For every 10 percent of recycled content in fiberglass insulation, the manufacturing energy needs decrease by roughly 3.25 percent (Miller, 2010).

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport fiberglass insulation from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 7-5, and are calculated using data on average shipping distances and modes from the Bureau of Transportation Statistics (2013) and on typical transportation fuel efficiencies from EPA (1998). Transportation emissions from the retail point to the consumer are not included.

Exhibit 7-5: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors ($MTCO_2E$/ Short Ton)
Fiberglass Insulation	356	0.39	0.03

7.4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction and landfilling pathways for materials management of fiberglass insulation. Source reduction results in net negative emissions (i.e., a net reduction in GHG emissions), while landfilling results in slightly net positive emissions.

7.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed previously, under the measurement convention used in this analysis, source reduction for fiberglass insulation has negative raw material and manufacturing GHG emissions (i.e., it avoids baseline emissions attributable to current production) and zero materials management GHG emissions. For more information, please refer to the module on Source Reduction.

Exhibit 7-6 outlines the source reduction emission factor for fiberglass insulation. GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see section 3) of fiberglass insulation produced from a “current mix” of virgin and recycled inputs. Fiberglass insulation is usually not manufactured from 100 percent virgin inputs, and is rarely manufactured from 100 percent recycled inputs. WARM assumes that, on average, the “current mix” of fiberglass is composed of 40 percent recycled glass content.

Exhibit 7-6: Source Reduction Emission Factors for Fiberglass Insulation ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Fiberglass Insulation	(0.38)	(0.48)	NA	NA	(0.38)	(0.48)

NA = Not applicable.

Post-consumer emissions are the emissions associated with materials management pathways that could occur at end of life. There are no post-consumer emissions from source reduction because production of the material is avoided in the first place. Forest carbon storage is not applicable to fiberglass insulation, and thus does not contribute to the source reduction emission factor.

It should be noted that source reduction of fiberglass does not necessarily imply less insulating of buildings. Rather, source reduction could come from reuse of insulation or other means. The WARM factors do not consider how the source reduction would occur, or the GHG implications of using less or different types of insulation.

7.4.1.1 Developing the Emission Factor for Source Reduction of Fiberglass Insulation

To produce fiberglass insulation, energy is used both in the acquisition of raw materials and in the manufacturing process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2. In addition, manufacturing fiberglass insulation also results in process non-energy CO_2 emissions from the heating of carbonates (soda ash and limestone). Hence, the RMAM component consists of process energy, non-process energy and transport emissions in the acquisition and manufacturing of raw materials, as shown in Exhibit 7-7. Please note that the tables in this section reflect the "current mix" of inputs, as fiberglass insulation usually contains recycled glass cullet.

Exhibit 7-7: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Fiberglass Insulation ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Fiberglass Insulation	0.27	0.06	0.15	0.48

Avoided Process Energy. To calculate this factor, EPA first obtained an estimate of the amount of energy required to acquire and produce one short ton of fiberglass insulation. Lippiatt (2007) provides estimates on the percent of each of the raw materials needed for manufacturing fiberglass, which include borax, soda ash, limestone, sand, glass cullet, and binder coatings; EPA adjusted these percentages to increase the portion of recycled cullet from 34 to 40 percent, based on information received from Miller (2010). EPA obtained raw material acquisition data from the National Renewable Energy Laboratory (NREL, 2009) for soda ash and limestone, and from Athena (2000) for sand. NREL also provided estimates for borax, but these estimates include energy requirements of the infrastructure that were outside the boundaries of a WARM analysis; therefore, WARM allocates the fraction of borax in fiberglass among soda ash, limestone, and sand on a proportional basis. Lippiatt (2007) also provides information on binder coatings. However, binder coatings represent a small component of fiberglass insulation (five percent), and additional information on binder coating manufacture was not available; therefore, WARM does not include binder coatings in this analysis. NREL (2009), Lippiatt (2007) and Athena (2000) all provided energy estimates by fuel type.

Next, EPA multiplied the fuel consumption (in Btu) by the fuel-specific carbon content. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in fiberglass insulation production. The process energy used to produce fiberglass insulation and the resulting emissions are shown in Exhibit 7-8.

Exhibit 7-8: Process Energy GHG Emissions Calculations for Virgin Production of Fiberglass Insulation

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Fiberglass Insulation	4.73	0.27

Avoided Transportation Energy. Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for fiberglass insulation production. The methodology for estimating these emissions is the same as the one used for process energy emissions. EPA obtained transportation distances of raw materials from Lippiatt (2007). The assumed current mix of raw material inputs (including glass cullet) indicates that the materials are transported approximately 187 miles on a weighted average basis. EPA assumed they are transported by truck, and applies the standard WARM estimate of 0.0118 gallons diesel consumed per ton-mile. EPA estimated retail transportation using U.S. Census Bureau (2007), as shown in Exhibit 7-5. The calculations for estimating the transportation energy emission factor are shown in Exhibit 7-9.

Exhibit 7-9: Transportation Energy Emissions Calculations for Virgin Production of Fiberglass Insulation

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Fiberglass Insulation	0.44	0.03

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 7-5.

Avoided Non-Process Energy. Non-energy GHG emissions occur during manufacturing but are not related to consuming fuel for energy. For fiberglass insulation, non-energy CO_2 emissions (based on data from ICF (1994)) are emitted in the virgin glass manufacturing process during the melting and refining stages from the heating of carbonates (soda ash and limestone). This number is then multiplied by 95 percent, which is the approximate glass content of fiberglass insulation, and then by 60 percent, the approximate content of the glass that comes from raw materials. Exhibit 7-10 shows the components for estimating process non-energy GHG emissions for fiberglass insulation.

Exhibit 7-10: Process Non-Energy Emissions Calculations for Virgin Production of Fiberglass Insulation

Material	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)
Fiberglass Insulation	0.15	–	–	–	–	0.15

– = Zero emissions.

7.4.2 Recycling

While fiberglass insulation could be recycled in theory, it generally is not done (Crane, 2009). Because fiberglass is light, the amount of glass recovered in a given truckload would be relatively small, and much of the energy savings from recycling the fiberglass would be lost through the transportation processes (Miller, 2009). However, fiberglass is a major market for recycled glass, so it can be viewed as an open-loop pathway for glass recycling. WARM does not include this open-loop pathway for glass at this time, as EPA could not locate sufficient information to develop the pathway during development.

7.4.3 Composting

Fiberglass is not subject to aerobic bacterial degradation, and therefore, cannot be composted. Therefore, EPA did not include an emission factor in WARM for the composting of fiberglass insulation.

7.4.4 Combustion

Fiberglass is generally not combusted, thus EPA did not include an emission factor in WARM for the combustion of fiberglass insulation.

7.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since fiberglass insulation does not contain biodegradable carbon, there are zero emissions from landfill methane, no landfill carbon storage, and zero avoided utility emissions associated with landfilling fiberglass insulation. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for fiberglass is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. The landfilling emission factor for fiberglass insulation is summarized in Exhibit 7-11. For more information, please see the chapter on Landfilling.

Exhibit 7-11: Landfilling Emission Factor for Fiberglass Insulation ($MTCO_2E$/Short Ton)

Material	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)
Fiberglass	–	0.02	–	–	–	0.02

– = Zero Emissions.

7.4.6 Anaerobic Digestion

Because of the nature of fiberglass insulation components, fiberglass insulation cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of fiberglass insulation.

7.5 LIMITATIONS

Although this analysis is based upon best available life-cycle data, it does have certain limitations. EPA was unable to obtain sufficient life-cycle information on the raw material acquisition of borax, which represents about eight percent of fiberglass raw materials by weight. Therefore, the analysis does not account for the emissions associated with obtaining and processing borax.

Furthermore, drywall contains a small amount of binder coatings—materials for which EPA was unable to obtain life-cycle information. Therefore, EPA's analysis did not consider the life-cycle GHG impact of binder coatings, which represent about five percent of fiberglass insulation by weight.

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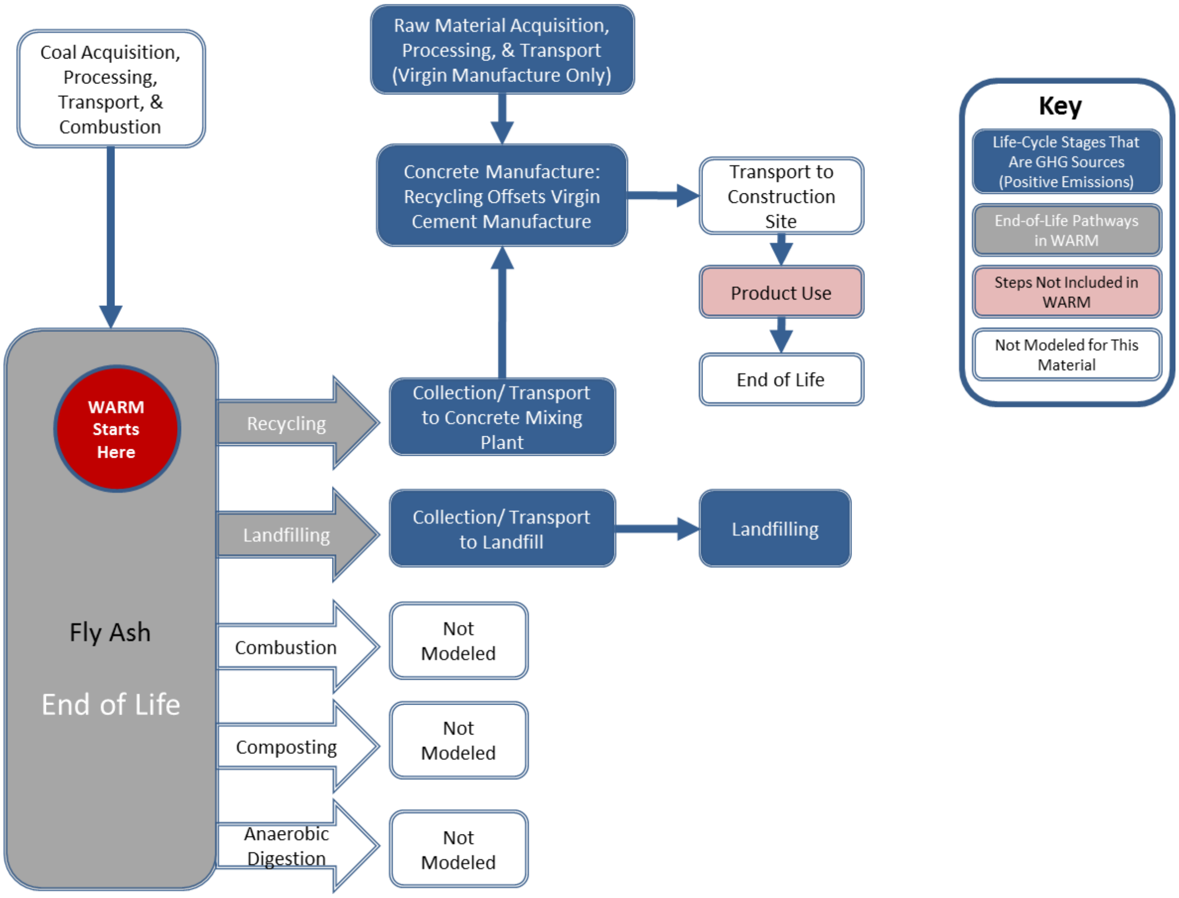
8 FLY ASH

8.1 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 8-1 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 WARM Background & 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 8-1: 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 8-2). 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 8-2: 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).

8.2 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.[24]

As Exhibit 8-3 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, combustion, or anaerobic digestion 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 8-3, all the GHG sources relevant to fly ash in this analysis are contained in the materials management section of the life cycle assessment.

Exhibit 8-3: 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** • Transport of cement raw materials and products • Virgin cement manufacture process energy • Virgin cement manufacture process non-energy	NA	**Emissions** • 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** • Transport to landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because fly ash cannot be anaerobically digested		

NA = Not available.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 8-3 and calculates net GHG emissions per short ton of fly ash inputs (see Exhibit 8-4). For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

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[24] 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 8-4: Net Emissions for Fly Ash Under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Fly Ash	NA	(0.87)	NA	NA	0.02	NA

NA = Not applicable.

8.3 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.[25] 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.

8.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM analyzes all the GHG sources and sinks outlined in Exhibit 8-3 and calculates net GHG emissions per short ton of fly ash. Recycling fly ash leads to reductions in GHG emissions because 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.

8.4.1 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.

8.4.2 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.[26] Therefore, the GHG benefits of using fly ash are equivalent to the emissions associated with

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

[26] 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.

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.

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 8-5 presents a summary of these components. The following sections contain descriptions of how each component is calculated.

Exhibit 8-5: Components of the Fly Ash Recycling Emission Factor ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) 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.

8.4.2.1 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, 2018). 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, EPA first obtained an estimate of the total energy required to produce one ton of cement, which is reported as 4.77 million Btu (PCA, 2003).[27] 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 conducted a similar analysis for fugitive methane (CH_4) emissions, using fuel-specific CH_4 coefficients. Finally, EPA calculated the total process energy GHG emissions as the sum of GHG

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

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 than three to four 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 (five to nine 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 8-6 provides the process energy emissions from production of cement and fly ash as calculated in WARM.

