

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)**

***Containers, Packaging, and Non-Durable Good
Materials Chapters***

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

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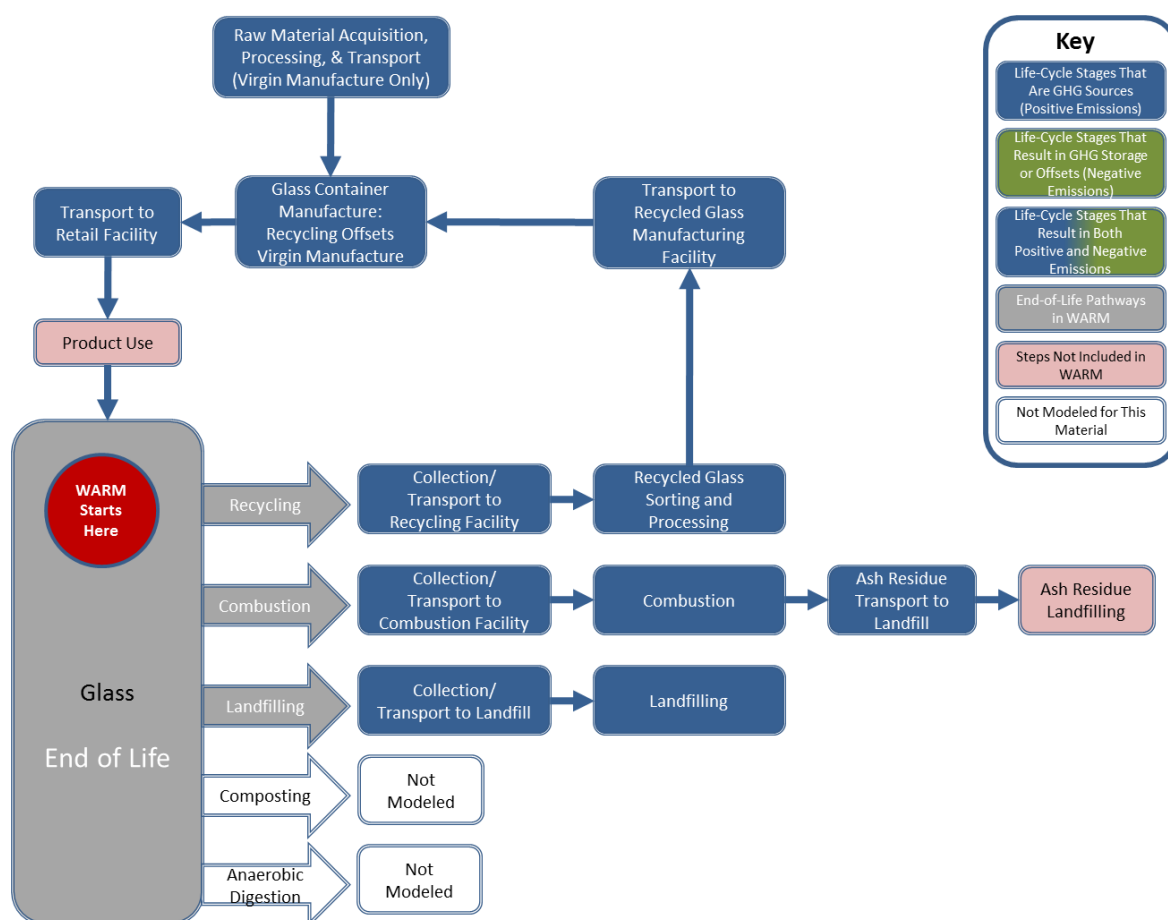
1 GLASS

1.1 INTRODUCTION TO WARM AND GLASS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined streamlined life-cycle greenhouse gas (GHG) emission factors for glass, beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with glass in glass in the following four materials management alternatives: source reduction, recycling, landfilling, and and combustion.

Exhibit 1-1 shows the general outline of materials management pathways for glass 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](#), [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.

Exhibit 1-1: Life Cycle of Glass in WARM



WARM assumes that all glass waste is in the form of containers and packaging, including beer and soft drink bottles, wine and liquor bottles, and food and other bottles and jars. The model does not account for glass waste that is a component of durable goods such as appliances, furniture and consumer electronics, or for other types of glass such as the flat or plate glass used in picture frames, mirrors or windows.

The recovery and subsequent recycling of glass is considered to be a closed-loop process (i.e., glass bottles and jars are remanufactured into more glass bottles and jars).

1.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

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

The overall life-cycle energy associated with manufacturing glass from virgin inputs and recycled inputs is shown in Exhibit 1-2.

Exhibit 1-2: Process and Transportation Energy for Manufacture of Glass Using Virgin and Recycled Inputs

Material	Virgin Manufacture			Recycled Manufacture		
	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Total	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Transportation Energy per Short Ton Made from Recycled Inputs (Million Btu)	Total
Glass	6.49	0.58	7.08	4.32	0.34	4.66

Source: RTI (2004).

As Exhibit 1-3 illustrates, most of the GHG sources relevant to glass in this analysis fall under the raw materials acquisition and manufacturing section of the life-cycle. The recycling and source reduction pathways are most relevant to glass since the upstream emissions associated with glass production are significant. Glass does not contain carbon and does not generate CH₄ emissions when landfilled. Therefore, the emissions associated with landfilling glass include only transportation- and landfill-equipment-related emissions. Glass cannot be composted or anaerobically digested and therefore these pathways are not considered in WARM.

Exhibit 1-3: Glass GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Glass	GHG Sources and Sinks Relevant to Glass		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Offsets <ul style="list-style-type: none"> • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy 	NA	NA

¹ 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 Glass	GHG Sources and Sinks Relevant to Glass		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Recycling	Emissions <ul style="list-style-type: none"> • Transport of recycled materials • Recycled manufacture process energy • Recycled manufacture process non-energy Offsets <ul style="list-style-type: none"> • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy 	NA	Emissions <ul style="list-style-type: none"> • Collection and transportation to recycling center • Sorting and processing energy
Composting	Not applicable since glass cannot be composted		
Combustion	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to WTE facility • Energy required for combustion
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to landfill • Landfilling machinery
Anaerobic Digestion	Not applicable since glass cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 1-3 and calculates net GHG emissions per short ton of glass generated for each materials management alternative as shown in Exhibit 1-4. For additional discussion on the detailed methodology used to develop these emission factors, see sections 1.3 and 1.4.

Exhibit 1-4: Net Emissions for Glass under Each Materials Management Option (MTCO₂E/Short Ton)

Material	Net Source Reduction (Reuse) GHG Emissions For Current Mix of Inputs	Net Recycling GHG Emissions	Net Composting GHG Emissions	Net Combustion GHG Emissions	Net Landfilling GHG Emissions	Net Anaerobic Digestion Emissions
Glass	-0.53	-0.28	NA	0.03	0.02	NA

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

NA = This materials management option is not applicable to this material.

1.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

For glass, the 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 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.

The typical composition of container glass is shown in Exhibit 1-5. The first step in glass manufacture is mining, transporting and processing the minerals that will be the glass inputs. The mining, transportation and processing steps use energy and emit energy-related GHGs. Once the glass inputs are transported to the glass manufacturing facility, the main processes in glass manufacture are batch preparation, melting and refining, forming and post forming (DOE, 2002).

Batch preparation. Varied quantities of raw ingredients are blended together, based on the type of glass being manufactured. Glass inputs must include: *formers*, the main component of the glass; *fluxes*, which lower the temperature at which the glass melts; and *stabilizers*, which make the glass more chemically stable and increase the strength of the finished product. The typical composition of container glass is shown in Exhibit 1-5; other ingredients such as colorants may be added. This manufacturing stage consumes fossil fuels used for energy production, resulting in energy-related GHG emissions (DOE, 2002).

Exhibit 1-5: Typical Composition of Modern Container Glass

Chemical	Purpose	Source	% Composition
Silica (SiO ₂)	Former	Sand	72% to 73.5%
Soda (Na ₂ O)	Flux	Soda ash (Na ₂ CO ₃) from trona ore	12% to 14%
Potash (K ₂ O)	Flux	Mined and processed potassium salts	0.6%
Lime (CaO)	Stabilizer	Limestone (CaCO ₃)	9% to 12%
Magnesia (MgO)	Stabilizer	Impurity in limestone	1.2% to 2.0%
Alumina (Al ₂ O ₃)	Stabilizer	Feldspar	1.2% to 2.0%

Source: DOE (2002).

Melting and refining. The glass is melted in a furnace to the correct temperature, and bubbles and other inclusions are removed. This manufacturing stage results in both energy emissions and non-energy process CO₂ emissions from the heating of carbonates (soda ash and limestone) (DOE, 2002).

Forming. The molten glass is formed into its final shape. The glass can be molded, drawn, rolled, cast, blown, pressed or spun into fibers. Commercial glass containers are formed using molds. This manufacturing stage consumes fossil fuels used for energy production, resulting in energy-related GHG emissions (DOE, 2002).

Post-Forming. Various processes may be applied to the formed glass, depending on the results desired, including curing, annealing, tempering, coating and cutting. Container glass is annealed and usually coated with scratch-resistant coatings consisting of a thin layer of tin or titanium oxide followed by a lubricant such as polyethylene. This manufacturing stage uses energy and results in energy-related GHG emissions (DOE, 2002).

The RMAM calculation in WARM also incorporates “retail transportation,” which consists of the average truck, rail, water and other-modes transportation emissions required to get the glass from the manufacturing facility to the retail/distribution point. The energy and GHG emissions from retail transportation are presented in Exhibit 1-6, and are calculated using data on average shipping distances and modes from the U.S. Bureau of Transportation Statistics (BTS, 2013) and on typical transportation fuel efficiencies from EPA (1998). Transportation emissions from the retail point to the consumer are not included.

Exhibit 1-6: 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)
Glass	356	0.39	0.03

The total RMAM emissions for glass manufacturing are shown in the section on source reduction. The net emission factors for source reduction and recycling of glass include RMAM “upstream” emissions.

1.4 MATERIALS MANAGEMENT METHODOLOGIES

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

Glass is rarely manufactured from 100 percent virgin inputs or 100 percent recycled inputs. Exhibit 1-7 shows the range of recycled content used for manufacturing glass. Therefore “virgin” glass as referred to in the rest of this chapter is assumed to contain 5 percent recycled inputs.

Exhibit 1-7: Typical Glass Recycled Content Values in the Marketplace

Material	Recycled Content Minimum	Recycled Content Maximum
Glass	5%	30%

Glass is most frequently manufactured using “virgin” inputs, or a very low percentage of recycled inputs. However, it is also manufactured using higher amounts of recycled inputs than in “virgin” production. The current mix of production from recycled and “virgin” inputs used for manufacturing glass is shown in Exhibit 1-8.

Exhibit 1-8: Current Mix of Production from Virgin and Recycled Inputs for Glass Manufacturing

Product	% of Current Production from Recycled Inputs	% of Current Production from "Virgin" Inputs
Glass	23%	77%

Note: Rounded to nearest percentage.

The emission factors for source reduction and recycling are affected by the mix of inputs used for the manufacturing process. The emission factor for glass produced from the current mix of virgin and recycled inputs is calculated using a weighted average of virgin and recycled glass production data, based on the values in Exhibit 1-8. WARM also calculates an emission factor for producing glass from “virgin” inputs, assuming a recycled content of 5 percent (the industry minimum recycled content). GHG implications and emission factors for glass in each pathway are discussed in sections 4.1 through 4.5.