Exhibit 8-6: Process Energy GHG Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash

Material	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 8-7), the transportation energy emissions associated with fly ash recycling are estimated to be zero.

Exhibit 8-7: Transportation Energy Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash

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

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

Material	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 8-9: Difference in Emissions between Virgin Cement Production and Recycled Fly Ash Use ($MTCO_2E$/Short Ton)

Material	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	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation 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).

8.4.3 Composting

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

8.4.4 Combustion

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

8.4.5 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 8-2). 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 8-10.

Exhibit 8-10: Landfilling Emission Factor for Fly Ash ($MTCO_2E$/Short Ton)

Material	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	–	0.02	–	–	–	0.02

– = Zero emissions.

For more information, please see the chapter on Landfilling.

8.4.6 Anaerobic Digestion

Because of the nature of fly ash components, fly ash cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of fly ash.

8.5 LIMITATIONS

The following are limitations of this analysis:

- The analysis does not consider emissions from construction of special leak-proof landfills for fly ash.
- The analysis does not include energy associated with the processing of fly ash with high carbon content (five to nine percent) because this process currently takes place on a limited scale.
- There are uncertainties in the final emission factors as they relate to potential changes in the combustion processes, manufacturing processes, and recycling processes in the future. As additional data about these changes becomes available, EPA will investigate the need to revise emission factors.
- 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.

8.6 REFERENCES

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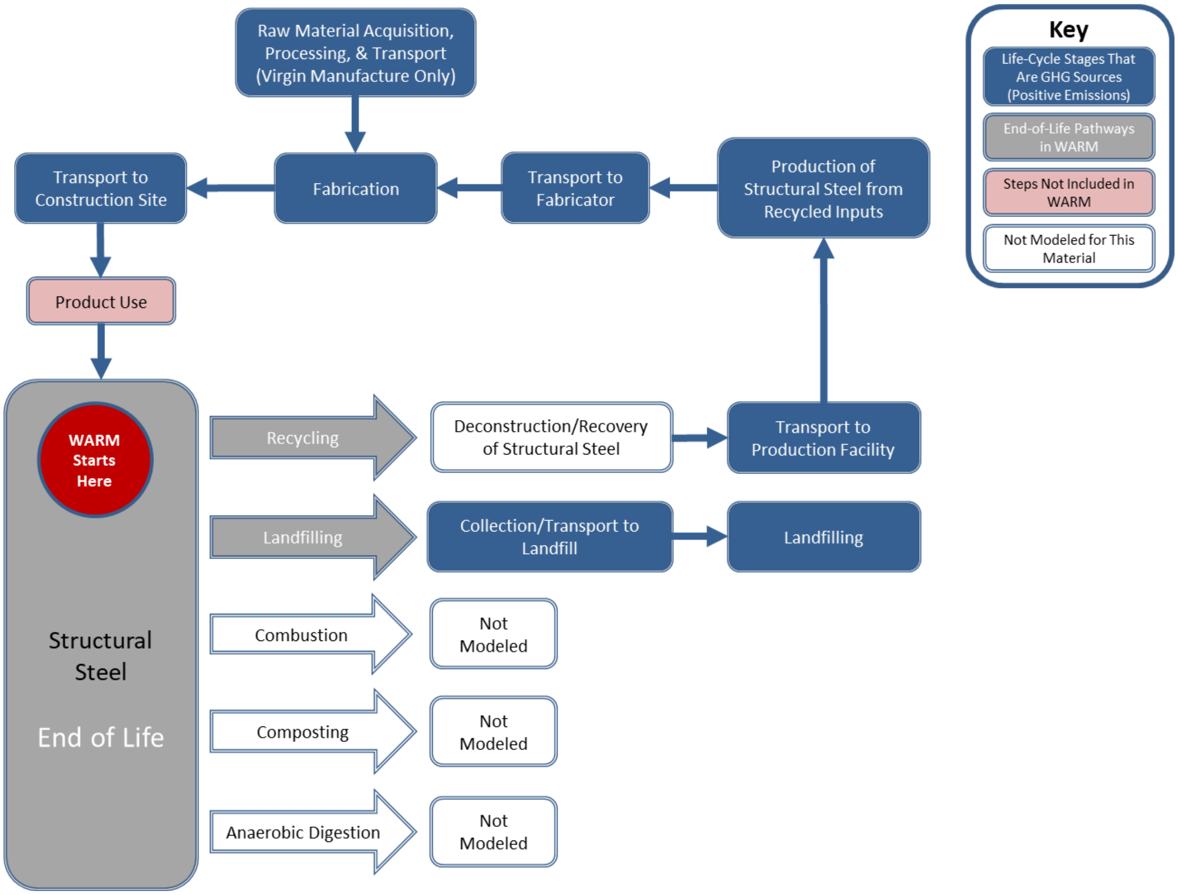
9 STRUCTURAL STEEL

9.1 INTRODUCTION TO WARM AND STRUCTURAL STEEL

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for structural steel beginning at the waste generation reference point. EPA uses the WARM GHG emission factors to compare the net emissions associated with structural steel in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 9-1 shows the general outline of materials management pathways for structural steel in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, and Landfilling, see the chapters devoted to those processes.

Exhibit 9-1: Life Cycle of Structural Steel in WARM



Structural steel products are commonly used in buildings, bridges, and industrial applications. There are three main types of structural steel products: hot-rolled structural sections, hollow structural sections (HSS), and steel plates. Hot-rolled structural sections, including beams, I-beams, H-piles and channels; HSS, including coil steel that is used in the automotive industry; and steel plates. For the purposes of WARM, EPA models the impacts associated with hot-rolled structural sections for the structural steel material category.

9.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The GHG life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and considers upstream GHG emissions only when the production of new materials is affected by material management decisions. Recycling and source reduction are the two materials management options that affect the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling, and Source Reduction.

WARM considers emission factors only for source reduction, recycling, and landfilling for structural steel. As Exhibit 9-2 illustrates, all the GHG sources and sinks relevant to structural steel in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 9-2: Structural Steel GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Structural Steel	GHG Sources and Sinks Relevant to Structural Steel		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Production of structural sections via BF/BOF or EAF • Fabrication • Extraction and transport of raw materials • Transport of structural sections to the fabricator • Transport to construction site	NA	NA
Recycling	**Emissions** • Production of structural sections via EAF • Fabrication • Transportation of structural sections to the fabricator • Transport to construction site **Offsets** • Production of structural sections via BF/BOF or EAF • Fabrication • Extraction and transport of raw materials • Transport of structural sections to the fabricator • Transport to construction site	NA	**Emissions** • Collection of steel scrap and transport to structural steel manufacturer
Composting	Not applicable because structural steel cannot be composted		
Combustion	Not modeled in WARM		
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because structural steel cannot be anaerobically digested		

WARM analyzes all the GHG sources and sinks outlined in Exhibit 9-2 and calculates net GHG emissions per short ton of structural steel inputs. For more detailed methodology on emission factors, see Sections 9.4.1 through 9.4.6. Exhibit 9-3 outlines the net GHG emissions for structural steel under each materials management option.

Exhibit 9-3: Net Emissions for Structural Steel under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Structural Steel	(1.67)	(1.93)	NA	NA	0.02	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
NA = Not applicable.

9.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For structural steel, GHG emissions associated with raw materials acquisition and manufacturing (RMAM) include: (1) GHG emissions from energy used during the RMAM processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing. Process non-energy GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption. Process and non-process energy GHG emissions are generated during the production of structural steel sections from materials such as iron ore, coal, limestone, and steel scrap (or recycled scrap), as well as during the fabrication process. Transportation GHG emissions are generated during the transport of materials to the production facility, transport of the structural sections to the fabricator, and transport of the fabricated sections to the construction site.

There are two main methods used to produce structural steel: Blast Furnace/Basic Oxygen (BF/BOF) and Electric Arc Furnace. In BF/BOF steelmaking, blast furnaces are first used to product iron from raw materials such as ore or sinter pellets. The melted iron and steel scrap are then added to a furnace, which has oxygen blown into it to remove carbon. The EAF method uses electrodes to create electric arcs to melt scrap steel or other iron material. After the BF/BOF or EAF process, the molten steel is sent to a secondary refining station to finalize the steel chemistry. Once the secondary refinement process is complete, the molten steel is sent to the caster where it is transformed into a solid shape (AISI 2020). The steel is then transported to a fabricator, where it is prepared for installation based on structural design plans.

Globally, 72% of steel is produced using the BF/BOF method while the remaining 28% of steel is produced using the EAF method (World Steel Association, 2020). In the United States, hot-rolled structural sections are only produced using the EAF method (AISC, 2020). An estimated 40% of hot-rolled structural sections that are consumed in the United States are imported (AISC, 2020).

The RMAM calculation in WARM also incorporates “retail transportation”, which includes the average truck, rail, water, and other-modes required to transport structural steel from the manufacturing facility to the retail/distribution point, which may be the customer or various other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation appear in Exhibit 9-4. Transportation emissions from the retail point to the consumer are not included. EPA obtained the miles-travelled fuel-specific information from the 2007 U.S. Census Commodity Flow Survey (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 9-4: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions ($MTCO_2E$ per Short Ton of Product)
Structural Steel	331	0.36	0.03

9.4 MATERIALS MANAGEMENT METHODOLGIES

This analysis considers source reduction, recycling, and landfill pathways for materials management of structural steel. For structural steel, source reduction and recycling result in net negative emissions (i.e., a net reduction in GHG emissions), while landfilling results in slightly positive net emissions.

9.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed previously, source reduction for structural steel comes from avoided emissions associated with raw material acquisition, the production of structural sections, and fabrication. For more information about source reduction, refer to the chapter on Source Reduction.

Exhibit 9-5 outlines the GHG emission factor for source reducing structural steel. EPA calculated the GHG benefits of source reduction as the emissions savings from avoided raw materials acquisition and manufacturing, production, and fabrication (see Section 9.3) of structural steel produced from 100-percent virgin inputs. In the United States, hot-rolled structural sections are produced solely using the EAF method, which relies on 100% recycled inputs. However, more than half of the steel that is imported into the United States is manufactured using the BF/BOF method using virgin inputs (U.S. Department of Commerce, 2020; World Steel Association, 2020). Since 40% of hot-rolled structural sections that are consumed in the United States are imported (AISC, 2020), EPA assumes that, on average, the current mix of structural steel is comprised of 78% recycled content.

Exhibit 9-5: Source Reduction Emission Factors for Structural Steel (MTCO$_2$E/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Structural Steel	(1.67)	(3.42)	NA	NA	(1.67)	(3.42)

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

9.4.1.1 Developing the Emission Factor for Source Reduction of Structural Steel

To calculate the avoided GHG emissions for structural steel, EPA first looked at three components of GHG emissions from RMAM activities: (1) process energy, (2) transportation energy, and (3) process non-energy GHG emissions. Exhibit 9-6 shows the results for each component and the total GHG emission factors for source reduction of structural steel from 100% virgin inputs. More information on each component making up the final emission factor follows.

Exhibit 9-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Structural Steel (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Structural Steel	2.06	0.16	1.20	3.42

To calculate this factor, EPA obtained an estimate of the amount of energy required to produce and fabricate one short ton of structural steel. EPA obtained data on the energy requirements associated with the manufacture of structural steel sections from virgin inputs using the BF/BOF method from a life cycle assessment report prepared by the American Iron and Steel Institute (AISI, 2017) on

Structural Steel Production in China. The study also accounts for emissions associated with transporting the steel sections from China to the United States. EPA obtained data on the energy requirements associated with fabrication from an environmental production declaration prepared by the American Institute of Steel Construction (AISC, 2016).

EPA then multiplied the amount of energy required to produce and fabricate one short ton of structural steel, broken down by fuel mix, by the fuel-specific carbon content. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions from all fuel types used in structural steel production. The process energy used to produce structural steel and the resulting emissions appear in Exhibit 9-7. The transportation energy used during the production process and the resulting emissions appear in Exhibit 9-8.

Exhibit 9-7: Process Energy GHG Emissions for Virgin Production of Structural Steel

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Structural Steel	23.34	2.06

Exhibit 9-8: Transportation Energy GHG Emissions for Virgin Production of Structural Steel

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Structural Steel	1.80	0.13

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 9-4.

GHG emissions that are not associated with energy consumption are also generated during the production and fabrication process of structural steel. During the virgin production of steel sections, combustion of collected gases and other fuels in the boiler contribute to GHG emissions (AISI, 2017). Process emissions from welding gases and electrodes that occur during fabrication also contribute to GHG emissions (AISC, 2016). Exhibit 9-9 shows the components for estimating process non-energy GHG emissions for structural steel.

Exhibit 9-9: Process Non-Energy Emissions for Virgin Production of Structural Steel ($MTCO_2E$/Short Ton)

Material	Virgin Production	Fabrication	Total Non-Energy Process Emissions
Structural Steel	1.19	0.01	1.20

9.4.2 Recycling

Structural steel is a highly durable material, allowing it to be repeatedly reused and recycled while still maintaining the inherent properties of steel produced from virgin materials. Although not all hot-rolled structural sections that are recycled become new structural members, EPA models recycling of structural steel in a closed loop process (i.e., back into structural steel) in WARM. A recycled input credit is calculated for structural steel by assuming that the recycled material avoids (or offsets) the GHG emissions associated with the production of structural steel from virgin inputs. GHG emissions associated with management (i.e., collection, transportation, and processing) of recycled structural steel are included in the recycling credit calculation. Each component of the recycling emission factor as shown in Exhibit 9-10 is discussed further below. For more information on Recycling, please see the chapter on Recycling.