1.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the post-consumer waste are avoided. As discussed previously, under the measurement convention used in this analysis, source reduction for glass 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 1-9 outlines the GHG emission factor for source reducing glass. GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see section 3) of glass produced from a “current mix” of virgin and recycled inputs or from glass produced from “100-percent virgin” inputs.²

² The “100 percent virgin” inputs emission factor assumes a minimum recycled content of 5 percent, since glass is rarely manufactured from entirely virgin inputs.

Exhibit 1-9: Source Reduction Emission Factors for Glass (MTCO₂E/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
Glass	-0.53	-0.60	NA	NA	-0.53	-0.60

NA = Not applicable.

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

1.4.1.1 Developing the Emission Factor for Source Reduction of Glass

To produce glass, substantial amounts of energy are 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 CO₂. In addition, manufacturing glass also results in process non-energy CO₂ 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 1-10.

Exhibit 1-10: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Glass (MTCO₂E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Glass	0.37	0.07	0.16	0.60

Source: RTI (2004).

To calculate this factor, EPA obtained an estimate of the amount of energy required to acquire and produce one short ton of glass, which is reported as 6.49 million Btu (RTI, 2004). Next, we determined the fuel mix that comprises this Btu estimate (RTI, 2004) and then 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 CO₂ and CH₄, from all fuel types used in glass production. The process energy used to produce glass and the resulting emissions are shown in Exhibit 1-11.

Exhibit 1-11: Process Energy GHG Emissions Calculations for Virgin Production of Glass

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
Glass	6.49	0.37

Source: RTI (2004).

Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for glass production. The methodology for estimating these emissions is the same as the one used for process energy emissions. Based on estimated total glass transportation energy (RTI, 2004), EPA calculates the total emissions using fuel-specific carbon coefficients. The calculations for estimating the transportation energy emission factor for glass are shown in Exhibit 1-12.

Exhibit 1-12: Transportation Energy Emissions Calculations for Virgin Production of Glass

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Glass	0.58	0.04

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 1-6.

Non-energy GHG emissions occur during manufacturing but are not related to consuming fuel for energy. For glass, non-energy CO₂ 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). Exhibit 1-13 shows the components for estimating process non-energy GHG emissions for glass.

Exhibit 1-13: Process Non-Energy Emissions Calculations for Virgin Production of Glass

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
Glass	0.16	–	–	–	–	0.16

– = Zero emissions.

1.4.2 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. According to EPA, 34 percent of glass containers and packaging in the U.S. municipal solid waste stream are recycled each year (EPA, 2015). Glass, like most of the materials in WARM, is modeled as being recycled in a closed loop. This section describes the development of the recycling emission factor for glass, which is shown in the final column of Exhibit 1-14. For more information, please refer to the [Recycling](#) chapter.

Exhibit 1-14: Recycling Emission Factor for Glass (MTCO₂E/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)
Glass	–	–	-0.12	-0.02	-0.14	–	-0.28

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

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

1.4.2.1 Developing the Emission Factor for the Recycling of Glass

EPA calculates the GHG benefits of recycling glass by comparing the difference between the emissions associated with manufacturing a short ton of glass from recycled materials and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in 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 process non-energy sources in recycling glass relative to virgin production of glass.

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

Step 1. *Calculate emissions from virgin production of one short ton of glass.* We apply fuel-specific carbon coefficients to the process and transportation energy use data for virgin RMAM of glass (RTI, 2004). This estimate is then summed with the emissions process non-energy emissions (ICF, 1994) to calculate the total emissions from virgin production of glass. The calculations for virgin process, transportation and process non-energy emissions for glass are presented in Exhibit 1-11, Exhibit 1-12, and Exhibit 1-13, respectively.

Step 2. *Calculate GHG emissions for recycled production of glass.* WARM applies the same fuel-specific carbon coefficients to the process and transportation energy use data from RTI (2004) for the production of recycled glass, as shown in Exhibit 1-15 and Exhibit 1-16. There were no process non-energy emissions from recycled production of glass. These sources are summed to calculate the total emissions from the production of recycled glass.

Exhibit 1-15: Process Energy GHG Emissions Calculations for Recycled Production of Glass

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO ₂ E/Short Ton)
Glass	4.32	0.23

Exhibit 1-16: Transportation Energy GHG Emissions Calculations for Recycled Production of Glass

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO ₂ E/Short Ton)
Glass	0.34	0.02

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 1-6.

Step 3. *Calculate the difference in emissions between virgin and recycled production.* To calculate the GHG emissions savings from recycling one short ton of glass, WARM subtracts the recycled 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 1-17.

Exhibit 1-17: Differences in Emissions between Recycled and Virgin Glass Manufacture (MTCO₂E/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs (MTCO ₂ E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO ₂ E/Short Ton)			Difference Between Recycled and Virgin 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
Glass	0.37	0.07	0.16	0.23	0.05	–	-0.14	-0.02	-0.16

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 glass collected for recycling that is lost during the recovery or remanufacturing process, and ultimately disposed of. WARM applies a 2.4 percent loss rate for glass (FAL, 2003; RTI, 2004). The differences in emissions from virgin versus recycled process energy, transportation energy and non-energy processing are adjusted to account for the loss rates by multiplying the final three columns of Exhibit 1-17 by 97.6 percent, the amount of material retained after losses (i.e., 100 percent input – 2.4 percent lost = 97.6 percent retained).

1.4.3 Composting

Glass is not subject to aerobic bacterial degradation, and therefore, cannot be composted. Consequently, WARM does not include composting as an end-of-life pathway for glass.

1.4.4 Combustion

WARM estimates (1) gross emissions of CO₂ and N₂O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) CO₂ emissions avoided due to displaced electric utility generation. WARM subtracts GHG emissions avoided from energy recovery from direct combustion GHG emissions to obtain an estimate of the net GHG emissions from MSW.

Glass, however, cannot be combusted, and instead absorbs a small amount of heat during MSW combustion that could otherwise be recovered and used to produce electricity. Consequently, Exhibit 1-18 shows that the emission factor for combusting glass includes transportation to the facility and a small increase in utility emissions for power generation that would otherwise have been avoided if the glass were not sent to the combustor.

Exhibit 1-18: Components of the Combustion Net Emission Factor for Glass (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO ₂ from Combustion	N ₂ O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Glass	–	0.01	–	–	0.02	–	0.03

– = Zero emissions.

1.4.4.1 Developing the Emission Factor for Combustion of Glass

Raw Material Acquisition and Manufacturing: Since 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 0.01 MTCO₂E for one short ton of glass (FAL, 1994).

CO₂ from Combustion and N₂O from Combustion: Glass does not contain any C or N, so the emission factors for CO₂ and N₂O from combustion are estimated to equal zero.³

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 CO₂ emissions associated with combustion of waste in a WTE plant. Avoided utility emissions for glass, however, are positive. This means that, instead of being avoided, emissions increase slightly due to the presence of glass in MSW at combustion facilities. EPA developed these estimates from data on the specific heat of glass (Incropera and DeWitt, 1990), and calculated the energy required to raise the temperature of glass from ambient temperature to the temperature found in a combustor (about 750° Celsius). Therefore, the amount of energy absorbed by one ton of glass in an MSW combustor would have resulted in less than 0.02 MTCO₂E of avoided utility CO₂, if the glass had not been sent to the combustor.

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

³ At the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N₂O emissions is derived from the waste, not from the combustion air. Because glass does not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N₂O emissions.

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

1.4.5 Landfilling

WARM considers the CH₄ emissions, transportation-related CO₂ emissions and carbon storage that will result from landfilling each type of organic waste and mixed MSW. Because glass is not an organic material, it does not generate CH₄ or sequester any carbon when landfilled. The only emissions associated with landfilling glass are those from transporting glass to the landfills and moving waste around in the landfills. Transportation of waste materials results in anthropogenic CO₂ emissions due to the combustion of fossil fuels in the vehicles used to haul the wastes. For further information, please refer to the chapter on [Landfilling](#). Exhibit 1-19 provides the net emission factor for landfilling glass.

Exhibit 1-19: Landfilling Emission Factor for Glass (MTCO₂E/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)
Glass	–	0.02	–	–	–	0.02

– = Zero emissions.

1.4.6 Anaerobic Digestion

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

1.5 LIMITATIONS

EPA did not consider glass contained in durable goods as part of this analysis due to the lack of relevant data.

1.6 REFERENCES

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2 METALS

2.1 INTRODUCTION TO WARM AND METALS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for aluminum and steel cans and copper wire, beginning at the waste generation reference point. The WARM GHG emission factors are used to compare the net emissions associated with these three types of metal in the following four materials management options: source reduction, recycling, landfilling and combustion. The rest of this module provides details on these materials management options as life-cycle pathways for metals. Exhibit 2-1 through Exhibit 2-3 show the general outlines of materials management pathways for metals 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](#), [Landfilling](#), and [Combustion](#), see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHG emissions. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the [Energy Impacts](#) chapter.

Exhibit 2-1: Life Cycle of Aluminum Ingot and Cans in WARM

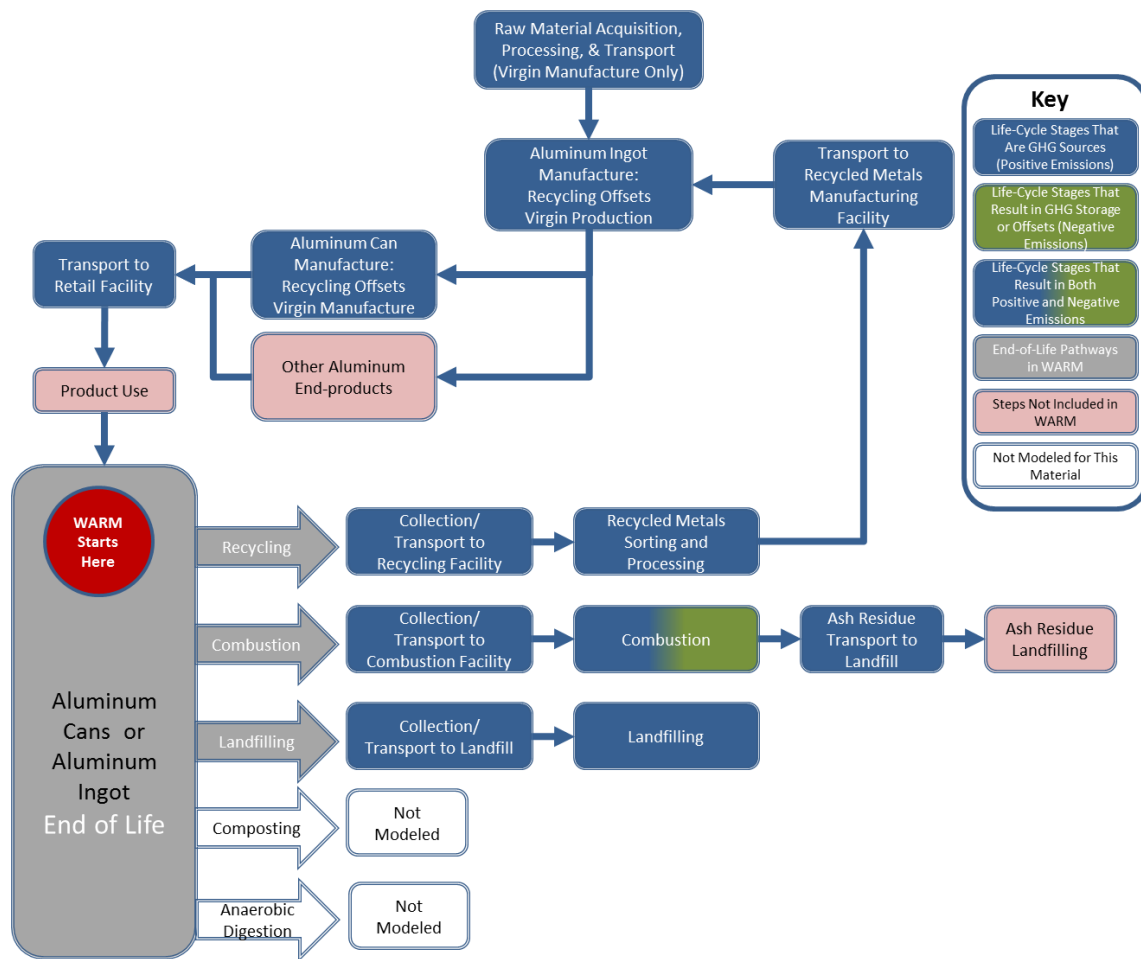


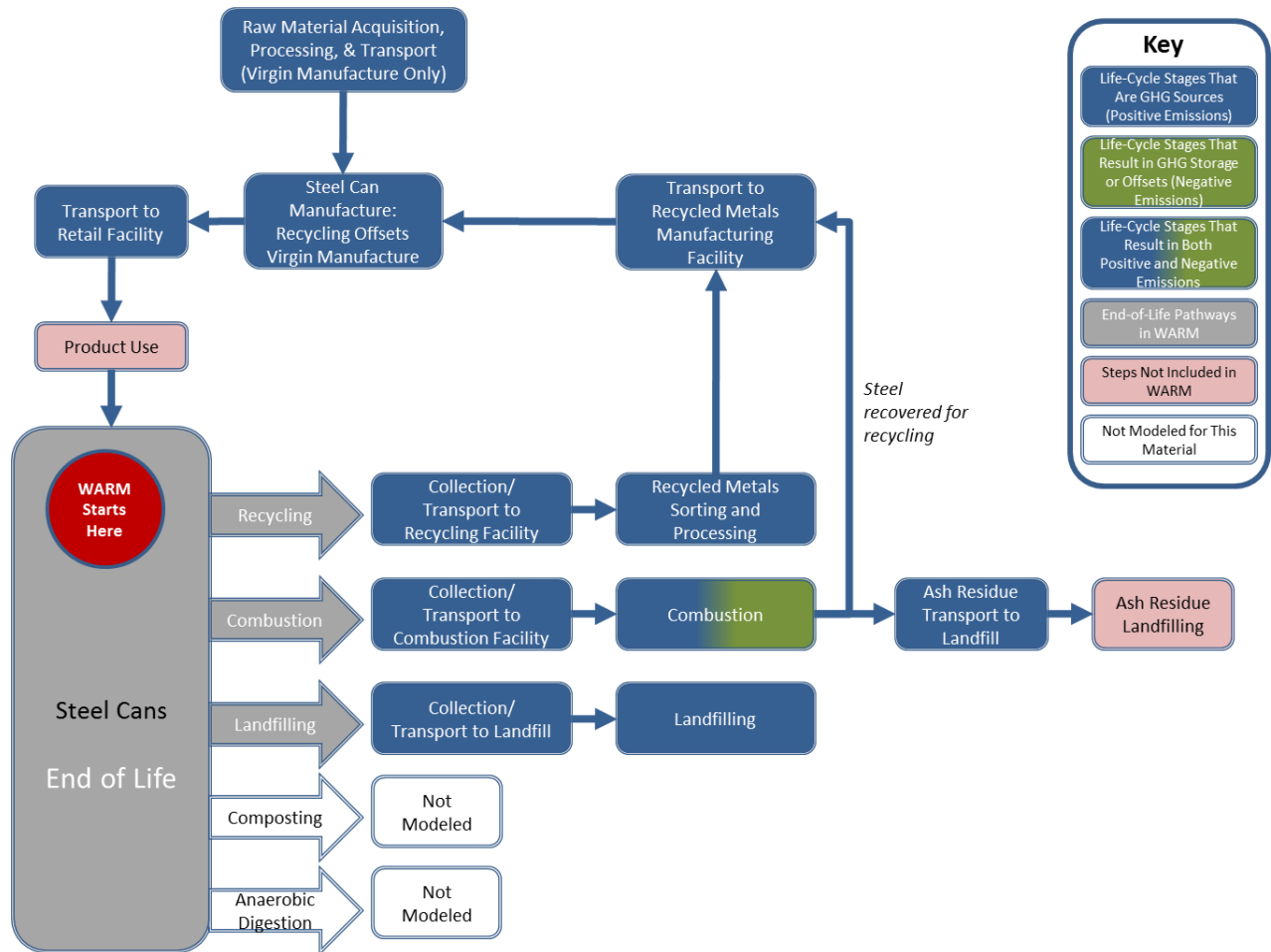
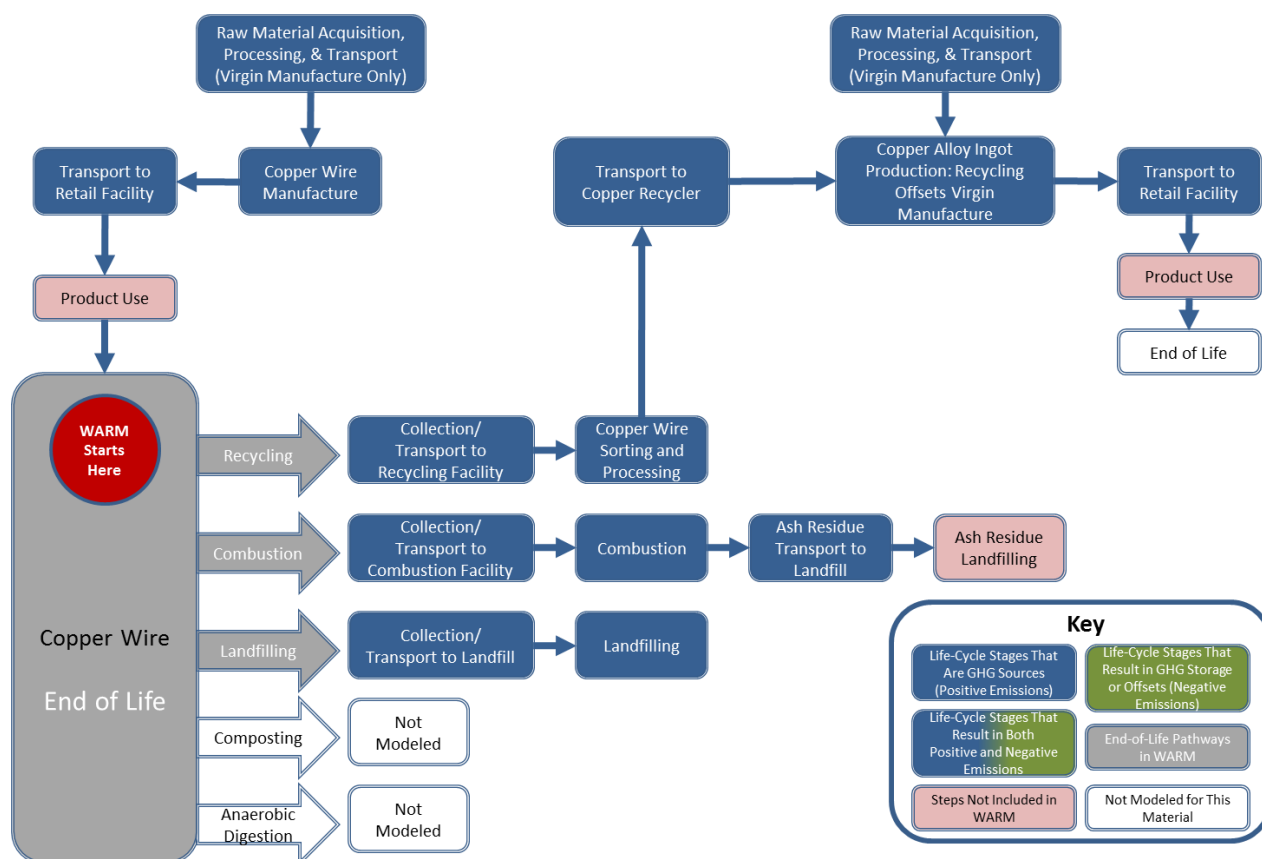
Exhibit 2-2: Life Cycle of Steel Cans in WARM

Exhibit 2-3: Life Cycle of Copper Wire in WARM

The metals category in WARM comprises copper wire, steel cans, and aluminum cans and ingot.⁴ There are many types of metals in the waste stream, but these three categories were selected because they are among the most common materials found in municipal solid waste (MSW), and because these have been identified as having a large GHG impact across their life cycles; they also have well-developed recycling infrastructures and good data availability.

According to EPA's (2015a) report, *Advancing Sustainable Materials Management: Facts and Figures 2013*, steel cans and aluminum cans represent the majority of the metals used for "containers and packaging" (i.e., excluding durable goods) in the MSW stream, as indicated in column (c) of

Exhibit 2-4. Copper wire is not accounted for separately in the *Facts and Figures* report, and probably makes up a relatively small percentage of the metals waste generated in the United States. However, copper has a large difference in energy use between virgin and recycled manufacture, and thus was added to broaden the range of metals in WARM. Life-cycle data for copper wire were obtained in part

⁴ Metals can be employed in various sectors and products, but WARM focuses on container and packaging end-uses for aluminum and steel and electrical end-uses for copper wire. Other major uses of aluminum in addition to those considered in WARM are: construction, consumer durables, electrical, machinery and equipment, transportation and other industrial uses. For steel, other major uses are: service centers and distributors, construction, transportation and other industrial uses. Other major uses of copper include building construction, industrial machinery and equipment, transportation equipment, and consumer and general products.

from research on personal computers and their raw material inputs as explained in the Personal Computers chapter.

Exhibit 2-4: Relative Prevalence of Metals in the Waste Stream in 2013

(a) Material	(b) Generation (Short Tons)	(c) % of Total Container Metal Generation	(d) Recovery (Short Tons)	(e) % of Total Metals Recovery	(f) Recovery Rate
Aluminum Cans	1,390,000	43%	700,000	35%	50%
Aluminum Ingot	NA	NA	NA	NA	NA
Steel Cans	1,870,000	57%	1,320,000	65%	71%
Copper Wire	NA	NA	NA	NA	NA

Source: EPA (2015a).

NA = Not available.

The recovery and subsequent recycling of aluminum and steel cans is considered to be a closed-loop process (i.e., primary material type is remanufactured into the same material type). The recycling of copper wire is considered open loop, where copper wire is remanufactured into a different secondary product (namely, copper alloy). The basic WARM definitions of the materials are shown below:

Aluminum Ingot: Aluminum ingot is processed from molten aluminum in the form of a sheet ingot suitable for rolling, extruding, or shape casting. Thus, it serves as a pre-cursor to manufacture of aluminum products such as aluminum cans (PE Americas, 2010).