Exhibit 9-10: Recycling Emission Factor for Structural Steel ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] – Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Structural Steel	–	–	(1.06)	(0.10)	(0.78)	NA	(1.93)

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
NA = Not applicable.
[a] Includes emissions from the initial production of the material being managed.
– = Zero emissions.

9.4.2.1 *Developing the Emission Factor for Recycling of Structural Steel*

EPA calculated the GHG benefits of recycling structural steel by taking the difference between producing structural steel from virgin inputs and producing structural steel from recycled inputs, after accounting for losses that occur during the recycling process. This difference is called the “recycled input credit” and represents the net change in GHG emissions from process energy, transportation energy, and non-energy process emissions associated with recycling structural steel relative to virgin production of structural steel. To calculate each component of the recycling emission factor EPA used the following four steps:

Step 1. *Calculate GHG emissions from virgin production of one short ton of structural steel.* The GHG emissions from virgin production of structural steel are provided in Exhibit 9-7, Exhibit 9-8, and Exhibit 9-9. EPA calculated emissions from production of virgin structural steel using the data sources and methodology also used to calculate the source reduction factor. EPA applied fuel-specific carbon coefficients to the process and transportation energy use for virgin RMAM of structural steel.

Step 2. *Calculate GHG emissions from recycled production of structural steel.* Similar to the virgin production process, the process for manufacturing structural steel from recycled inputs (i.e., steel scrap) involves two main steps: (1) production of structural sections and (2) fabrication. Structural steel sections that are manufactured from recycled inputs are manufactured using the EAF method. EPA obtained data on the energy requirements associated with the manufacture and fabrication of structural steel sections from recycled input from an environmental product declaration prepared by the American Institute of Steel Construction (AISC, 2016). Exhibit 9-11 and Exhibit 9-12 provide the process and transportation emissions associated with producing recycled structural steel.

Exhibit 9-11: Process Energy GHG Emissions for Recycled Production of Structural Steel

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Structural Steel	12.96	0.82

Exhibit 9-12: Transportation Energy GHG Emissions for Recycled Production of Structural Steel

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Structural Steel	0.25	0.02

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 9-4.

GHG emissions that are not associated with energy consumption are also generated during the production and fabrication process of structural steel. During the recycling production of steel sections, facility emissions account for around 30% of the global warming impact (AISC, 2015). Process emissions from welding gases and electrodes that occur during fabrication also contribute to GHG emissions (AISC, 2016). Non-energy process emissions associated with the recycled production of structural steel are summarized in Exhibit 9-13.

Exhibit 9-13: Process Non-Energy Emissions for Recycled Production of Structural Steel ($MTCO_2E$/Short Ton)

Material	Recycled Production	Fabrication	Total Non-Process Energy Emissions
Structural Steel	0.28	0.01	0.29

Step 3. *Calculate the difference in emissions between virgin and recycled production.* To calculate the GHG emissions implications of recycling one short ton of structural steel, WARM subtracts the recycled product emissions (calculated in Step 2) from the virgin product emissions (calculated in Step 1) to calculate the GHG savings. These results appear in Exhibit 9-14.

Exhibit 9-14: Differences in Emissions between Recycled and Virgin Structural Steel Manufacture ($MTCO_2E$/Short Ton)

	Product Manufacture Using 100% Virgin Inputs			Product Manufacture Using 100% Recycled Inputs			Difference Between Recycled and Virgin Manufacture		
Material	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Structural Steel	2.06	0.16	1.20	0.82	0.04	0.29	(1.27)	(0.12)	(0.91)

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. Processors discard this portion in either the recovery stage or the remanufacturing stage; and consequently, less than one short ton of new material generally is made from one short ton of recovered material. Material losses are quantified and translated into loss rates. The recycled input credits calculated earlier are, therefore, adjusted to account for any loss of product during the recycling process. Because the recovered structural steel is valuable and typically recovered on-site, the recovery stage retention rate for structural steel is high. EPA assumes that the recovery stage retention rate of structural steel is 98% based on the World Steel Association (2015). Losses are also incurred during the manufacturing stage. EPA assumes a manufacturing stage retention rate of 87% based on required inputs of 1.15 MT of scrap to produce 1 MT of steel sections (AISC, 2015). The net retention rate is calculated as follows:

Net Retention Rate for Structural Steel = Recovery Stage Retention Rate x Manufacturing Stage Retention Rate

= 98% x 87% = 85%

9.4.3 Composting

Because of the nature of structural steel components, structural steel cannot be composted, and thus, WARM does not include an emission factor for the composting of structural steel.

9.4.4 Combustion

Structural steel cannot be combusted; consequently, WARM does not include an emission factor for the combustion of structural steel.

9.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage and avoided utility emissions from landfill gas-to-energy recovery. However, because structural steel does not contain bio-degradable carbon, there are no emissions or offsets from landfill methane, landfill carbon storage, and avoided utility emissions associated with landfilling structural steel. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for structural steel is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. The landfilling emission factor for structural steel is summarized in Exhibit 9-15. For more information on landfilling, see the chapter on Landfilling.

Exhibit 9-15: Landfilling Emission Factor for Structural Steel ($MTCO_2E$/Short Ton)

Material	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)
Structural Steel	–	0.02	–	–	–	0.02

– = Zero emissions.

9.4.6 Anaerobic Digestion

Because of the nature of structural steel components, structural steel cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of structural steel.

9.5 LIMITATIONS

Although this analysis is based upon best available life-cycled data, it does have certain limitations. No studies are available that quantify the environmental impacts associated with either the deconstruction or scrap processing. The impact associated with this activity, however, which involve cutting or slicing steel sections into shorter lengths to allow for easier shipping and loading into the bucket for melting, are not expected to be significant.

9.6 REFERENCES

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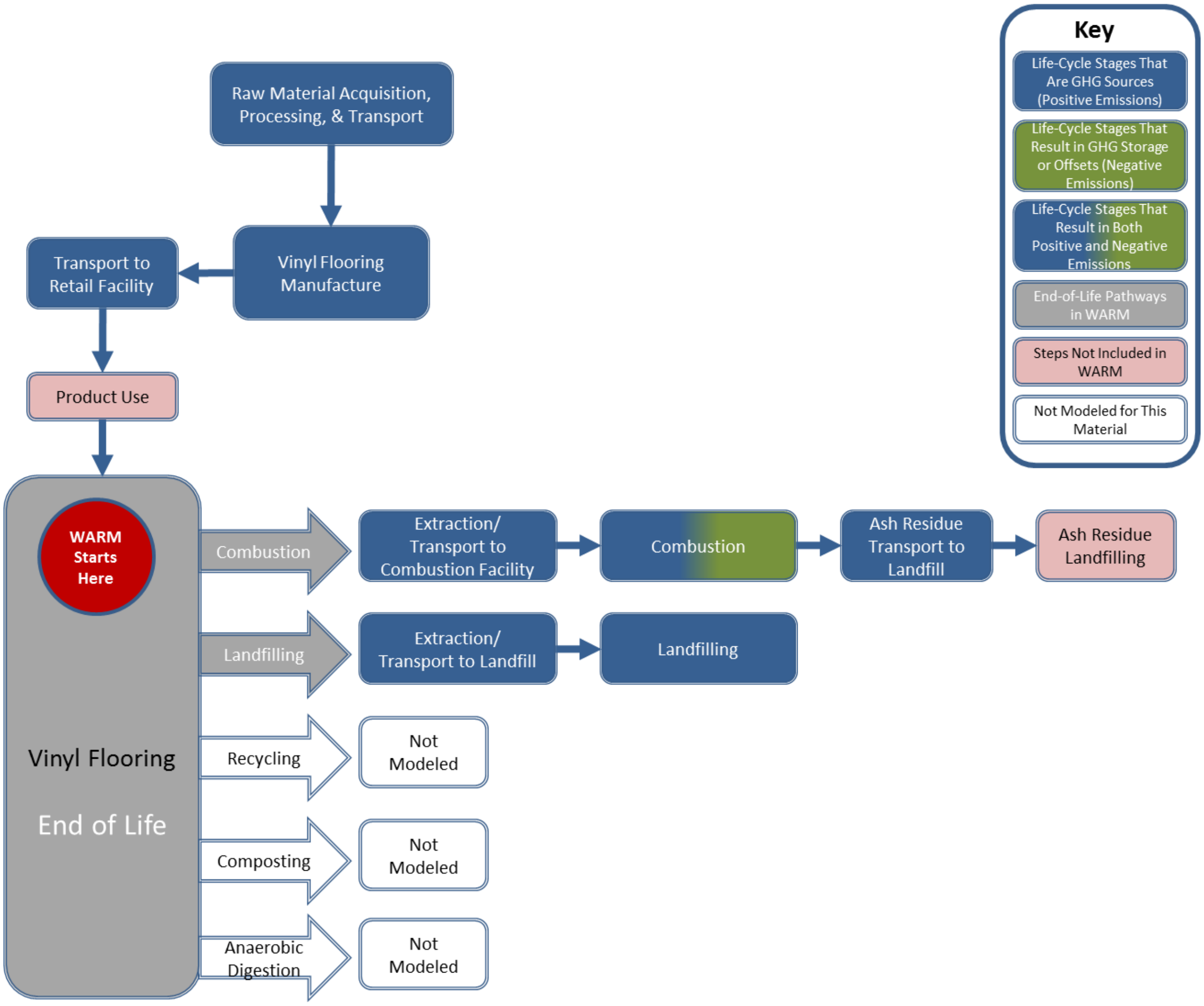
10 VINYL FLOORING

10.1 INTRODUCTION TO WARM AND VINYL FLOORING

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for vinyl flooring beginning at the waste generation reference point.[28] EPA uses the WARM GHG emission factors to compare the net emissions associated with vinyl flooring in the following three waste management alternatives: source reduction, combustion, and landfilling. Exhibit 10-1 shows the general outline of materials management pathways for vinyl flooring in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Combustion, and Landfilling, see the chapters devoted to those processes.

Exhibit 10-1: Life Cycle of Vinyl Flooring in WARM



Two major types of vinyl flooring, (1) sheet flooring and (2) tile, have applications in commercial and residential buildings. Vinyl composition tile (VCT) is the industry standard for most commercial

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[28] EPA would like to thank Mr. Richard Krock of The Vinyl Institute for his efforts to improve these estimates.

applications because it is durable, resilient, and relatively low cost. Sheet flooring is more commonly used in residential applications, such as kitchens and bathrooms, and generally it contains a higher percentage of vinyl resins, causing it to be more expensive.

All vinyl flooring is composed of polyvinyl chloride (PVC) resin along with additives, such as plasticizers, stabilizers, pigments, and fillers. Vinyl flooring products can be made using different manufacturing processes and material compositions. The density of vinyl flooring will also vary, depending on its intended use (Baitz et al., 2004). Some floors can contain as much as 55 percent vinyl, while others may contain as little as 11 percent (Vinyl in Design, 2009). For all PVC flooring products, the resin is applied over a backing material and a transparent protective wear layer is added on top. During installation, VCT is secured using adhesive tabs, spray, or a self-adhesive backing (Floor Ideas, 2009; Armstrong, 2009).

10.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The GHG life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and considers upstream GHG emissions only when the production of new materials is affected by material management decisions. Recycling and source reduction are the two materials management options that affect the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling, and Source Reduction.

WARM considers emission factors only for source reduction, combustion, and landfilling for vinyl flooring. As Exhibit 10-2 illustrates, all the GHG sources and sinks relevant to vinyl flooring in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 10-2: Vinyl Flooring GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Vinyl Flooring	GHG Sources and Sinks Relevant to Vinyl Flooring		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Virgin manufacture process energy • Virgin manufacture process non-energy • Transportation of raw materials and products	NA	NA
Recycling	Not modeled in WARM		
Composting	Not applicable because vinyl flooring cannot be composted		
Combustion	NA	NA	**Emissions** • Transport to combustion facility • Combustion emissions **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to construction and demolition landfill • Landfilling machinery
Anaerobic Digestion	Not applicable because vinyl flooring cannot be anaerobically digested		

WARM analyzes all the GHG sources and sinks outlined in Exhibit 10-2 and calculates net GHG emissions per short ton of vinyl flooring inputs. For more detailed methodology on emission factors, see

Sections 10.4.2 through 10.4.5. Exhibit 10-3 outlines the net GHG emissions for vinyl flooring under each materials management option.

Exhibit 10-3: Net Emissions for Vinyl Flooring under Each Materials Management Option (MTCO$_2$E/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Vinyl Flooring	(0.58)	NA	NA	(0.31)	0.02	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.
NA = Not applicable.
NE = Not estimated because data are insufficient.

10.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For vinyl flooring, the GHG emissions associated with RMAM are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes. Process non-energy GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption.