In WARM, the aluminum ingot energy and GHG emissions factors are designed to be used as a proxy for certain aluminum materials including:

- Electrical transmission and distribution wires⁵, other electrical conductors, some extruded aluminum products, and/or aluminum product cuttings, joinings, and weldings.
- Any products where aluminum alloy is used but the fabrication techniques are not clear or in a mixture. For instance, aluminum used in consumer durable products such as home appliances, computers, and electronics.

However, it should be noted that using the aluminum ingot material type as a proxy for the aluminum materials mentioned above does not factor in the energy and emissions associated with the additional processing of aluminum ingot to produce a final aluminum product, which are likely to be quite significant. Thus, the resultant energy and GHG emissions impacts of managing aluminum products as represented by the WARM aluminum ingot factors likely underestimate the true impacts.

Aluminum cans. Aluminum cans are produced out of sheet-rolled aluminum ingot and are used mostly as containers for beverages such as soft drinks and beer (PE Americas, 2010).

Steel cans. Steel cans are three-piece welded cans produced from sheet steel (made in a blast furnace and basic oxygen furnace for virgin cans, or electric arc furnace for recycled cans) and are used mostly for non-beverage canned foods (EPA, 1998a).

Copper wire. Copper wire is drawn from copper rod and is used in various applications, including power transmission and generation lines, building wiring, telecommunication and electrical and electronic products (EPA, 2005; FAL, 2002).

⁵ Note, not electric cables since the plastic, rubber or fiber skin of the cable are important contributors to life cycle GHG impacts

Mixed metals. The mixed metals category is estimated by taking a weighted average using the latest relative recovery rates for steel and aluminum cans (see column (e) of Exhibit 2-4).

2.2 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.⁶ 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. The upstream manufacturing process for each metal category considered for WARM is summarized in section 2.3. For further information on evaluating upstream emissions, see the chapters on [Recycling](#) and [Source Reduction](#).

The overall life-cycle energy associated with manufacturing aluminum cans, steel cans and copper wire from virgin inputs and recycled inputs is given in Exhibit 2-5.

Exhibit 2-5: Life-Cycle Energy Associated with Manufacture (with 100% Virgin and 100% Recycled Inputs)

Material	Virgin Manufacture		Recycled Manufacture	
	Process Energy per Ton Made from Virgin Inputs (Million Btu)	Transportation Energy per Ton Made from Virgin Inputs (Million Btu)	Process Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)
Aluminum Cans	184.74	0.91	36.24	0.44
Aluminum Ingot	115.16	0.56	4.50	0.22
Steel Cans	31.58	4.60	11.78	4.03
Copper Wire	122.52	0.46	101.05	2.17

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 2-8.

As Exhibit 2-6 illustrates all of the GHG sources relevant to metals in this analysis fall under the raw materials acquisition and manufacturing and end-of-life sections of the life cycle. The recycling and source reduction pathways have the largest emission factors for metals since the upstream emissions associated with metals production are significant.⁷ Metals do not contain carbon and do not generate CH₄ emissions when landfilled. Therefore, the emissions associated with landfilling metals include only transportation- and landfill-equipment-related emissions. Metals cannot be composted or anaerobically digested and therefore these pathways are not considered in WARM.

⁶ 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.

⁷ In versions of WARM prior to version 13, source reduction of mixed material categories (e.g., metals, plastic, and paper) was not activated because mixed categories are not an individual product and therefore cannot be directly source reduced. The source reduction pathway for mixed metals, however, has been activated since general efficiency improvements and reduction strategies that affect aluminum and steel use broadly may result in source reduction across the mixed metal category. In some cases, WARM users may not have information on exactly which types of metals are being reduced, and may therefore wish to approximate changes using the mixed category.

Exhibit 2-6: Metals GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Metals	GHG Sources and Sinks Relevant to Metals		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Offsets <ul style="list-style-type: none"> • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy • Transport of metals to point of sale 	NA	NA
Recycling	Emissions <ul style="list-style-type: none"> • Transport of recycled materials • Recycled manufacture process energy • Recycled manufacture process non-energy Offsets <ul style="list-style-type: none"> • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy 	NA	Emissions <ul style="list-style-type: none"> • Collection and transportation to recycling center A. Sorting and processing energy
Composting	Not applicable since metals cannot be composted		
Combustion	NA	NA	Emissions <ul style="list-style-type: none"> B. Transport to WTE facility • Energy required for combustion Offsets <ul style="list-style-type: none"> C. Steel recovery and recycling
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to landfill D. Landfilling machinery
Anaerobic Digestion	Not applicable since metals cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 2-6 and calculates net GHG emissions per short ton of metal generated for each materials management alternative as shown in Exhibit 2-7. For additional discussion on the detailed methodology used to develop these emission factors, see sections 2.3 and 2.4.

Exhibit 2-7: Net Emissions for Metals under Each Materials Management Option (MTCO₂E/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
Aluminum Cans	-4.91	-9.11	NA	0.04	0.02	NA
Aluminum Ingot	-7.47	-7.19	NA	0.04	0.02	NA
Steel Cans	-3.06	-1.81	NA	-1.57	0.02	NA
Copper Wire	-7.01	-4.71	NA	0.03	0.02	NA
Mixed Metals	-3.70	-4.34	NA	-1.02	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 metals, the 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 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. For example, the production of steel and aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or CaCO₃), and the manufacture of lime results in CO₂ emissions.

The RMAM calculation in WARM also incorporates “retail transportation,” which includes the average truck, rail, water and other-modes transportation emissions required to transport these metals from the manufacturing facility to the retail/distribution point. The energy and GHG emissions from retail transportation are presented in Exhibit 1-6. Transportation emissions from the retail point to the consumer are not included. The number of miles traveled and mode-specific fuel use information is obtained from the 2012 Bureau of Transportation Statistics *Commodity Flow Survey* (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998c), respectively. The “base metal in primary or semifinished forms and in finished basic shapes” commodity in the Commodity Flow Survey is used as a proxy for all three metal types.

Exhibit 2-8: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emission Factors (MTCO ₂ E per Short Ton of Product)
Aluminum Cans	331	0.359	0.027
Aluminum Ingot	331	0.359	0.027
Steel Cans	331	0.359	0.027
Copper Wire	331	0.359	0.027

The total RMAM emissions for metals manufacturing are shown in the section on source reduction. The net emission factors for source reduction and recycling of metals include RMAM “upstream” emissions.

2.3.1 Aluminum Cans and Ingot

Aluminum cans are produced out of sheet-rolled aluminum ingot. Raw material inputs to the aluminum smelting process include bauxite, limestone, salt and coal, which must be mined and transported; crude oil, which must be extracted, refined and transported; and petroleum coke and caustic soda, which must be produced from their respective raw material sources and transported. All of these processes (mining, raw material extraction/production and transportation) result in emissions through the burning of fossil fuels for process energy and transportation, and through non-energy production processes. These inputs are necessary to produce alumina (aluminum oxide—Al₂O₃— from bauxite, which is the most important commercial aluminum ore), smelt it to aluminum, cast ingots, roll them to sheet and produce cans from aluminum sheet.

Anode production: This life-cycle analysis also considers production of anodes for electrolysis of alumina. After the alumina is refined, it undergoes electrolysis in reduction cells to produce molten aluminum. These reduction cells are generally pre-bake and Söderberg.⁸ The anodes in a pre-bake cell are pre-fired blocks of solid carbon suspended in the cell. The Söderberg has a single anode covering

⁸ PE Americas, 2010 assumes 85 percent of aluminum production is from prebake and the remaining 15% is from Söderberg facilities as per International Aluminum Institute data.

most of the top surface of the cell into which the anode paste (or briquettes) is fed. The anodes (prebake blocks or briquettes) are manufactured identically through calcining and grinding of petroleum coke and blending it with pitch. This paste is allowed to cool into briquettes or blocks. The briquettes are used directly in the Söderberg cell, but the blocks are first sent to a baking facility before being used in the pre-bake reduction cell. The embedded energy component of the carbon anode, which is consumed during the electrolytic reduction process and made from coal, is included in this analysis.

Aluminum smelting: Smelting (reducing) of alumina to pure aluminum metal requires a great deal of energy, leading to high process-energy emissions from aluminum production. Smelting takes place in a molten cryolitic (Na_3AlF_6) bath that is lined with carbon, which serves as the cathode. The alumina breaks down into aluminum and oxygen when electric current is passed through this solution. Non-energy process emissions occur in the form of CO_2 because during reduction most of the carbon is oxidized and released to the atmosphere as CO_2 . Non-energy process emissions also occur in the form of PFCs (perfluorocarbons), tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6). During smelting, the fluorine in the cryolite reacts with the carbon in the anode. Although the quantities of PFCs emitted are small, these gases are significant because of their high global warming potentials. .

Ingot casting: Molten aluminum is discharged to an ingot casting facility, where it is pretreated and combined with high quality scrap and cast into aluminum ingots. Ingot casting and smelting usually occur in the same facility; hence, the fuel mix for electricity consumption by both processes is assumed to be the same.

The life-cycle fuel consumption and emissions up to the ingot casting life cycle stage are used to calculate the energy and GHG emission factors for aluminum ingot.

Aluminum sheet rolling: Ingots cast from recycled and/or virgin metal are processed into intermediate products like can stock by heating and rolling. Trim and other internally generated scrap is collected and remelted. The energy inputs account for the large amounts of scrap that are rolled, collected, remelted and recycled back into the sheet rolling process.

Aluminum can and lid fabrication: Aluminum coil (coiled aluminum sheet) is transported to can fabrication plants.⁹ Lids and the bodies of the cans are fabricated separately but are usually manufactured at the same facility. However, dedicated lid plants may also exist. The lids are formed from a different alloy than that used for can bodies. Fabrication involves stamping of stock sheet into a circular blank that is formed into a cup and then drawn, ironed and shaped into the can body. Various coatings and decorations are added to cans to form the final product (PE Americas, 2010).

2.3.2 Steel Cans

Steel cans for WARM are defined as three-piece welded cans produced from sheet steel that is made in a blast furnace and basic oxygen furnace (for virgin cans) or electric arc furnace (for recycled cans). Production of (tin-coated) steel cans involves mining of iron ore, limestone, coal and lime. These inputs are then used to produce pig iron, manufacture steel sheet and finally produce steel cans.

Pig iron production. Iron is produced by first reducing iron oxide or the iron ore with metallurgical coke in a blast furnace to produce an impure form of iron called pig iron. This pig iron is then used as a raw material for the production of steel.

Steel manufacture. Pig iron forms the basic material for steel manufacture. Steel can be produced in either of two ways: a basic oxygen furnace (BOF) or an electric arc furnace (EAF). Steel

⁹ These plants are typically located within a few miles of large breweries or near concentrations of beverage filling plants.

production in a BOF involves high-purity oxygen being blown onto a bath of hot metal (carbon, silicon, manganese, phosphorus, pig iron and other elements), steel scrap and fluxes (such as limestone). Small quantities of natural gas and coke oven gas are used to provide supplemental heat to the furnace. EAFs, on the other hand, are mostly used in the recycling process. The heating of fluxes and the use of metallurgical coke result in non-energy process emissions of CO₂.

Tin-coated steel sheet manufacture: The raw steel goes through a number of milling processes. The steel is refined by vacuum degassing before casting. Continuous casting is used to produce slabs that are passed through the hot and cold rolling mills sequentially to produce sheet. This sheet is cleaned with acid and coated with a very thin layer of tin to produce a steel strip. The resource requirements and environmental emissions for producing this small amount of tin were unavailable and are assumed to be negligible (FAL, 1998). It is assumed that heat is supplied by natural gas for the milling operations.¹⁰

Steel can production: Cans are produced by stamping a body blank that is lacquered and decorated prior to can manufacture. A can is made with a narrow overlap, then welded and flanged. A protective strip of lacquer is applied to the side seam after joining (USSC, 1985). Can ends are usually stamped at the same time but, while one end is applied at the production site, the other end is sealed at the canning facility. The steel scrap (trim and “skeletons”) resulting from stamping the can body and ends are collected and sent back to the tinplate manufacturer for recycling.

2.3.3 Copper wire

Copper wire is used in various applications, including power transmission and generation lines, building wiring, telecommunication, and electrical and electronic products (EPA, 2002). Copper is similar to the other metals analyzed by EPA, with energy consumed in obtaining the ore, operating equipment, and extracting and processing fuels used in manufacturing. The virgin manufacturing process begins with the extraction of ore. The ore is smelted and refined; the use of limestone flux in this part of the process results in very small process non-energy emissions of CO₂ (USGS, 2004a). The refined copper is cast into rods, which are drawn into coils of copper wire that is annealed to facilitate ductility and conductivity. The wire may then be coated/plated with tin or other metals and also covered with insulating materials.

2.4 MATERIALS MANAGEMENT

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 2-6 and calculates net GHG emissions per short ton of metal inputs. Source reduction and recycling have the lowest net emission factors among the various materials management options for metals.

Steel is rarely manufactured from 100 percent virgin inputs. Exhibit 2-9 shows the range of recycled content used for manufacturing steel, and value for “virgin” steel used in WARM.

¹⁰ Available data for steel milling operations suggest that coke oven gas is used to supply energy for reheating during hot milling. However, this analysis assumed that this energy is supplied by natural gas instead, as data were available for natural gas, and it was assumed to be a reasonable proxy for coke oven gas.

Exhibit 2-9: Typical Recycled Content Values in the Marketplace

Material	Recycled Content Minimum	Recycled Content Maximum	Recycled Content Used in WARM for "Virgin" Steel Cans
Steel Cans	20%	50%	28%

Source: FAL (2003a)

The current mix of recycled and virgin inputs used for manufacturing each metal is provided in Exhibit 2-10. The emission factors for source reduction and recycling are affected by the mix of inputs used for the manufacturing process. The emission factors for metals produced from the current mix of virgin and recycled inputs is calculated using a weighted average of virgin and recycled metals production data, based on the values in Exhibit 2-10. WARM also calculates an emission factor for producing metals from "virgin" inputs, assuming a recycled content of 33 percent for steel cans. Copper wire has the least recycled content in the current mix because of the need for high purity to meet safety standards. Aluminum and steel can manufacturing processes both use internal scrap (scrap produced within the facility during manufacturing) recycling in addition to end-of-life recycling.

Exhibit 2-10: Current Mix of Inputs for Metals Manufacturing

Material	% of Current Production from Recycled Inputs	% of Current Production from "Virgin" Inputs
Aluminum Cans	67.8%	32.2%
Aluminum Ingot	NA	NA
Steel Cans	32.7%	67.3%
Copper Wire	5%	95%

Source: Steel: FAL (2003a); aluminum (PE Americas 2010); copper wire: USGS (2004a).

NA = Not applicable.

2.4.1 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 discussed above, under the measurement convention used in this analysis, source reduction for metals has negative raw material and manufacturing GHG emissions (i.e., it avoids emissions attributable to production) and zero end-of-life management GHG emissions. For more information, please refer to the [Source Reduction](#) chapter.

Exhibit 2-11 presents the inputs to the source reduction emission factor for both current mix of inputs and 100 percent virgin inputs manufacture of each metals category. Aluminum cans have the lowest net emission factor, implying greatest emissions savings due to source reduction, owing to the large amount of emissions released during RMAM of aluminum cans. It is worth noting that emission reductions from source reduction of aluminum cans produced from the current mix of inputs are higher than those from recycling. This is because a majority (68 percent) of current production of aluminum cans is sourced from recycled content. Therefore, the quantity of virgin material that can be avoided through source reduction amounts to only 32 percent for the current mix of inputs. Please see the [Source Reduction](#) chapter for more information.

Exhibit 2-11: Source Reduction Emission Factors for Metals (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Sequestration for Current Mix of Inputs	Forest Carbon Sequestration for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Aluminum Cans	-4.91	-11.09	NA	NA	-4.91	-11.09
Aluminum Ingot	-7.47	-7.47	NA	NA	-7.47	-7.47
Steel Cans	-3.06	-3.67	NA	NA	-3.06	-3.67
Copper Wire	-7.01	-7.08	NA	NA	-7.01	-7.08
Mixed metals	-3.70	-6.24	NA	NA	-3.70	-6.24

NA = Not applicable.

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

For Aluminum ingot, 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

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

2.4.1.1 Developing the Emission Factor for Source Reduction of Metals

To produce metals, substantial amounts of energy are 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 CO₂. In addition, manufacturing metals also results in process non-energy CO₂ emissions from the use of limestone fluxes. Hence, the RMAAM component consists of process energy, non-process energy and transport emissions in the acquisition and manufacturing of raw materials. Exhibit 2-12 shows the results for each component and the total GHG emission factors for source reduction of metals. The methodology for estimating emissions from metals manufacture from recycled materials is discussed below in section 2.4.2, Recycling.

Exhibit 2-12: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Metals (MTCO₂E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Aluminum Cans	7.27	0.09	3.72	11.09
Aluminum Ingot	4.23	0.07	3.18	7.47
Steel Cans	2.43	0.37	0.87	3.67
Copper Wire	7.02	0.06	0.00	7.08

To calculate this factor, EPA obtained an estimate of the amount of energy required to acquire and produce one short ton of each type of metal, in Btu. Next, we determined the fuel mix that comprises this Btu estimate (aluminum: AA, 2011; steel: EPA, 1998a; copper: FAL, 2002) and then multiplied the fuel consumption (in Btu) by the fuel-specific carbon content. The sums of the resulting GHG emissions by fuel type comprise the total process energy GHG emissions, including both CO₂ and CH₄, from all fuel types used in metals production. The process energy used to produce metals and the resulting emissions are shown in Exhibit 2-13.

Exhibit 2-13: Process Energy GHG Emissions Calculations for Virgin Production of Metals

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	184.74	7.27
Aluminum Ingot	115.16	4.23
Steel Cans	31.58	2.43
Copper Wire	122.52	7.02

Electricity Grid for Aluminum: The electricity consumption profile for aluminum is different from all other materials in WARM. The smelting process is very electricity-intensive and uses a large amount (approximately 67.5 percent) of hydropower. This differs greatly from the U.S. national average electricity grid mix, which is comprised of a relatively small fraction of hydropower. The representative electricity factor for electrolysis and ingot casting (both processes occurring at the same site) is developed using a fuel mix that is a weighted average of the North American and global grid fuel mix (AA 2010). This requires two different adjustments to the primary energy use and the emissions profile.

Primary Energy Profile – The Aluminum Association data provide electric power consumption in useful energy terms (i.e., the amount of energy consumed by the end-user). However, WARM calculates the energy consumption and emissions associated with primary energy use (i.e., the source energy that was used to produce and deliver the consumed energy). Thus, this primary energy calculation accounts for energy losses during transformation, transmission and distribution. The useful electric power consumption provided by AA (2010) is converted to primary energy for the purposes of WARM in two steps. Electric power consumption in all manufacturing steps, except electrolysis and ingot casting, is converted to primary energy using the national grid efficiency factor derived from eGRID data (EPA, 2015b). The primary energy calculation for electrolysis and ingot casting uses the weighted average grid efficiency that is specific to the actual grid mix of the aluminum industry. Since, hydropower is more efficient at converting primary energy into electricity and electrolysis facilities are often located right next to the hydropower stations, grid efficiencies for hydropower are high compared to other forms of energy. Thus, the aluminum industry weighted average grid efficiency was calculated using the primary energy conversion efficiency data provided in PE Americas (2010) and the weighted average fuel mix.

Emissions Profile – The appropriate emissions profile for electricity consumption is calculated by using a weighted average emissions factor. Electricity consumption (in primary energy terms) during all the aluminum manufacturing stages except electrolysis and ingot casting is calculated using the carbon coefficient for the national average fuel mix for electricity. The appropriate U.S.-specific carbon coefficient for each fuel is applied to the aluminum industry's weighted electric power mix to arrive at a weighted carbon coefficient for these two manufacturing stages. Finally, the overall emissions profile is calculated as a weighted average of all the manufacturing processes including electrolysis and ingot casting.

Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for metals production. The methodology for estimating these emissions is the same as that used for process energy emissions. Based on estimated total metals transportation energy (aluminum: RTI, 2004; steel: EPA, 1998a; copper: FAL, 2002), EPA calculates the total emissions using fuel-specific carbon coefficients. The calculations for estimating the transportation energy emission factor for metals are shown in Exhibit 2-14.

Exhibit 2-14: Transportation Energy Emissions Calculations for Virgin Production of Metals

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	0.91	0.09
Aluminum Ingot	0.56	0.04

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Steel Cans	4.60	0.37
Copper Wire	0.46	0.06

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 1-6.

Non-energy GHG emissions occur during manufacturing but are not related to the consumption of fuel for energy. For metals, non-energy CO₂ emissions are emitted in the virgin metals manufacturing process. Exhibit 2-15 shows the components for estimating process non-energy GHG emissions for each category of metals.

Exhibit 2-15: Process Non-Energy Emissions Calculations for Virgin Production of Metals

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	2.14	–	0.01	0.01	–	3.72
Aluminum Ingot	1.60	–	0.01	0.01	–	3.18
Steel Cans	0.87	–	–	–	–	0.87
Copper Wire	0.00	–	–	–	–	0.00

– = Zero emissions.

2.4.2 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. Most of the materials in WARM are modeled as being recycled in a closed loop, including aluminum and steel cans. However, copper wire recycling is modeled in a quasi-open loop. Special considerations for the metals' recycling processes are described in the following paragraphs.

Recycled production of aluminum and steel cans. Manufacturing from recycled cans involves can recovery and processing and melting of cans to cast ingots. The steps succeeding ingot casting are the same for both virgin manufacture and recycling, with ingots being rolled into sheets that are fabricated into cans and lids.

Steel cans. While “virgin” steel manufacture generally involves some content of steel scrap (see Exhibit 2-9), steel production from fully recycled steel cans involves limestone mining and lime use to produce steel in an electric arc furnace. Steel from electric arc furnaces is structurally unsuited to milling into thin sheets to make steel cans. Therefore, although EPA models steel can recycling as a closed-loop process (steel cans made into steel cans), statistically, this is not entirely accurate. By modeling recovery of steel cans as a closed-loop process, EPA implicitly assumes that one short ton of steel produced from recovered steel cans in an electric arc furnace displaces one short ton of steel produced from virgin inputs in a basic oxygen furnace, after accounting for material losses during the recycling process. However, EPA considers the values from the two furnaces to be close enough to make closed-loop recycling a reasonable assumption. (For the fabrication energy required to make steel cans from steel sheet, EPA used the values for fabrication of steel cans from steel produced in a basic oxygen furnace.)