Vinyl flooring is composed of PVC resin along with additives such as plasticizers, stabilizers, pigments, and fillers. Each material is acquired, transported, and processed individually before being transported to the vinyl flooring processing facility. Vinyl flooring products can be made using different manufacturing processes and material compositions. EPA located publicly available life-cycle inventory (LCI) data for virgin VCT in *Building for Environmental and Economic Sustainability* (BEES®) (Lippiatt, 2007) and general data on PVC flooring in a European Commission report on PVC materials (Baitz et al., 2004). EPA used VCT data primarily from BEES to develop GHG emission factors for virgin manufacturing of vinyl flooring because of its applicability to the U.S. market and the transparency of the data relative to other sources.

According to BEES, VCT is manufactured from a vinyl polymer, plasticizer, and limestone with an acrylic latex finishing coat applied at tile manufacture (Lippiatt, 2007). Similarly, Baitz et al. (2004) estimates that, on average, vinyl flooring contains PVC resin, filler, plasticizers, pigments, and stabilizers. Today, the standard filler for vinyl is limestone; common stabilizers tend to be made of zinc, calcium, and tin; and the industry uses two plasticizers from the phthalate family, diisononyl phthalate and benzyl butyl phthalate (Helm, 2009). While stabilizers and process aides typically are used in vinyl flooring, they are not included in this analysis because sufficient data are lacking.

The RMAM calculation in WARM also incorporates retail transportation, which includes emissions for the average truck, rail, water, and other modes required to transport vinyl flooring from the manufacturing facility to the retail/distribution point, which may be the customer or various other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation appear in Exhibit 10-4. Transportation emissions from the retail point to the consumer are not included. EPA obtained the miles-travelled fuel-specific information from the 2007 U.S. Census Commodity Flow Survey (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 10-4: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions (MTCO$_2$E per Short Ton of Product)
Vinyl Flooring	497	0.54	0.04

10.4 MATERIALS MANAGEMENT METHODOLGIES

This analysis considers source reduction, landfilling, and combustion pathways for materials management of vinyl flooring. For vinyl flooring, source reduction and combustion result in net negative emissions (i.e., a net reduction in GHG emissions), while landfilling results in slightly positive net emissions.

10.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed previously, source reduction for vinyl flooring comes from avoided emissions associated with raw material acquisition and the VCT manufacturing process. For more information about source reduction, refer to the chapter on source reduction.

Exhibit 10-5 outlines the GHG emission factor for source reducing vinyl flooring. EPA calculated the GHG benefits of source reduction as the emissions savings from avoided raw materials acquisition and manufacturing (see Section 10.3) of vinyl flooring produced from 100-percent virgin inputs. EPA assumed the current mix is 100-percent virgin inputs because very little vinyl flooring is produced from recycled inputs.

Exhibit 10-5: Source Reduction Emission Factors for Vinyl Flooring (MTCO$_2$E/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Vinyl Flooring	(0.58)	(0.58)	NA	NA	(0.58)	(0.58)

– = Zero emissions.

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

10.4.1.1 Developing the Emission Factor for Source Reduction of Vinyl Flooring

To calculate the avoided GHG emissions for vinyl flooring, EPA first looked at three components of GHG emissions from RMAM activities: (1) process energy, (2) transportation energy, and (3) non-energy GHG emissions. Exhibit 10-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor follows.

Exhibit 10-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Vinyl Flooring (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Vinyl Flooring	0.51	0.09	0.01	0.61

To calculate this factor, EPA first obtained an estimate of the amount of energy required to acquire and produce one short ton of vinyl flooring. EPA obtained data on the extraction and processing of PVC resin from the National Renewable Energy Laboratory's (NREL) U.S. LCI Database, based on LCI data developed by Franklin Associates for the American Chemistry Council (Franklin Associates, 2007). EPA also used data on limestone manufacturing at the mine from the U.S. LCI Database. EPA obtained energy inputs for plasticizer manufacturing from a report prepared for the European Council for Plasticisers and Intermediates (ECPI) (ECOBILAN, 2001).

EPA gathered manufacturing data for vinyl acetate and styrene-butadiene adhesive from ecoinvent version 2.1 (ecoinvent Centre, 2008). The data for vinyl acetate manufacturing represents the European average at the plant, while data for adhesive manufacturing represents styrene-butadiene dispersion for latex at the plant. Both of these life-cycle datasets include infrastructure (i.e., energy and GHG emissions associated with producing the capital equipment used to make the products), which is not included in WARM's life-cycle boundaries. Because energy and GHG emissions associated with infrastructure are typically small, and the vinyl acetate and adhesive GHG emissions contribute to one percent and 10 percent of the total process energy respectively, EPA concluded that the additional inputs associated with infrastructure are likely small.

EPA took data on the manufacturing of vinyl flooring from the BEES model (Lippiatt, 2007). This source specifically analyzes VCT. Because the processing energy estimates for limestone, PVC, vinyl acetate, and VCT manufacturing do not include the pre-combustion energy of the fuels, pre-combustion values were added based on pre-combustion estimates by fuel types in Franklin Associates (2007). Although the plasticizer data do include pre-combustion energy, these estimates are representative of European processes. For consistency with the other inputs, EPA applied Franklin Associates pre-combustion energy estimates to the plasticizer. Pre-combustion energy is already included with the aggregated adhesive manufacturing data supplied by ecoinvent, and EPA was not able to disaggregate this data into pre-combustion and combustion estimates.

EPA then multiplied the amount of energy required to acquire and produce one short ton of vinyl flooring, broken down by fuel mix, by the fuel-specific carbon content. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions, including both carbon dioxide (CO_2) and methane (CH_4), from all fuel types used in vinyl flooring production. The process energy used to produce vinyl flooring and the resulting emissions appear in Exhibit 10-7.

Exhibit 10-7: Process Energy GHG Emissions Calculations for Virgin Production of Vinyl Flooring

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Vinyl Flooring	9.34	0.49

Transportation energy emissions result from fossil fuels used to transport raw materials and intermediate products for vinyl floor production. EPA obtained data on transportation of PVC resin from the NREL U.S. LCI Database, which is based on LCI data developed by Franklin Associates for the American Chemistry Council (Franklin Associates, 2007). The LCI Database assumes limestone manufacturing requires no transportation. EPA took transportation information for vinyl acetate from ecoinvent version 2.1 (ecoinvent Centre, 2008). Energy use associated with the transport of raw materials for plasticizer manufacturing is based on a report prepared for ECPI (ECOBILAN, 2001).

The BEES Model (Lippiatt, 2007) provides data on the transportation of each component to VCT flooring manufacturing, as well as the transportation of adhesives to the end user. EPA obtained data on retail transportation of the VCT flooring to the construction site from the U.S. Census Bureau (BTS, 2013).

The calculations for estimating the transportation energy emission factor for vinyl flooring appear in Exhibit 10-8.

Exhibit 10-8: Transportation Energy Emissions Calculations for Virgin Production of Vinyl Flooring

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Vinyl Flooring	0.72	0.05

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 10-4.

Process non-energy GHG emissions occur during manufacturing, but they are not related to consuming fuel for energy. Petrochemical processes generate process non-energy emissions in the production of PVC for vinyl flooring. To estimate these emissions, EPA applied non-energy process GHG emission factors for ethylene and ethylene dichloride and vinyl chloride monomer developed by the Intergovernmental Panel on Climate Change (IPCC) (2006, p. 3.74, 3.77). Exhibit 10-9 shows the components for estimating process non-energy GHG emissions for vinyl flooring.

Exhibit 10-9: Process Non-Energy Emissions Calculations for Virgin Production of Vinyl Flooring

Material	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)
Vinyl Flooring	0.00	0.00	–	–	–	0.01

– = Zero emissions.

10.4.2 Recycling

Use of post-consumer recycled PVC is possible, but the number of different VCT manufacturers and an inconsistent supply of post-consumer vinyl material make it difficult to develop a representative estimate. Lippiatt (2007, p. 167) assumes a conservative composition of one percent post-consumer recycled PVC. According to Helm (2009), vinyl manufacturers use post-consumer recycled content in the bottom layer of their vinyl products, where less purity is required. Numerous manufacturers, including Mannington, Centiva, and Toli, currently use post-consumer recycled PVC on the back of their products, although the PVC is generally sourced from other PVC products other than discarded vinyl flooring. Because the data available is insufficient, EPA did not include an emission factor in WARM for vinyl flooring recycling.

10.4.3 Composting

Vinyl flooring is not subject to aerobic bacterial degradation and cannot be composted; therefore, EPA did not include an emission factor in WARM for composting of vinyl flooring.

10.4.4 Combustion

Although vinyl flooring is not typically combusted in the United States, combustion is a common end-of-life pathway for vinyl flooring in other countries, specifically in Europe. Franklin Associates (2007) provides energy content of PVC resin. The combustion emission factor for vinyl flooring is summarized in Exhibit 10-10. For more information on combustion, please see the chapter on Combustion.

Exhibit 10-10: Components of the Combustion Net Emission Factor for Vinyl Flooring ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery Offsets	Net Emissions (Post-Consumer)
Vinyl Flooring	–	0.01	0.28	0.00	(0.62)	–	(0.33)

– = Zero emissions.

Note: Negative values denote net GHG emission reductions or carbon storage from a material management practice.

10.4.4.1 Developing the Emission Factor for Combustion of Vinyl Flooring

Raw Material Acquisition and Manufacturing: Because WARM takes a materials-management perspective (i.e., starting at end-of-life disposal of a material), RMAM emissions are not included for this materials management pathway.

Transportation to Combustion: EPA estimated GHG emissions from transportation energy use by relying on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL, 2009). The NREL emission factor assumes a diesel, short-haul truck.

CO_2 from Combustion and N_2O from Combustion: Vinyl flooring contains no nitrogen, and therefore, EPA estimated the emission factor for N_2O from combustion to equal zero.[29] EPA calculated CO_2 emissions from combustion based on the carbon contents of the PVC, vinyl acetate, and plasticizer components of vinyl flooring (38-, 49-, and 74-percent carbon, respectively).

Avoided Utility Emissions: Most Waste-to-Energy (WTE) plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with municipal solid waste (MSW) combustion would be in the form of electricity, and thus, EPA estimated the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant. Avoided utility emissions for vinyl flooring are negative. Exhibit 10-11 shows the calculation for the avoided utility emissions. EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in vinyl flooring to delivered electricity,[30] and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.[31] EPA used the energy content of PVC from FAL (2007, p. 1–12).

Exhibit 10-11: Utility GHG Emissions Offset from Combustion of Vinyl Flooring

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) ($e = b \times c \times d$)
Vinyl Flooring	15.8	17.8%	0.21	0.60

Because avoided utility emissions are greater than the combined emissions from transportation and CO_2 from combustion, net GHG emissions for combustion are negative for vinyl flooring.

10.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage and avoided utility emissions from landfill gas-to-energy recovery. Because vinyl flooring does not biodegrade, there are zero

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[29] At the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because vinyl flooring does not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N_2O emissions.

[30] EPA used a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, 1997), a MSW heat content of 10 million Btu per short ton, and a five percent transmission and distribution loss rate.

[31] The utility offset credit is calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, because it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling vinyl flooring. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for vinyl flooring is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. The landfilling emission factor for vinyl flooring appears in Exhibit 10-12. For more information on landfilling, see the chapter on Landfilling.

Exhibit 10-12: Landfilling Emission Factor for Vinyl Flooring ($MTCO_2E$/Short Ton)

Material	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)
Vinyl Flooring	–	0.02	–	–	–	0.02

– = Zero emissions.

10.4.6 Anaerobic Digestion

Because of the nature of vinyl flooring components, vinyl flooring cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of vinyl flooring.

10.5 LIMITATIONS

The vinyl flooring emission factor EPA developed in this chapter is representative of VCT, not sheet flooring. To the extent that data were available, the factor is representative of current VCT manufacturing processes in the U.S.

The life-cycle data EPA used to develop the emission factors for vinyl flooring were collected from various data sources because a literature search did not identify a complete, publicly available U.S.-specific dataset for vinyl flooring. In particular, EPA based the data used to evaluate the GHG emissions from manufacturing plasticizer and vinyl acetate and styrene-butadiene adhesive on European data; those data are representative of European practices. To address data quality issues arising from the use of a number of different data sources, EPA reviewed each source thoroughly to ensure that these data were high quality and applied in a manner that was consistent with WARM's life-cycle boundaries, and industry and life-cycle experts peer reviewed the final emission factors. Based on these quality-control checks and a review of the contribution of the European-specific data sets to the overall emission factors, EPA believes the overall impact on the final emission factor results is likely small.