Aluminum Cans. The PE Americas 2010 report for aluminum beverage can production describes life cycle inventory results based on two different approaches, named the “closed loop approach”¹¹ and

¹¹ This is not the same as EPA's use of closed loop approach for WARM which refers to the manufacture of a recycled material back into the same material.

the “recycled content approach”, to account for the recovery and recycling of used aluminum cans. The main difference between these two approaches is the allocation of burdens and benefits associated with the recovered aluminum from used beverage can scrap during recycling. In the PE Americas report’s “closed loop approach”, the recovered aluminum material from used beverage cans includes an environmental burden associated with a specific amount of primary metal resulting from insufficient secondary material. The “recycled content approach” uses a slightly different approach under which secondary aluminum material (aluminum metal made from aluminum scrap, both pre-consumer and post-consumer excluding “run-around” or pre-consumer scrap from aluminum production facilities and aluminum can sheet manufacturing facilities) is considered as one of the ingredients in making aluminum cans and is introduced to the system “burden free” up to the scrap collection process. The recycled-content approach in this case is more reflective of the actual aluminum can production processes, is more easily understood by most non-LCA professionals, more commonly used by LCA practitioners in North America,¹² and is most consistent with the WARM approach. Thus, EPA developed emission and energy factors using the material, fuel, and environmental inputs and outputs for the production of a 1000 aluminum cans or 13.34 kg of aluminum beverage cans produced in the United States based on the “recycled content” approach adapted by the Aluminum Association for use in WARM (PE Americas, 2010).¹³

Recycled production of copper. Copper wire is usually recovered from recycled computers. Copper wire is a highly recyclable material that has the potential to be nearly completely recovered after its useful life in most applications. Additionally, copper wire is the most common form of unalloyed copper recycled post-consumer. However, given the high virgin content of copper wire (due to purity standards), recovered copper wire is usually recycled into lower-grade copper alloys (CDA, 2003; EPA, 2002). The recycling of copper wire can be considered quasi-open loop in that the material is not typically used to produce new copper wire, but is utilized in other copper products and alloys. Therefore, the most accurate approach is to determine the energy and emissions associated with the production of smelted copper (ingot), rather than finished copper wire.

There are two basic classifications of recycled copper scrap. Copper No. 1 scrap is typically high-quality unburned copper that is free of contaminants. Copper No. 2 scrap is slightly lower in quality, with small amounts of impurities. Therefore, the copper wire recycling emission factor for WARM compares a weighted average of No. 1 and No. 2 copper scrap to virgin copper ingot. No. 1 and No. 2 scrap are weighted based on the mix of wire scrap typically used to create recycled copper ingot, according to USGS (2004b), as shown in Exhibit 2-16. For details on the recycling life-cycle analysis for copper wire, please review EPA (2005), *Background Document for Life-Cycle Greenhouse Gas Emission Factors for Copper Wire*.

Exhibit 2-16: Copper Wire Scrap Mix Used to Create Copper Ingot

Copper No. 1 Scrap	93%
Copper No. 2 Scrap	7%

Source: USGS (2004b).

This section describes the development of the recycling emission factors for metals, which are shown in the final column of Exhibit 2-17. Because recycling compares 100 percent virgin to 100 percent recycled inputs manufacture, recycling aluminum cans provides greater GHG benefits than source reduction in WARM, which uses the current mix of inputs as the baseline.

¹² Based on conversations with Marshall Wang, Senior Sustainability Specialist, Aluminum Association.

Exhibit 2-17: Recycling Emission Factor for Metals (MTCO₂E/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)
Aluminum Cans	–	–	-5.35	-0.04	-3.72	–	-9.11
Aluminum Ingot	–	–	-3.98	-0.03	-3.18	–	-7.19
Steel Cans	–	–	-1.77	-0.04	–	–	-1.81
Copper Wire	–	–	-4.65	-0.06	–	–	-4.71
Mixed Metals	–	–	-3.01	-0.04	-1.29	–	-4.34

– = Zero emissions.

^a Includes emissions from the initial production of the material being managed, except for food waste, yard waste and mixed MSW.**2.4.2.1 Developing the Emission Factor for Recycling Metals**

EPA calculates the GHG benefits of recycling metals by comparing the difference between the emissions associated with manufacturing a short ton of recycled or secondary materials/products and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy.

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

Step 1. Calculate emissions from virgin production. WARM applies fuel-specific carbon coefficients to the data for virgin RMAM of virgin aluminum and steel cans and virgin copper ingot. This estimate is then summed with the emissions from transportation and process non-energy emissions to calculate the total emissions from virgin production of each product or material. The components of these emissions are shown in Exhibit 2-13, Exhibit 2-14, and Exhibit 2-15 in the source reduction section for aluminum and steel and in Exhibit 2-18 and Exhibit 2-19 for copper. Process non-energy emissions for copper ingot were not available, so we assumed them to be the same as for virgin production of copper wire.

Exhibit 2-18: Process Energy GHG Emissions Calculations for Virgin Production of Copper Ingot

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
Copper Ingot	109.23	6.22

Exhibit 2-19: Transportation Energy Emissions Calculations for Virgin Production of Copper Ingot

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Copper Ingot	3.06	0.23

Step 2. Calculate GHG emissions from recycled production. WARM then applies the same carbon coefficients to the energy data for the production of the recycled (aluminum and steel cans) or secondary (No. 1 and No. 2 copper scrap to recycled ingot and aluminum ingot) products from recycled metals, and incorporates non-energy process GHGs from recycled product manufacture. WARM does not model manufacture of recycled aluminum products other than aluminum cans beyond secondary aluminum ingot. Recycled production energy emissions for No. 1 and No. 2 copper scrap are weighted by the percentages in Exhibit 2-16. Data specifically on non-energy process emissions from No. 1 and No. 2 copper scrap were not available, so non-energy emissions from copper wire production were used. Exhibit 2-20, Exhibit 2-21, and Exhibit 2-22 present the results for recycled or secondary product

process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

Exhibit 2-20: Process Energy GHG Emissions Calculations for Recycled Production of Metals

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	36.24	1.92
Aluminum Ingot	4.50	0.24
Steel Cans	11.78	0.62
Copper No. 1 Scrap	7.89	0.44
Copper No. 2 Scrap	22.40	1.40

Exhibit 2-21: Transportation Energy GHG Emissions Calculations for Recycled Production of Metals

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	0.44	0.03
Aluminum Ingot	0.22	0.02
Steel Cans	4.03	0.30
Copper No. 1 Scrap	1.85	0.14
Copper No. 2 Scrap	2.42	0.18

Exhibit 2-22: Process Non-Energy Emissions Calculations for Recycled Production of Metals

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
Aluminum Cans	–	–	–	–	–	–
Aluminum Ingot	–	–	–	–	–	–
Steel Cans	0.87	–	–	–	–	0.87
Copper Wire	0.00	–	–	–	–	0.00

– = Zero emissions.

Step 3. Calculate the difference in emissions between virgin and recycled production. We then subtract the recycled product emissions (Step 2) from the virgin product emissions (Step 1) to get the GHG savings. These results are shown in Exhibit 2-23.

Exhibit 2-23: Differences in Emissions between Recycled and Virgin Metals Manufacture (MTCO₂E/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs (MTCO ₂ E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO ₂ E/Short Ton)			Difference Between Recycled and Virgin 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
Aluminum Cans	7.27	0.09	3.72	1.92	0.06	–	-5.35	-0.04	-3.72
Aluminum Ingot	4.23	0.07	3.18	0.24	0.04	–	-3.98	-0.03	-3.18
Steel Cans	2.43	0.37	0.87	0.62	0.32	0.87	-1.77	-0.04	–
Copper Wire	7.02	0.06	0.00	5.59	0.18	0.00	-1.43	0.12	–

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. Material losses occur in both the recovery and manufacturing stages of recycling, and the net retention rates shown in Exhibit 2-24 are the product of the recovery and manufacturing retention rates.

Exhibit 2-24: Material Loss (Retention) Rates for Recycled Metals

Material	% of Recovered Materials Retained	Short Tons of Product Produced per Short Ton of Recycled Inputs	Short Tons of Product Produced per Short Ton of Collected Material
Aluminum Cans	100%	1.00	1.00
Aluminum Ingot	100%	1.00	1.00
Steel Cans	100%	0.98	0.98
Copper Wire	82%	0.99	0.81

Source: Aluminum cans: PE Americas (2010) RTI (2004); steel cans: FAL (2003); copper wire: EPA (2003).

The losses associated with recovery and manufacturing of aluminum beverage cans are already implicitly included in the data used to develop the emissions and energy factors for the 100% virgin and 100% recycled inputs. Hence, in order to avoid double-counting, retention rates for aluminum in this analysis are assumed to be 100%.

For the final recycling emission factors, the differences in emissions from process energy, transportation energy, and non-energy processing are adjusted to account for the loss rates by multiplying the final three columns of Exhibit 2-23 by the retention rates in the last column of Exhibit 2-24.

2.4.3 Composting

Because metals are not subject to aerobic bacterial degradation, they cannot be composted. As a result, WARM does not consider GHG emissions or storage associated with composting.

2.4.4 Combustion

This study's general approach was to estimate (1) gross emissions of CO₂ and N₂O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill), (2) CO₂ emissions avoided due to displaced electric utility generation, and (3) CO₂ emissions avoided due to recovery and recycling of ferrous metals at the combustor. To obtain an estimate of the net GHG emissions from MSW combustion, the value for GHG emissions avoided was subtracted from the direct GHG emissions. Exhibit 2-25 provides the emission factors related to combusting of metals.

Exhibit 2-25: Components of the Combustion Net Emission Factor for Metals (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO ₂ from Combustion	N ₂ O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Aluminum Cans	–	0.01	–	–	0.03	–	0.04
Aluminum Ingot	–	0.01	–	–	0.03	–	0.04
Steel Cans	–	0.01	–	–	0.02	-1.60	-1.57
Copper Wire	–	0.01	–	–	0.02	–	0.03
Mixed Metals	–	0.01	–	–	0.02	-1.04	-1.02

– = Zero emissions.

2.4.4.1 Developing the Emission Factor for Combustion of Metals

Because this study considers a material from end of life, RMAM emissions are considered to be zero for this materials management pathway. Additionally, metals do not contain any C or N, so CO₂ and

N₂O emissions from combustion do not occur.¹⁴ Transportation to combustion results in positive emissions for all metals.

Avoided Utility Emissions. Most waste to energy (WTE) facilities 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 CO₂ emissions associated with combustion of waste in a WTE plant. Avoided utility emissions for metals, however, are positive. This means that, instead of being avoided, emissions actually occur due to the presence of metals in MSW at combustion facilities. EPA developed these estimates based on data on the specific heat of aluminum and steel, and calculated the energy required to raise the temperature of aluminum and steel from ambient temperature to the temperature found in a combustor (about 750° Celsius) (Incropera and DeWitt, 1990). Therefore, the amount of energy absorbed by one short ton of steel cans, aluminum cans, aluminum ingot/(other aluminum products) or copper wire in a combustor would, if not absorbed, result in about 0.02 MTCO₂E of avoided utility CO₂.

Because transportation and avoided utility emissions are positive emission factors, net GHG emissions are positive for aluminum and copper. However, recovery of steel cans at a combustor, followed by recycling of the ferrous metal, results in negative net GHG emissions.

Steel Recovery. Most MSW combusted with energy recovery in the United States is combusted in WTE plants that recover ferrous metals (i.e., iron and steel).¹⁵ The recovered metals are then recycled. Therefore, in measuring GHG implications of combustion, one must also account for the change in energy use due to the recycling associated with metals recovery.