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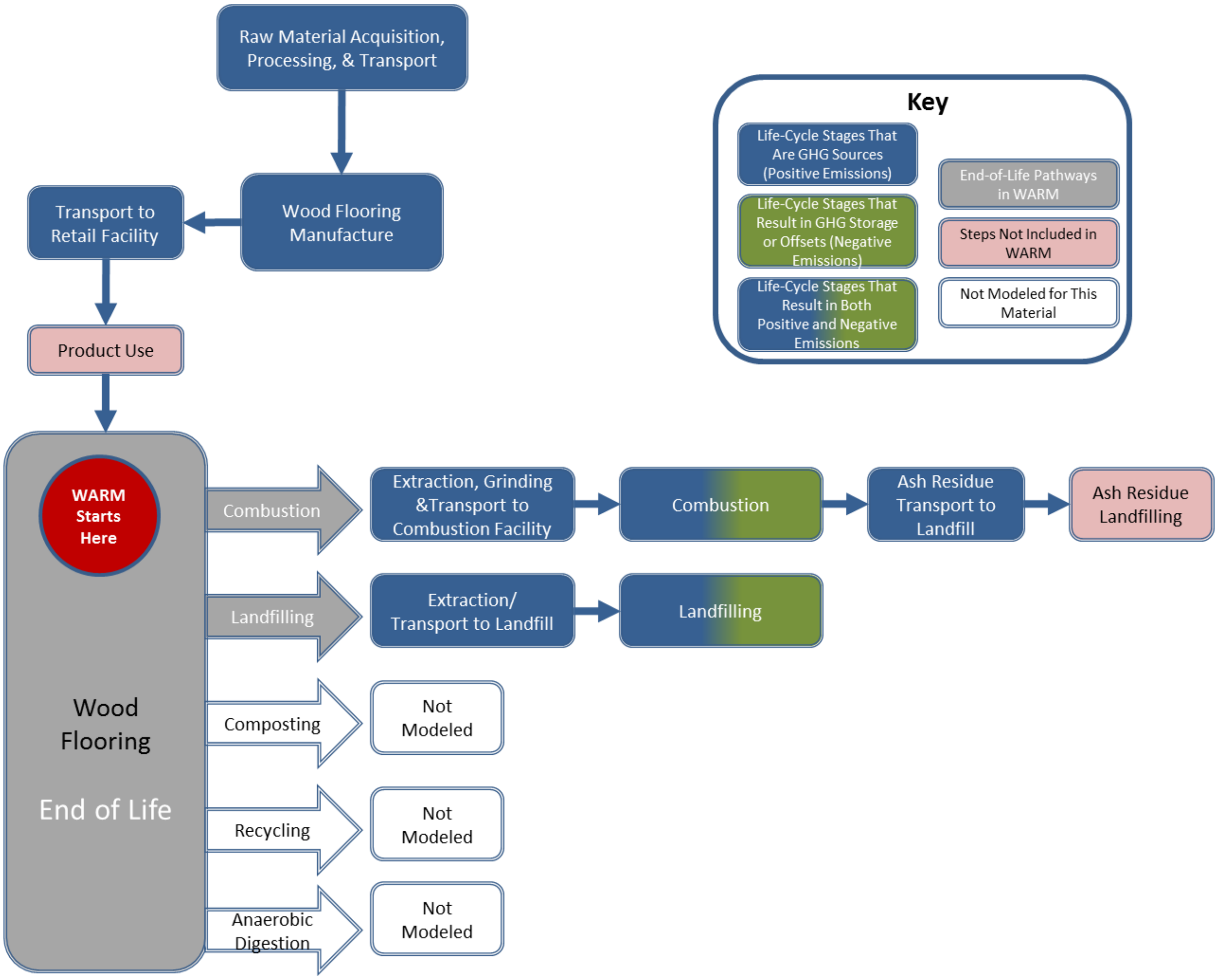
11 WOOD FLOORING

11.1 INTRODUCTION TO WARM AND WOOD FLOORING

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for wood flooring beginning at the waste generation reference point.[32] The WARM GHG emission factors are used to compare the net emissions associated with wood flooring in the following three waste management alternatives: source reduction, combustion, and landfilling. Exhibit 11-1 shows the general outline of materials management pathways for wood flooring in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Combustion, and Landfilling, see the chapters devoted to those 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 11-1: Life Cycle of Wood Flooring in WARM



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[32] EPA would like to thank Richard Bergman and Ken Skog of the USDA Forest Service, and Scott Bowe of the University of Wisconsin, for their efforts to improve these estimates.

Solid hardwood flooring is an established floor covering in the United States. Hubbard and Bowe (2008, p. 3) estimate that there are between 150 to 200 facilities that manufacture hardwood flooring in the country, accounting for 483 million square feet of annual production.

11.2 LIFECYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The streamlined[33] life-cycle boundaries in WARM start at the point of waste generation, 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 material management decisions. Recycling and Source Reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM considers emission factors for source reduction, combustion, and landfilling for wood flooring. As Exhibit 11-2 illustrates, the GHG sources and sinks relevant to wood flooring in this analysis are spread across all three sections of the life-cycle assessment: raw materials acquisition and manufacturing (RMAM), changes in forest or soil carbon storage, and materials management.

Exhibit 11-2: Wood Flooring GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Wood Flooring	GHG Sources and Sinks Relevant to Wood Flooring		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Avoided wood harvesting • Avoided lumber production • Avoided hardwood flooring production • Avoided transport to sawmill • Avoided on-site transport at sawmill • Avoided transport to flooring mill	**Offsets** • Increase in forest carbon storage **Emissions** • Decrease in carbon storage in in-use wood products	NA
Recycling	Not modeled in WARM		
Composting	Not modeled in WARM		
Combustion	NA	NA	**Emissions** • Transport to waste-to-energy facility • Transport of ash residue to landfill • Sizing wood flooring into wood chips • Nitrous oxide emissions **Offsets** • Avoided national average mix of fossil fuel power utility emissions

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[33] The analysis is streamlined in the sense that it examines GHG emissions only and is not a comprehensive environmental analysis of all environmental impacts from municipal solid waste management options.

Materials Management Strategies for Wood Flooring	GHG Sources and Sinks Relevant to Wood Flooring		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Landfilling	NA	**Offsets** • Landfill carbon storage	**Emissions** • Transport to C&D landfill • Landfilling machinery • Landfill methane emissions **Offsets** • Landfilling machinery
Anaerobic Digestion	Not modeled in WARM		

WARM analyzes all the GHG sources and sinks outlined in Exhibit 11-2 and calculates net GHG emissions per short ton of wood flooring inputs. For more detailed methodology on emission factors, please see the sections below on individual waste management strategies. Exhibit 11-3 below outlines the net GHG emissions for wood flooring under each materials management option.

Exhibit 11-3: Net Emissions for Wood Flooring under Each Materials Management Option (MTCO$_2$E/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Wood Flooring	(4.03)	NE	NA	(0.74)	(0.86)	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not Applicable.
NE = Not Estimated due to insufficient data.

11.3 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.[34] For virgin hardwood flooring, process energy GHG emissions result from wood harvesting, lumber production, planing, ripping, trimming, and molding. Transportation emissions are generated from transportation associated with wood harvesting, on-site transportation during lumber production and flooring manufacture, and transportation to the retail facility. EPA assumed that non-energy process GHG emissions from making wood flooring are negligible for two reasons. First, EPA was not able to locate data on the emissions associated with any sealants or other chemicals applied to wood flooring. Second, of the other processes that were modeled, the available data did not indicate that process non-energy emissions resulted.

To manufacture wood flooring, wood is harvested from forests and hardwood logs are transported to a sawmill. At the sawmill, hardwood logs are converted to green lumber. Next, green lumber is transported to the wood flooring mill, where it is loaded into a conventional kiln and dried to produce rough kiln-dried lumber. To bring the rough kiln-dried lumber into uniform thickness and to the desired lengths and widths, the lumber is subjected to planing, ripping, trimming, and molding. The output of these processes is unfinished solid strip or plank flooring with tongue-and-groove joinings. Finally, coatings and sealants can be applied to wood flooring in “pre-finishing” that occurs at the manufacturing facility, or on-site. Coatings and sealants applied to reclaimed wood flooring are most

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

likely applied on-site. The final wood flooring product is then packaged and transported to the retail facility.

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport wood flooring from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 11-4. Transportation emissions from the retail point to the consumer are not included. The miles travelled fuel-specific information is obtained from the *2007 U.S. Census Commodity Flow Survey* (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 11-4: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions ($MTCO_2E$ per Short Ton of Product)
Wood Flooring	293	0.32	0.02

11.4 MATERIALS MANAGEMENT METHODOLOGIES

The avoided GHG emissions from source reduction of wood flooring are sizable, due to both avoided process GHG emissions and increased forest carbon storage. GHG emissions are also reduced by combusting wood flooring at end of life. Emissions increase from landfilling wood flooring; this is primarily a result of methane emissions from the decomposition of wood in the landfill, although a large portion of the carbon stored within the wood does not degrade and remains sequestered in the landfill.

11.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed previously, under the measurement convention used in this analysis, the benefits of source reducing wood flooring come primarily from forest carbon sequestration, but additional savings also come from avoided emissions from the lumber harvesting process, production processes, and transportation. Since wood flooring is rarely manufactured from recycled inputs, the avoided emissions from source reducing wood flooring using the "current mix of inputs" is assumed to be the same as from using 100 percent virgin inputs. The avoided emissions are summarized in Exhibit 11-5. For more information about source reduction please refer to the chapter on Source Reduction.

Exhibit 11-5: Source Reduction Emission Factors for Wood Flooring ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Wood Flooring	(0.37)	(0.37)	(3.66)	(3.66)	(4.03)	(4.03)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.

11.4.1.1 Developing the Emission Factor for Source Reduction of Wood Flooring

To calculate the avoided GHG emissions associated with source reduction of wood flooring, EPA first looked at three components of GHG emissions from RMAM activities: process energy, transportation energy, and non-energy GHG emissions. There are no non-energy process GHG emissions from wood flooring RMAM activities. Exhibit 11-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 11-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Wood Flooring (MTCO$_2$E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Wood Flooring	0.27	0.10	–	0.37

– = Zero emissions.

There are three major stages in the production of virgin hardwood flooring: wood harvesting, lumber production, and hardwood flooring production. EPA was not able to locate a comprehensive resource that addresses all three stages, so three separate sources of life-cycle data were used: Venta and Nesbit (2000), Bergman and Bowe (2008), and Hubbard and Bowe (2008).

EPA obtained data on wood harvesting from Venta and Nesbit (2000), which represents North American harvesting practices.

EPA used estimates for wood flooring production in Bergman and Bowe (2008), which provided estimates for the process and transportation energy consumed during the manufacturing of rough kiln-dried lumber at hardwood sawmills in the U.S. Northeast/North Central regions. Process data obtained from this report includes electricity consumption (produced on- and off-site) and renewable fuel (biomass) burned in the production process. EPA assumed that the energy inputs consumed on-site are inclusive of the energy required to produce the wood residue and on-site electricity that are consumed in the lumber manufacturing process.

Hubbard and Bowe (2008) provided process data for hardwood flooring production in the U.S. Northeast/North Central regions. Process data obtained from this report includes grid electricity consumption, thermal usage (wood residue), and fossil fuels burned during flooring production. Because Hubbard and Bowe allocate energy inputs to wood flooring on a mass basis, EPA included energy inputs to the mass of wood residue that was used to provide thermal energy for the floor manufacturing process. Hubbard and Bowe do not include the pre-finishing application of coatings in their study due to "problematic weighting and data quality" (Hubbard and Bowe, 2008). Preliminary results from a study conducted by Richard Bergman on the environmental impact of pre-finishing engineered wood flooring on-site, however, suggest that the pre-finishing process consumes significant amounts of electricity. Systems used to dry the stains and coatings applied to the wood surface and systems to control emissions from pre-finishing both consume electricity (Bergman, 2010).

The estimates in Venta and Nesbit (2000), Bergman and Bowe (2008), and Hubbard and Bowe (2008) do not include the pre-combustion energy of the fuels. EPA added pre-combustion values based on pre-combustion estimates by fuel types in Franklin Associates (FAL, 2007). The process energy used to produce wood flooring and the resulting emissions are shown in Exhibit 11-7.

Exhibit 11-7: Process Energy GHG Emissions Calculations for Virgin Production of Wood Flooring

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO$_2$E/Short Ton)
Wood Flooring	12.97	0.27

Each of the three sources noted above contain transportation data for the various transportation steps required to produce wood flooring. Venta and Nesbit (2000) include data on transportation from the point of harvest to the sawmill. This source assumes a transportation distance of 350 kilometers by diesel-fueled truck. Bergman and Bowe (2008) include on-site transportation at the sawmill, which assumes consumption of off-road diesel, propane, and gasoline. Hubbard and Bowe (2008) include data on transportation from the sawmill to the flooring mills as well as on-site transportation at the flooring mill. This source assumes diesel-fueled trucks provide transportation to the flooring mill; on-site flooring mill transportation assumes consumption of off-road diesel, propane, and gasoline. The transportation energy used to produce wood flooring and the resulting emissions are shown in Exhibit 11-8.

Exhibit 11-8: Transportation Energy Emissions Calculations for Virgin Production of Wood Flooring

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Wood Flooring	1.08	0.08

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 11-4.

11.4.1.2 Forest Carbon Storage

In addition to RMAM emissions, forest carbon sequestration is factored into wood flooring's total GHG emission factor for source reduction. EPA calculated the increased forest carbon sequestration from wood flooring source reduction using the approach described in the Forest Carbon Storage chapter. This approach uses the U.S. Department of Agriculture Forest Service's (USDA-FS) FORCARB II model to estimate the change in forest carbon stocks as a function of marginal changes in harvest rates, and relates these changes to the reduction in harvesting from marginal increases in source reduction. The approach for wood flooring includes some unique characteristics not covered in the Forest Carbon Storage chapter, which are outlined here.

For wood flooring, EPA developed a separate analysis of the rates of change in carbon storage per cubic foot of wood harvested for hardwood forests. First, based on wood flooring mass balances in Hubbard and Bowe (2008) and Bergman and Bowe (2008), EPA assumed that source reducing one short ton of hardwood flooring would avoid harvesting 1.5 short tons of virgin hardwood.

Second, EPA investigated the effect that source reducing hardwood flooring has on non-soil carbon storage in forests. In contrast to FORCARB II's baseline scenario of hardwood harvests between 2010 and 2050, the USDA Forest Service runs a scenario where harvests from hardwood forests are reduced by 1.3 percent, or 13.8 million short tons, between 2010 and 2020 to examine the change in non-soil forest carbon stocks between 2020 and 2050. Harvests in all other periods are the same as the baseline.

EPA calculated the carbon storage benefit from reducing hardwood harvests by taking the difference in non-soil forest carbon stocks between the baseline and the reduced harvest scenario. EPA divided the change in carbon stocks by the incremental change in hardwood harvests to yield the incremental forest carbon storage benefit in metric tons of carbon per short ton of avoided hardwood harvest.

Third, EPA investigated the effect that source reduction of hardwood flooring has on carbon storage and GHG emissions from use and end-of-life disposal of hardwood flooring. Based on a model of harvested wood products developed by Ken Skog at the USDA Forest Service and parameters from Skog (2008) for the half-life of in-use wood products and end-of-life disposal fates, EPA investigated the change in carbon storage and GHG emissions across five hardwood flooring product pools: use, combustion, permanent storage in landfills, temporary storage in landfills, and emission as landfill gas from landfills.

This analysis showed that for source-reduced flooring that would have otherwise been sent to landfills for disposal, the foregone permanent carbon storage in landfills is largely cancelled out by the reduction in GHG emissions from the avoided degradation of hardwood into methane in landfills. As a result, the net forest carbon storage implications are driven primarily by forest carbon storage and storage in hardwood products. Furthermore, since WARM compares source reduction of wood flooring against a baseline waste management scenario, GHG emission implications from landfilling, combustion, or other practices used to manage end-of-life flooring are accounted for in the baseline. Consequently, the net forest carbon storage benefit from source reduction only needs to consider the effect that source reduction has on increasing forest carbon storage and decreasing carbon storage in in-use wood products.

The results of the analysis are shown below in Exhibit 11-9 and

Exhibit 11-10. The increase in non-soil forest carbon storage from source reducing flooring begins at 5.03 $MTCO_2E$ per short ton of hardwood flooring in 2030, and declines through 2050, although the rate of decline moderates over this time period. Carbon storage in products decreases as a result of source reducing hardwood, and this effect also declines over time as a greater fraction of hardwood leaves the in-use product pool for end-of-life management.

Over this time series, the net forest carbon storage benefit remains relatively insensitive to these changes, although moderating slightly in later years.

Exhibit 11-9: Components of the Cumulative Net Change in Forest Carbon Storage from Source Reduction of Wood Flooring

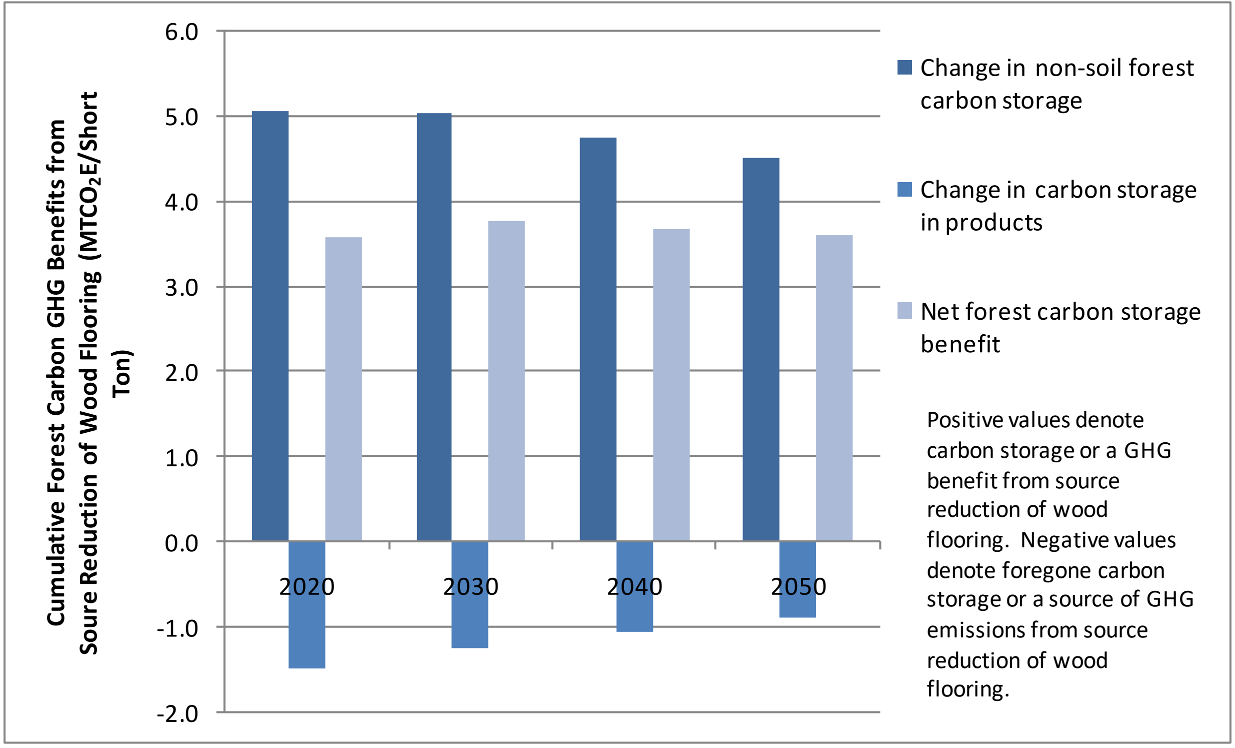

Exhibit 11-10: Forest Carbon Storage Calculations for Virgin Production of Wood Flooring (MTCO$_2$E/Short Ton)

Material	Forest Carbon Released	Carbon Released from Wood Products	Net Carbon Released
Wood Flooring	(4.84)	1.18	(3.66)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

The forest carbon storage estimate is subject to the same caveats and limitations discussed in the Forest Carbon Storage Section. Our results are also sensitive to the ratio of hardwood required to make flooring.

11.4.2 Recycling

Wood flooring that is in good condition at the end of a building's life can be recycled by using deconstruction or hand demolition to remove the flooring, followed by de-nailing, before reselling the wood for additional use (Falk & McKeever, 2004; Falk, 2002; Bergman, 2009). Larger wooden support timbers recovered from buildings prior to demolition can also be re-manufactured into wooden flooring. Although hand recovery of wood flooring is the most common procedure, heavy equipment such as power saws are increasingly being used to recover good-quality timbers and other materials during deconstruction (Bergman, 2009).

The USDA Forest Service has conducted primary data collection of recycled wood flooring and is in the process of compiling this data in a consistent LCI format. Because these data are not yet available, WARM does not include a recycling emission factor for wood flooring at this time.

11.4.3 Composting

Wood waste (including flooring) from C&D projects that has not been treated with chemical preservatives can be chipped or shredded for composting (FAL, 1998, pp. 3-7). While composting wood flooring is technically feasible, there is not much information available on composting wood products or the associated GHG emissions. As such, WARM does not consider GHG emissions or storage associated with composting wood flooring. However, this is a potential area for future research for EPA.

11.4.4 Combustion

Flooring and other wood wastes form a part of "urban wood waste" that is recovered from demolition sites or at C&D material recovery facilities, sized using wood chippers, and used as boiler fuel or combusted for electricity generation in biomass-to-energy facilities or co-firing in coal power plants (FAL, 1998, pp. 3-7; Hahn, 2009). Combustion of wood emits biogenic carbon dioxide and nitrous oxide emissions. For more information on Combustion, please see the chapter on Combustion.

To model the combustion of wood flooring, EPA used wood grinding fuel consumption data from Levis (2008, p. 231). To calculate the emissions, WARM relies on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL, 2009). The NREL emission factor assumes a diesel-fueled, short-haul truck. EPA assumed the energy content of wood flooring is 9,000 BTU per pound, or 18 million BTU per short ton (Bergman and Bowe, 2008, Table 3, p. 454).

To calculate avoided utility emissions from energy recovery, EPA assumed that wood flooring was combusted in a biomass power plant to produce electricity, with a heat rate of 15,850 BTU per kWh electricity output (ORNL, 2006, Table 3.11). EPA assumed that the energy supplied by wood flooring combustion offsets the national average mix of fossil fuel power plants, because these plants are most likely to respond to marginal changes in electricity demand. Exhibit 11-11 summarizes the combustion emission factor for wood flooring.

Exhibit 11-11: Components of the Combustion Net Emission Factor for Wood Flooring ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery Offsets	Net Emissions (Post-Consumer)
Wood Flooring	–	0.05[a]	–	0.04	(0.82)	–	(0.74)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.
[a] Includes wood grinding, transportation to combustion facility, and transportation of ash to landfill.

In addition to biomass power plants, urban wood waste and wood flooring may also be used to fuel co-fired coal power plant facilities, or in utility boilers. EPA conducted research to investigate the share of urban wood waste sent for different energy recovery applications, but was unable to develop an estimate of the relative share of wood sent to each pathway. This is an area for further study that could help refine the avoided utility emissions calculated for the wood flooring combustion pathway.

11.4.4.1 Developing the Emission Factor for Combustion of Wood Flooring

Raw Material Acquisition and Manufacturing: Because WARM takes a materials-management perspective (i.e., starting at end-of-life disposal of a material), RMAM emissions are not included for this materials management pathway.

Transportation to Combustion: EPA estimated GHG emissions from transportation energy use by relying on assumptions from FAL (1994) for the equipment emissions and NREL's US Life Cycle Inventory Database (USLCI) (NREL, 2009). The NREL emission factor assumes a diesel, short-haul truck.

CO_2 from Combustion and N_2O from Combustion: Combusting wood flooring results in emissions of nitrous oxide (N_2O) and those emissions are included in WARM's GHG emission factors for wood flooring.

Avoided Utility Emissions: Most waste-to-energy (WTE) plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with MSW combustion would be in the form of electricity, and thus estimated the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant (Exhibit 11-12).

Exhibit 11-12: Utility GHG Emissions Offset from Combustion of Wood Flooring

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
Wood Flooring	18.0	21.5%	0.21	0.82

Steel Recovery: There are no steel recovery emissions associated with wood flooring because it does not contain steel.

While N_2O and transportation emissions for wood flooring are positive emission factors, a greater amount of utility emissions are avoided, so the net GHG emissions for combustion are negative for wood flooring.

11.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. Wood flooring is an biodegradable material that results in some landfill methane emissions and carbon sequestration. Because C&D landfills generally do not have flaring systems, most of that methane is released to the atmosphere (Barlaz, 2009). In addition to these emissions, EPA assumed that the standard WARM landfilling emissions related to transportation and equipment use (EPA, 2006, p. 93). Several sources provide data on the moisture content, carbon storage factor, and methane yield of wood flooring (Levis et al., 2013; Wang et al., 2013; Wang et al., 2011). Due to lack of information about the decay conditions in C&D landfills, the landfilling emission factor assumes that the same conditions prevail as at municipal solid waste landfills, except that no collection of methane occurs. The methane and transportation emissions outweigh the carbon sequestration benefits, resulting in net emissions from the landfill, as illustrated in Exhibit 11-13. For more information on Landfilling, please see the chapter on Landfilling.

Exhibit 11-13: Landfilling Emission Factor for Wood Flooring ($MTCO_2E$/Short Ton)

Material	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)
Wood Flooring	–	0.02	0.16	0.00	(1.04)	(0.86)

— = Zero emissions.

11.4.6 Anaerobic Digestion

Because of the nature of wood flooring components, wood flooring cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of wood flooring.

11.5 LIMITATIONS

Composting is not included as a material management pathway due to a lack of information on the GHG implications of composting wood products. The composting factor in WARM, described in the Composting chapter, assumes a generic compost mix, rather than looking at materials in isolation. It is not currently known what effect adding large amounts of wood would have at a composting site, whether the GHG emissions or sequestration would be altered, or whether the carbon-nitrogen ratio would be affected. As a result, EPA has not estimated emission factors for composting. However, EPA is planning to conduct further research into this area that could enable better assessments of composting emission factors for wood products.