EPA assumes that 98 percent of WTE facilities recover ferrous metals, and that those facilities that do recover ferrous metals recover it at a rate of 90 percent (B. Bahor, personal communications, May 24, June 7, and July 14, 2010), which means that 88 percent of steel cans sent to MSW combustion facilities as waste are recovered and recycled.

Therefore, recovery of ferrous metals at combustors results in a GHG emissions offset due to the increased steel recycling made possible by the practice. This calculation is shown in Exhibit 2-26.

Exhibit 2-26: Avoided CO₂ Emissions Due to Steel Recovery per Ton of Waste Combusted

Material Combusted	Tons of Steel Recovered per Ton of Waste Combusted (Tons)	Avoided CO ₂ Emissions per Ton of Steel Recovered (MTCO ₂ E/Ton)	Avoided CO ₂ Emissions per Ton of Waste Combusted (MTCO ₂ E/Ton)
Steel Cans	0.88	1.81	1.60

2.4.5 Landfilling

Because metals do not contain biogenic carbon, they do not generate CH₄ or sequester any carbon when landfilled. The only emissions associated with landfilling for metals relate to those used for transporting metal waste to the landfills and moving waste around in the landfills. Transportation of waste and the use of landfilling equipment results in anthropogenic CO₂ emissions, due to the

¹⁴ At the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N₂O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans and copper wire do not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N₂O emissions.

¹⁵ EPA did not consider any recovery of materials from the MSW stream that might occur before MSW was delivered to the combustor. EPA considered such prior recovery to be unrelated to the combustion operation—unlike the recovery of steel from combustor ash, an activity that is an integral part of the operation of many combustors.

combustion of fossil fuels in the vehicles used. For further information please refer to the chapter on Landfilling. Exhibit 2-27 provides the net emission factor for landfilling of metals.

Exhibit 2-27: Landfilling Emission Factors for Metals (MTCO₂E/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)
Aluminum Cans	–	0.02	–	–	–	0.02
Aluminum Ingot	–	0.02	–	–	–	0.02
Steel Cans	–	0.02	–	–	–	0.02
Copper Wire	–	0.02	–	–	–	0.02
Mixed Metals	–	0.02	–	–	–	0.02

2.4.6 Anaerobic Digestion

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

2.5 LIMITATIONS

This version of WARM serves as an improvement over previous versions because it incorporates the latest industry-specific data for aluminum cans to calculate GHG emission factors. It also provides GHG emission factors for aluminum ingot, which can be used as a proxy for aluminum products other than cans, for the first time.

However, there are a few limitations worth noting with regard to the aluminum material factors. First, the life cycle inventory data provided by the Aluminum Association (PE Americas, 2010 and AA, 2011), and used in WARM, for manufacture of secondary aluminum only represents the production of secondary aluminum for the beverage can manufacturing industry in the United States, as opposed to other applications. Since no other current North America data are available for secondary aluminum ingot, these data are assumed to be representative of secondary aluminum ingot production in the United States. Second, while the aluminum ingot energy and GHG emission factors developed in this memo can be used as a proxy for certain products (other than aluminum cans) made from aluminum ingot, (e.g., building and construction materials¹⁶), the energy and emissions associated with the additional processing of aluminum ingot to produce a final aluminum product are likely to be quite significant. For instance, the energy associated with the additional processing of aluminum ingot to produce aluminum cans represents approximately 25 percent of the total life cycle energy for the manufacture of virgin aluminum cans.

In the combustion pathway for steel in this analysis, EPA used the national average recovery rate for steel. Where waste is sent to a WTE plant with steel recovery, the net GHG emissions for steel cans will be slightly lower (i.e., more negative). Where waste is sent to a WTE plant without steel recovery, the net GHG emissions for steel cans will be the same as they are for aluminum cans (i.e., close

¹⁶ These materials include electrical transmission and distribution wires, other electrical conductors, some extruded aluminum products, and aluminum used in consumer durable products such as home appliances, computers and electronics

to zero). EPA did not credit increased recycling of nonferrous materials, because of a lack of information on the proportions of those materials. This assumption tends to result in overstated net GHG emissions from combustion.

EPA expects updated industry data for the life cycle inventory for the production of steel cans. EPA will update the emission factors accordingly once the data is received, reviewed and analyzed.

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3 PAPER PRODUCTS

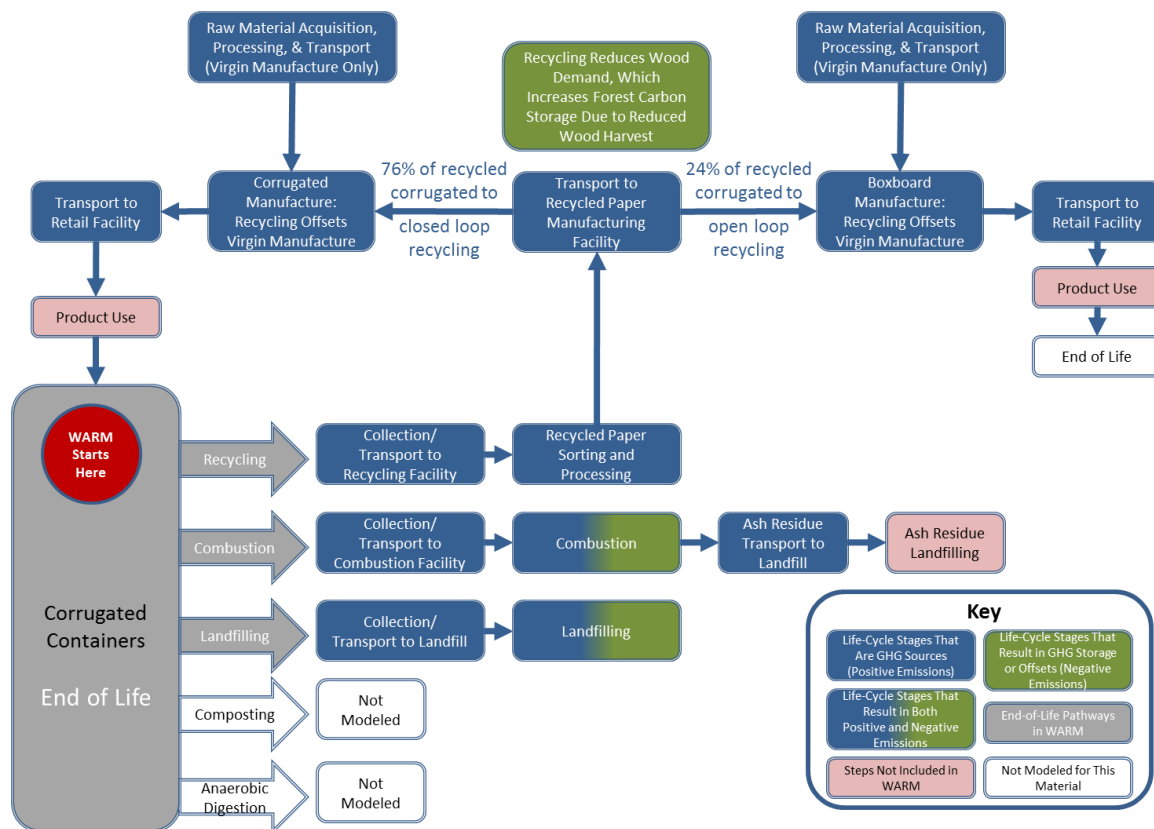
3.1 INTRODUCTION TO WARM AND PAPER PRODUCTS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for paper products beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with paper products in the following four waste 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](#), [Combustion](#), and [Landfilling](#), see the chapters devoted to those processes.

The paper products addressed in WARM comprise corrugated containers, magazines/third-class mail, newspaper, office paper, phone books, textbooks and three definitions of mixed paper.

Corrugated containers are boxes made from containerboard (liner and corrugating medium) used in packaging applications (EPA, 2006). Exhibit 3-1 shows the general outline of materials management pathways for corrugated containers in WARM.

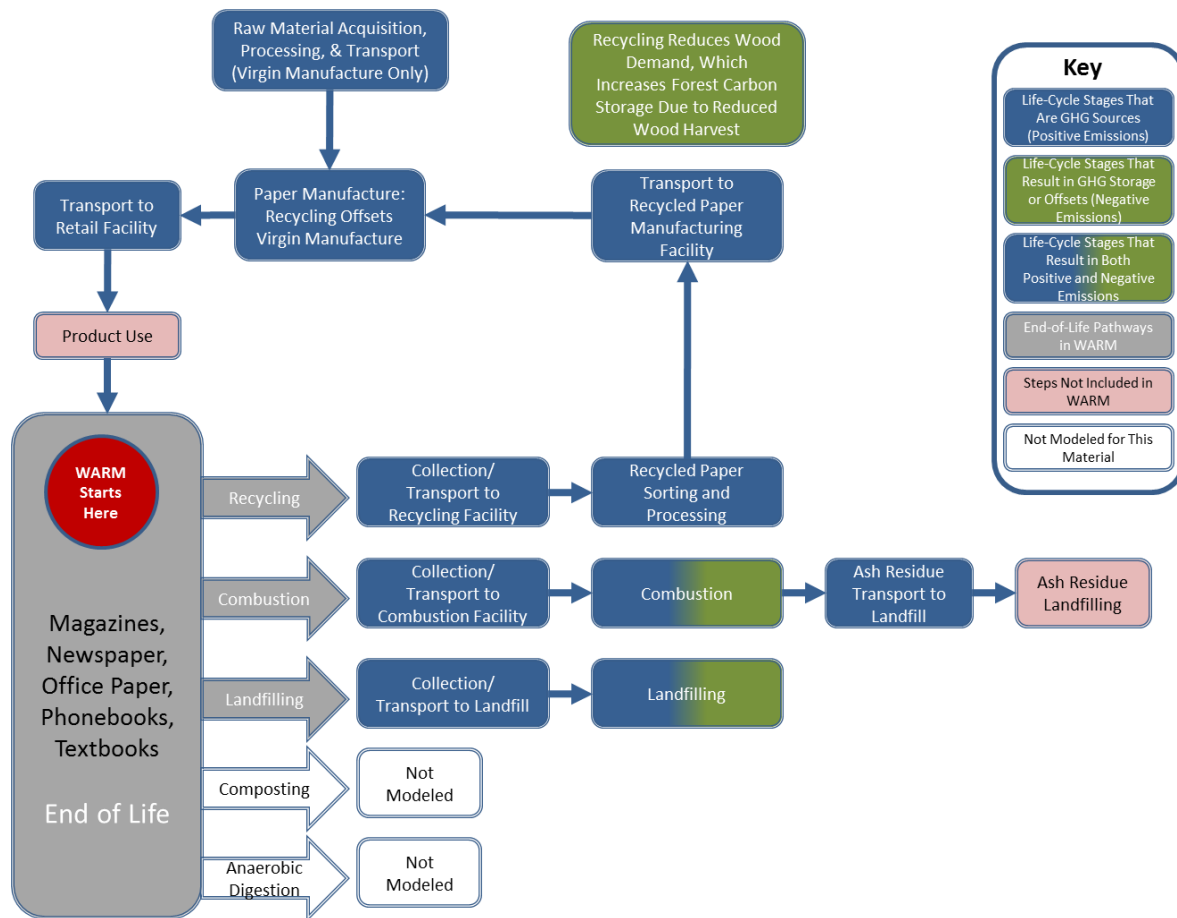
Exhibit 3-1: Life Cycle of Corrugated Containers in WARM



Third Class Mail is now called Standard Mail by the U.S. Postal Service and includes catalogs and other direct bulk mailings such as magazines, which are made of coated, shiny paper (EPA, 2006). The magazines/third-class mail category represents coated paper produced from mechanical pulp. Newspaper represents uncoated paper made from 70 percent mechanical pulp and 30 percent chemical

pulp (FAL, 1998a). Office paper refers to the type of paper used in computer printers and photocopiers (EPA, 2006) and represents paper made from uncoated bleached chemical pulp (FAL, 1998b). Phonebooks represent telephone books that are made from paper produced from mechanical pulp (EPA, 2006). Textbooks represent books made from paper produced from chemical pulp (EPA, 2006). Exhibit 3-2 shows the general outline of materials management pathways for magazines/third-class mail, newspaper, office paper, phone books and textbooks in WARM.