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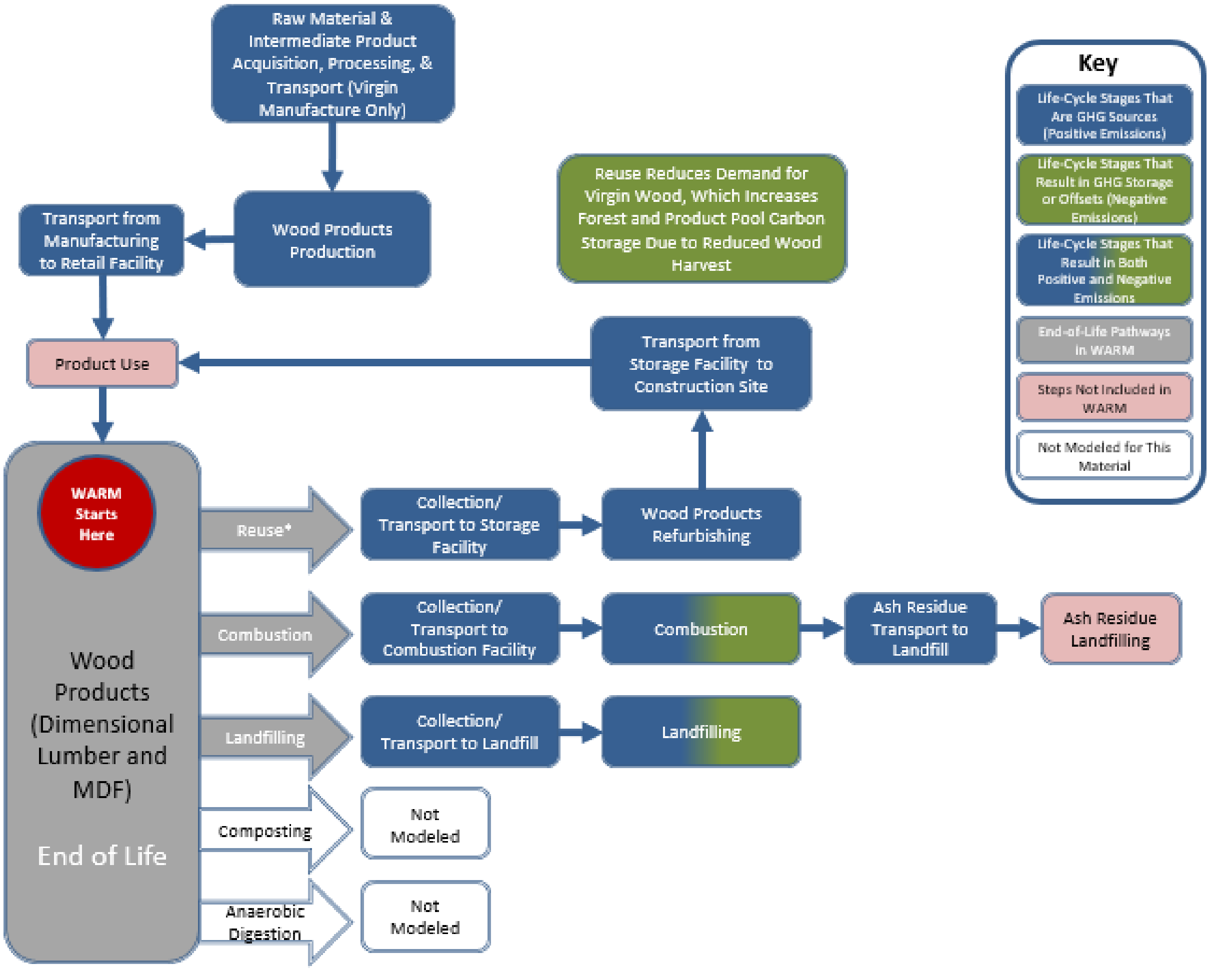
12 WOOD PRODUCTS

12.1 INTRODUCTION TO WARM AND WOOD PRODUCTS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for wood products beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with wood products in the following four materials management alternatives: source reduction, recycling, landfilling, and combustion. Although recycling of wood products is feasible, these materials are more commonly reused. As a result, EPA models the impacts associated with reuse (instead of recycling) under the recycling management pathway in WARM for wood products. Exhibit 12-1 shows the general outline of materials management pathways in WARM. For background information on the general purpose and function of WARM emission factors, see the WARM Background & Overview chapter. For more information on Source Reduction, Recycling, Combustion, and Landfilling, see the chapters devoted to those 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 12-1: Life Cycle of Wood Products in WARM



* Dimensional lumber is modeled as Reuse under the recycling management pathway in WARM.

The category “wood products” in WARM comprises dimensional lumber and medium-density fiberboard (MDF). Dimensional lumber includes wood used for containers, packaging, and buildings and includes crates, pallets, furniture, and lumber such as two-by-fours (EPA, 2018a). Fiberboard, including MDF, is a panel product that consists of wood chips pressed and bonded with a resin and is used primarily to make furniture (EPA, 1995). At end of life, dimensional lumber can be recovered for reuse, sent to a landfill or combusted; MDF can be sent to a landfill or combusted.

12.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle boundaries in WARM start at the point of waste generation—the point at which a material is discarded—and only consider upstream (i.e., material acquisition and manufacturing) GHG emissions when the production of new materials is affected by materials management decisions. Reuse (modeled under the Recycling management pathway) and source reduction are the two materials management options that impact the upstream production of materials and, consequently, are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

Composting is not included as a materials management pathway due to a lack of information on the GHG implications of composting wood products.[35] WARM also does not consider anaerobic digestion for wood products. Exhibit 12-2 illustrates the GHG sources and offsets that are relevant to wood products in this analysis.

Exhibit 12-2: Wood Products GHG Sources and Sinks from Relevant Materials Management Pathways

MSW Management Strategies for Wood Products	**GHG Sources and Sinks Relevant to Wood Products**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Transport of wood products to point of sale	**Losses** • Decrease in carbon storage in products **Offsets** • Increase in forest carbon storage	NA
Reuse	**Emissions** • Transport of recovered materials to construction site • Refurbishing process energy **Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Transport of wood products to point of sale	**Losses** • Decrease in carbon storage in products **Offsets** • Increase in forest carbon storage	**Emissions** • Deconstruction and transportation to storage facility
Composting	Not Modeled in WARM		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related N_2O **Offsets** • Avoided utility emissions

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[35] The composting factor in WARM, described in the Composting chapter, assumes a generic compost mix, rather than looking at materials in isolation. It is not currently known what effect adding large amounts of wood would have at a composting site, whether the GHG emissions/sequestration would be altered, or whether the carbon/nitrogen ratio would be affected.

MSW Management Strategies for Wood Products	GHG Sources and Sinks Relevant to Wood Products		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery **Offsets** • Carbon storage • Energy recovery
Anaerobic Digestion	Not Modeled in WARM		

NA = Not applicable.

WARM analyzes all the GHG sources and sinks outlined in Exhibit 12-2 and calculates net GHG emissions per short ton of inputs, shown in Exhibit 12-3 for the four materials management pathways. For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

Exhibit 12-3: Net Emissions for Wood Products under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction Emissions for Current Mix of Inputs	Net Reuse Emissions [a]	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Dimensional Lumber	(2.13)	(2.66)	NA	(0.58)	(0.92)	NA
MDF	(2.41)	NA	NA	(0.58)	(0.85)	NA

NA = Not applicable.

* Dimensional lumber is modeled as Reuse under the Recycling management pathway in WARM.

12.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

GHG emissions associated with raw materials acquisition and manufacturing (RMAM are (1) GHG emissions from energy used during the RMAM processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes. EPA assumes there are no non-energy process GHG emissions from wood product RMAM activities.

Dimensional lumber is mechanically shaped to standard dimensions in sawmills. Sawmill operations vary widely, but typically full logs are transported by truck to the mill, where they are graded for different uses. Electrically powered saws are used to cut the logs into different lengths, widths, and thicknesses. The cut boards are then stacked and placed in drying kilns. Waste wood from the process is used to generate process heat and, in some cases, electricity.[36] Once dry, the boards are planed to specific dimensions and a smooth finish before being shipped (NFI, 2010b).

In addition to serving as a source of energy for the lumber manufacturing process, waste wood is also used in the manufacture of structural panels, including MDF. The first step in manufacturing MDF is breaking down waste woodchips into their cellulosic fibers and resin. The fibers and resin are combined with wax or other binders and then subjected to high temperatures and pressure, requiring energy inputs that result in GHG emissions, to form the MDF (English et al., 1994; NFI, 2010a).

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average emissions from truck, rail, water, and other modes of transportation required to transport wood products from the manufacturing facility to the retail/distribution point, which may be the

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[36] CO_2 emissions produced from the combustion of waste wood for energy are considered biogenic and are excluded from WARM's emission factors.

customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 12-4. Transportation emissions from the retail point to the consumer are not included in WARM. The miles travelled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 12-4: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors ($MTCO_2E$/ Short Ton)
Dimensional Lumber	246	0.27	0.02
MDF	675	0.73	0.05

12.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM models four materials management alternatives for wood products: source reduction, reuse, combustion, and landfilling. For source reduction, net emissions depend not only on the management practice but also on the recycled content of the wood products. While MDF can be made from a combination of virgin and post-consumer recycled materials, EPA has not located evidence that MDF is manufactured with recycled material in the United States. Dimensional lumber cannot be manufactured from recycled material. As a result, WARM assumes that wood products that are source reduced or reused in the United States will offset 100% virgin inputs. Although all materials management options have negative emissions—driven primarily by carbon storage—as Exhibit 12-3 indicates, reusing wood products is the most beneficial.

12.4.1 Source Reduction

Source reduction activities reduce the quantity of dimensional lumber and MDF manufactured, reducing the associated GHG emissions. For more information on source reduction in general see the Source Reduction chapter. Exhibit 12-5 provides the breakdown of the GHG emissions factors for source reducing wood products. GHG benefits of source reduction are calculated as the avoided emissions from RMAM of each product. The GHG emission sources and sinks from source reduction include:

- *Process and transportation energy GHG emissions.* Producing dimensional lumber and MDF results in GHG emissions from energy consumption in manufacturing processes and transportation.
- *Carbon storage.* Reducing the quantity of dimensional lumber and MDF manufactured results in increased forest carbon stocks from marginal changes in harvest rates, but also reduces the carbon stored in in-use wood products. For more information, see the Forest Carbon Storage chapter.

Exhibit 12-5: Source Reduction Emission Factors for Wood Products ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Dimensional Lumber	(0.19)	(0.19)	(1.95)	(1.95)	(2.13)	(2.13)
MDF	(0.30)	(0.30)	(2.11)	(2.11)	(2.41)	(2.41)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.

12.4.1.1 *Developing the Emission Factor for Source Reduction of Wood Products*

To calculate the avoided GHG emissions for wood products, EPA first looked at three components of GHG emissions from RMAM activities: process energy, transportation energy, and non-energy GHG emissions. There are no non-energy process GHG emissions from wood product RMAM activities. Exhibit 12-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 12-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Wood Products ($MTCO_2E$/Short Ton)

(a) Material	(b) Process Energy [a]	(c) Transportation Energy [b]	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Dimensional Lumber	0.17	0.02	-	0.19
MDF	0.25	0.05	-	0.30

– = Zero emissions.

[a] Includes transportation energy that occurs during raw material acquisition and manufacturing.

[a] Represents retail transportation only.

Data on the processing and transportation energy requirements associated with producing dimensional lumber from virgin materials were obtained from Bergman et. al (2013) and American Wood Council (2013). Data on the processing and transportation energy requirements associated with producing MDF from virgin materials were obtained from Wilson (2010) and Composite Panel Association (2018). For each material, EPA multiplied the amount of energy required, broken down by fuel mix, by the fuel-specific carbon content and averaged the results from the two sources for each material. The process and transportation energy used to produce wood products and the resulting emissions appear in Exhibit 12-7.

Exhibit 12-7: Process and Transportation Energy GHG Emissions for Virgin Production of Wood Products

Material	Process and Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process and Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Dimensional Lumber	7.06	0.17
MDF	21.66	0.25

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 12-4.

In addition to RMAM emissions, forest carbon sequestration is factored into each wood product's total GHG emission factor for source reduction. Reducing the quantity of dimensional lumber and MDF manufactured increases forest carbon stocks from marginal changes in harvest rates, resulting in increased forest carbon storage. Conversely, source reduction also reduces the quantity of carbon stored in in-use wood products. Exhibit 12-8 provides the components of the overall forest carbon sequestration factor for wood products. For more information, see the Forest Carbon Storage chapter.

Exhibit 12-8: Net Change in Carbon Storage per Unit of Reduced Wood Product Production

(a) Material	(b) Reduction in Timber Harvest per Unit of Reduced Wood Product Production (Short Tons Timber/ Short Ton)	(c) Change in Forest C Storage per Unit of Reduced Timber Harvest (Metric Tons Forest C/ Metric Ton Timber)	(d) Change in C Storage in In-use Products per Unit of Reduced Wood Product Production ($MTCO_2E$/Short Ton)	(e) Net Change in C Storage per Unit of Reduced Wood Product Production ($MTCO_2E$/Short Ton) (e = b × c × 0.907 + d)
Dimensional Lumber	1.10	0.99	(1.66)	1.95
MDF	1.10	0.99	(1.50)	2.11

Note: Positive values denote an *increase* in carbon storage; negative values denote a *decrease* in carbon storage.

One metric ton = 0.907 short tons.

12.4.2 Reuse

In theory, dimensional lumber can be recycled in a closed-loop process (i.e., back into dimensional lumber). While recycling of dimensional lumber is an open-loop process is feasible, dimensional lumber that is recovered at end-of-life is more commonly reused. As a result, EPA models the impacts associated with reuse (instead of recycling) under the recycling management pathway in WARM for wood products. When dimensional lumber is recovered for reuse, it is transported for storage and product refurbishing (if necessary), and then transported to the construction site for reinstallation.

MDF is not an easy material to reprocess at end of life due to the resin used to bind the wood together. Several technologies have been developed to remove the resin including solutions or microwaves to break down the MDF and remove resin for manufacturing into a new MDF, but these technologies are typically energy and water intensive and are yet to be taken up by the industry (Greenxchange, 2014). As a result, recycling is not considered a viable management pathway for MDF.

The upstream GHG emissions from manufacturing the wood products are included as a “reuse input credit” by assuming that the reused material avoids (or offsets) the GHG emissions associated with producing the wood products from virgin inputs. Consequently, GHG emissions associated with management (i.e., collection, transportation, and processing) of waste wood products are included in the reuse credit calculation. In addition, there are forest carbon benefits associated with reuse. Each component of the reuse emission factor as provided in Exhibit 12-9 is discussed further in Section 12.4.2.1.

Exhibit 12-9: Reuse Emission Factor for Wood Products ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Reuse Input Credit[a] – Process and Transportation Energy	Reuse Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Dimensional Lumber	–	–	(0.11)	–	(2.55)	(2.66)
MDF	NA	NA	NA	NA	NA	NA

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.
[a] Includes emissions from the initial production of the material being managed.

12.4.2.1 Developing the Emission Factor for Reuse of Wood Products

EPA calculated the GHG benefits of reusing wood products by taking the difference between producing wood products from virgin inputs and producing wood products from recovered inputs, after accounting for losses that occur during the deconstruction process. This difference is called the “reuse input credit” and represents the net change in GHG emissions from process and transportation energy sources in reusing wood products relative to virgin production of wood products. There are no process non-energy emissions from the reusing of wood products.

To calculate each component of the reuse emission factor, EPA followed six steps, which are described in detail below.

Step 1. *Calculate emissions from virgin production of one short ton of wood products.* The GHG emissions from virgin production of wood products are provided in Exhibit 12-7.

Step 2. *Calculate GHG emissions for reuse production of wood products.* EPA obtained data on the process and transportation energy requirements associated with the reuse of dimensional lumber from Bergman et. al (2013). Exhibit 12-10 provides the process and transportation energy emissions associated with producing reused wood products.

Exhibit 12-10: Process and Transportation Energy GHG Emissions for Reuse of Wood Products

Material	Process Energy and Transportation per Short Ton Made from Reused Inputs (Million Btu)	Process Energy and Transportation Emissions ($MTCO_2E$/Short Ton)
Dimensional Lumber	0.55	0.04
MDF	NA	NA

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 12-4.

Step 3. *Calculate the difference in emissions between virgin and reused production.* To calculate the GHG emissions implications of reusing one short ton of wood products, WARM subtracts the reuse product emissions (calculated in Step 2) from the virgin product emissions (calculated in Step 1) to get the GHG savings. These results are shown in Exhibit 12-11. As shown, the energy and GHG emissions from reuse are less than those associated with virgin production of dimensional lumber.

Exhibit 12-11: Differences in Emissions between Reuse and Virgin Wood Product Manufacture ($MTCO_2E$/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)		Product Manufacture Using 100% Reused Inputs ($MTCO_2E$/Short Ton)		Difference Between Reuse and Virgin Manufacture ($MTCO_2E$/Short Ton)	
	Process and Transportation Energy [a]	Process Non-Energy	Process and Transportation Energy [a]	Process Non-Energy	Process and Transportation Energy [a]	Process Non-Energy
Dimensional Lumber	0.19	–	0.06	–	0.13	–

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.

[a] Includes emissions from retail transportation.

Step 4. *Adjust the emissions differences to account for reuse losses.* The reuse input credit calculated above is then adjusted to account for any loss of product during the reuse process. The difference between virgin and reused manufacture is multiplied by the product's net retention rate, which EPA assumes to be 83% based on Bergman et al. (2013).

Step 5. *Calculate the net change in carbon storage associated with reusing wood products.* These adjusted credits are then combined with the estimated forest carbon sequestration from reusing wood products to calculate the final GHG emission factor for reusing dimensional lumber. EPA estimated forest carbon storage in wood products, involving three parameters, as mentioned in the section on source reduction:

1. The change in timber harvests resulting from increased reuse of wood products;
2. The change in forest carbon storage as a result of a reduction in timber harvests; and
3. The change in carbon stored in in-use wood products from increased reuse.

Exhibit 12-12 provides data on these components of the overall forest carbon sequestration factor for dimensional lumber. Compared to source reduction of dimensional lumber, reuse results in a larger increase in net carbon storage (i.e., an additional 0.7 $MTCO_2e$ of carbon storage from reuse compared to source reduction, or the difference between 2.6 and 1.9 $MTCO_2e$). This result is driven by the change in carbon storage in in-use products. When wood products are reused, the reused wood remains in in-use products; when virgin wood products are avoided through source reduction, however, they do not enter the in-use pool of wood products. Consequently, the reduction in carbon storage in in-use wood products is less for reuse than it is for source reduction. For more information on forest carbon storage and each component of the overall factor, see the Forest Carbon Storage chapter.

Exhibit 12-12: Net Change in Carbon Storage per Unit of Increased Wood Product Reuse

(a) Material	(b) Reduction in Timber Harvest per Unit of Increased Wood Product Reuse (Short Tons Timber/ Short Ton)	(c) Change in Forest C Storage per Unit of Reduced Timber Harvest (Metric Tons Forest C/ Metric Ton Timber)	(d) Change in C Storage in In-use Products per Unit of Increased Wood Product Reuse ($MTCO_2E$/Short Ton)	(e) Net Change in C Storage per Unit of Increased Wood Product Reuse ($MTCO_2E$/Short Ton) ($e = b \times c \times 0.907 + d$)
Dimensional Lumber	0.88	0.99	(0.33)	2.55

Note: Positive values denote an increase in carbon storage; negative values denote a decrease in carbon storage.
One metric ton = 0.907 short tons.

Step 6. *Calculate the net GHG emission factor for reusing wood products.* The reuse credit calculated in Step 4 is added to the estimated forest carbon sequestration from reusing wood products to calculate the final GHG emission factor for reusing dimensional lumber, as shown in Exhibit 12-9.

12.4.3 Composting

While composting wood products is technically feasible, there is not much information available on composting wood products or the associated GHG emissions. As such, WARM does not consider GHG emissions or storage associated with composting wood products. However, this is a potential area for future research for EPA.

12.4.4 Combustion

Because carbon in wood products is considered to be biogenic, CO_2 emissions from combustion of wood products are not considered in WARM.[37] Combusting wood products results in emissions of nitrous oxide (N_2O), however, and these emissions are included in WARM's GHG emission factors for wood products. Transporting wood products to combustion facilities also results in GHG emissions from the combustion of fossil fuels in vehicles. Electricity produced from waste combustion energy recovery is used to offset the need for electricity production at power plants, consequently reducing the power sector's consumption of fossil fuels. WARM takes this into account by calculating an avoided utility emission offset.[38] Exhibit 12-13 provides the breakdown of each wood product's emission factor into these components.

Exhibit 12-14 provides the calculation for the avoided utility emissions. EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a waste-to-energy (WTE) plant: (1) the energy content of each waste material,[39] (2) the combustion system efficiency in converting energy in municipal solid waste (MSW) to delivered electricity,[40] and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants. For more information on combustion in general, see the Combustion chapter.

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[37] WARM assumes that biogenic CO_2 emissions are balanced by CO_2 captured by regrowth of the plant sources of the material. Consequently, these emissions are excluded from net GHG emission factors in WARM.

[38] The utility offset credit is calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, because it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

[39] Based on the higher end of the heat content range of basswood from the USDA Forest Service (Fons et al., 1962). Basswood is relatively soft wood, so its high-end energy content value is likely most representative of dimensional lumber and MDF wood products.

[40] EPA used a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, 1997) and accounted for transmission and distribution losses.

Exhibit 12-13: Components of the Combustion Net Emission Factor for Wood Products ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion[a]	N_2O from Combustion	Utility Emissions	Steel Recovery Offsets	Net Emissions (Post-Consumer)
Dimensional Lumber	–	0.01	–	0.04	(0.63)	–	(0.58)
MDF	–	0.01	–	0.04	(0.63)	–	(0.58)

– = Zero emissions.

[a] CO_2 emissions from combustion of wood products are assumed to be biogenic and are excluded from net emissions.

Exhibit 12-14: Utility GHG Emissions Offset from Combustion of Wood Products

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
Wood Products	16.6	17.8%	0.21	0.63

12.4.5 Landfilling

Wood products are often sent to landfills at the end of life. When wood products are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. Only CH_4 emissions are counted in WARM, because the CO_2 emissions are considered to be biogenic. In addition, because wood products are not completely decomposed by anaerobic bacteria, some of the carbon in these materials remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation. In addition, WARM factors in transportation of wood products to landfill, which results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in vehicles and landfilling equipment. Exhibit 12-15 provides the emission factors for dimensional lumber and MDF broken down into these components. More information on the development of the emission factor is provided in section 4.5.1. For more information on landfilling in general, see the Landfilling chapter.

Exhibit 12-15: Landfilling Emission Factors for Wood Products ($MTCO_2E$/Short Ton)

Material	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)
Dimensional Lumber	–	0.02	0.15	(0.00)	(1.09)	(0.92)
MDF	–	0.02	0.05	(0.00)	(0.92)	(0.85)

– = Zero emissions.

Negative values denote GHG emission reductions or carbon storage.

Note: The emission factors for landfill CH_4 presented in this table are based on national-average rates of landfill gas capture and energy recovery. Avoided CO_2 emissions from energy recovery are calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, because it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

12.4.6 Developing the Emission Factor for Landfilling of Wood Products

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. As detailed in the Landfilling chapter, there are three categories of landfills modeled in WARM: (1) landfills that do not recover landfill gas (LFG), (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. Direct use of landfill gas for process heat is not modeled. WARM calculates emission factors for each of these three landfill types and uses the national average mix of collection systems installed at landfills in the United States to calculate a national average emission factor that accounts for the extent to which CH_4 : (1) is not captured, (2) is flared without energy recovery, or (3) is combusted on-site for energy recovery.[41] The Landfill CH_4 column of Exhibit 12-15 presents emission factors based on the national average of LFG collection usage.

Exhibit 12-16 depicts the specific emission factors for each landfill gas collection type. Overall, landfills that do not collect LFG produce the most CH_4 emissions.

Exhibit 12-16: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2E$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation	Net Landfill Carbon Storage	GHG Emissions from Transport-ation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Dimensional Lumber	0.15	0.06	0.05	(1.09)	0.02	(0.92)	(1.01)	(1.02)
MDF	0.05	0.02	0.01	(1.92)	0.02	(0.85)	(0.88)	(0.89)

Note: Negative values denote GHG emission reductions or carbon storage.

WARM calculates landfill carbon storage from wood products based on laboratory test data on the ratio of carbon storage per wet short ton of wood landfilled documented in Barlaz (1998), Wang et al. (2011), and Wang et al. (2013). Exhibit 12-17 provides the landfill carbon storage calculation used in WARM.

Exhibit 12-17: Calculation of the Carbon Storage Factor for Landfilled Wood Products

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (g C Stored/Dry g)	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of C Storage to Wet Weight (g C/Wet g) (d = b × c)	(e) Amount of C Stored ($MTCO_2E$ per Wet Short Ton)
Dimensional Lumber	0.44	0.75	0.33	1.09
MDF	0.37	0.75	0.28	0.92

12.4.7 Anaerobic Digestion

Because of the nature of wood product components, wood products cannot be anaerobically digested, and thus, WARM does not include an emission factor for the anaerobic digestion of wood products.

12.5 LIMITATIONS

In addition to the limitations associated with the forest carbon storage estimates as described in the Forest Carbon Storage chapter, the following limitations are associated with the wood products emission factors:

- The source reduction factors for dimensional lumber and MDF are calculated by averaging the energy requirements associated with virgin production from two LCA studies.

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[41] Although gas from some landfills is piped to an off-site power plant and combusted there, for the purposes of this report, the assumption was that all gas for energy recovery was combusted onsite.

- A recycling factor is currently not provided for either dimensional lumber or MDF. A recycling factor may be developed in the future based on the availability of data.
- The process and transportation energy requirements associated with virgin production and reuse are presented as a combined total due to the level of granularity of the data used to develop the source reduction and reuse factors.
- Composting is not included as a material management pathway because of a lack of information on the GHG implications of composting wood products. The composting factor in WARM, described in the Composting chapter, assumes a generic compost mix, rather than looking at materials in isolation. It is not currently known what effect adding large amounts of wood would have at a composting site, whether the GHG emissions/sequestration would be altered, or whether the carbon/nitrogen ratio would be affected. As a result, EPA has not estimated emission factors for composting. However, EPA is planning to conduct further research in this area that could enable better assessments of composting emission factors for wood products.
- The energy content (by weight) for dimensional lumber and MDF is assumed to be the same, while in fact they may be different since MDF contains resins that bind the wood fibers together. EPA does not expect that this difference would have a large influence of the combustion emission factors.

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