Exhibit 3-2: Life Cycle of Magazines/Third-Class Mail, Newspaper, Office Paper, Phonebooks, and Textbooks in WARM



Mixed paper is recycled in large quantities and is an important class of scrap material in many recycling programs. Presenting a single definition of mixed paper is difficult, however, because recovered paper varies considerably, depending on the source. For purposes of WARM, we identified three categories of mixed paper according to the dominant source: (1) general, (2) primarily residential and (3) primarily from offices. General mixed paper includes almost all printing-writing paper, folding boxes, and most paper packaging. Primarily residential mixed paper includes high-grade office paper, magazines, catalogues, commercial printing, folding cartons and a small amount of old corrugated containers. Mixed paper primarily from offices includes copier and printer paper, stationary and envelopes, and commercial printing.

Exhibit 3-3 shows the composition of mixed paper categories assumed by WARM. EPA uses the compositions of mixed paper as defined by FAL (1998b). This document presents data specific to the

composition of mixed paper recycled to produce boxboard and tissue paper, which are the recycling pathways modeled by WARM (read more in section 3.4.2).

Exhibit 3-3: Composition of Mixed Paper Categories

Paper Grade	Mixed Paper (General)	Mixed Paper (Primarily Residential)	Mixed Paper (Primarily from Offices)
Corrugated Containers	48%	53%	5%
Magazines/Third-Class Mail	8%	10%	36%
Newspaper	24%	23%	21%
Office Paper	20%	14%	38%
Total	100%	100%	100%

Because the data in FAL (1998b) is more than 10 ten years old, EPA compared the percentages used in WARM for the general mixed paper definition to paper products recovery numbers presented in EPA's *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2007* (EPA, 2008). EPA used the detailed characterization of mixed paper generation in Table 4 of the *Facts and Figures* report and assigned proxies to each of the product categories using the four paper grades tested by Dr. Barlaz.¹⁷ Exhibit 3-4 presents the results of this analysis, which shows that the composition of mixed paper assumed in WARM is similar to the data presented in EPA's *Facts and Figures for 2007* report. Due to the changing composition of mixed paper and the fact that the FAL data is more than 10 years old, EPA may consider revising the mixed paper composition definitions in future WARM updates.

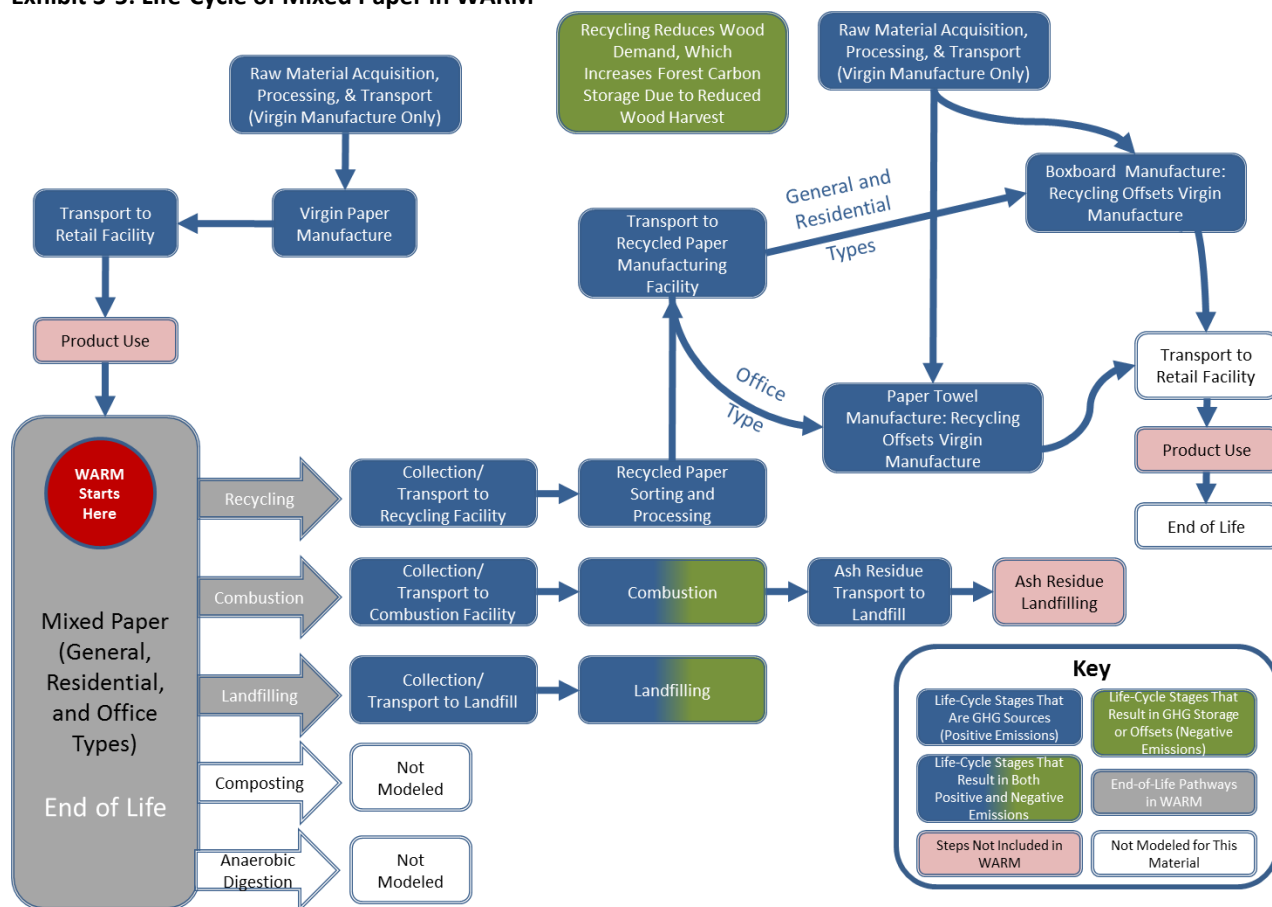
Exhibit 3-4: Comparison of WARM Mixed Paper (General) Definition to EPA Facts and Figures

Paper Grade	WARM: Mixed Paper (General)	EPA Facts and Figures
Corrugated Containers	48%	49%
Magazines/Third-Class Mail	8%	10%
Newspaper	24%	14%
Office Paper	20%	27%
Total	100%	100%

Source: EPA (2008).

Exhibit 5 shows the general outline of materials management pathways for the three definitions of mixed paper in WARM.

¹⁷ The corrugated containers category was used to proxy tissue paper and towels, paper plates and cups, other non-packaging paper and corrugated boxes. The magazines/third-class mail category was used to proxy magazines and standard mail. Newspaper was used to proxy newsprint, groundwood inserts and telephone directories. Office paper was used to proxy books, office-type papers, other commercial printing, milk cartons, folding cartons, other paperboard packaging, bags and sacks, and other paper packaging.

Exhibit 3-5: Life-Cycle of Mixed Paper in WARM

3.2 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. 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](#).

Although paper can be composted, composting is not currently included as a materials management pathway for paper products because 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 paper would have at a composting site, including whether the GHG emissions/sequestration would be altered or whether the carbon/nitrogen ratio would be affected. In addition, anaerobic digestion is not currently included as a materials management pathway for paper products. WARM models the source reduction of mixed paper as a weighted average of its components (see Exhibit 3-3), but users may also choose to model the source

reduction of each type of paper individually.¹⁸ Exhibit 3-6 illustrates the GHG sources and offsets that are relevant to paper products in this analysis.

Exhibit 3-6: Paper Products GHG Sources and Sinks from Relevant Materials Management Pathways

Waste Management Strategies for Paper Products	GHG Sources and Sinks Relevant to Paper Products		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Offsets <ul style="list-style-type: none"> • Transport of raw materials and intermediate products • Virgin process energy and non-energy • Transport of paper products to point of sale 	Offsets <ul style="list-style-type: none"> • Increase in forest carbon storage 	NA
Recycling	Emissions <ul style="list-style-type: none"> • Transport of recycled materials • Recycled process energy and non-energy Offsets <ul style="list-style-type: none"> • Transport of raw materials and intermediate products • Virgin process energy and non-energy • Transport of paper products to point of sale 	Offsets <ul style="list-style-type: none"> • Increase in forest carbon storage 	Emissions <ul style="list-style-type: none"> • Collection of paper products and transportation to recycling center
Composting	Not Modeled in WARM		
Combustion	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to WTE facility • Combustion-related N₂O Offsets <ul style="list-style-type: none"> • Avoided utility emissions
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to landfill • Landfilling machinery Offsets <ul style="list-style-type: none"> • Carbon storage in landfill • Energy recovery
Anaerobic Digestion	Not Modeled in WARM		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 3-6 and calculates net GHG emissions per short ton of inputs, shown in Exhibit 3-7 for the four materials management pathways. For more detailed methodology on emission factors, please see sections 3.4.1, 3.4.2, 3.4.3, 3.4.4, and 3.4.5.

¹⁸ In versions of WARM prior to version 13, source reduction of mixed material categories (e.g., metals, plastic, and paper) was not activated because mixed categories are not an individual product and therefore cannot be directly source reduced. Source reduction for mixed paper categories, however, has been activated since general efficiency improvements and reduction strategies that affect paper use broadly may result in source reduction across mixed paper categories. In some cases, WARM users may not have information on exactly which types of paper are being reduced, and may therefore wish to approximate changes using a mixed category.

Exhibit 3-7: Net Emissions for Paper Products under Each Materials Management Option (MTCO₂E/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
Corrugated Containers	-5.60	-3.12	NA	-0.51	0.23	NA
Magazines/Third-Class Mail	-8.60	-3.07	NA	-0.37	-0.39	NA
Newspaper	-4.77	-2.75	NA	-0.58	-0.82	NA
Office Paper	-7.97	-2.86	NA	-0.49	1.22	NA
Phone Books	-6.22	-2.64	NA	-0.58	-0.82	NA
Textbooks	-9.07	-3.11	NA	-0.49	1.22	NA
Mixed Paper (general)	-6.75	-3.53	NA	-0.51	0.13	NA
Mixed Paper (primarily residential)	-6.65	-3.53	NA	-0.51	0.07	NA
Mixed Paper (primarily from offices)	-7.96	-3.59	NA	-0.47	0.17	NA

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

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) from the manufacturing of paper products 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. In paper product manufacture, non-energy process emissions result primarily from the conversion of limestone (CaCO₃) into lime (CaO), which results in CO₂ emissions (EPA, 2006).

Paper pulp production can be categorized generally into two methods: chemical pulp manufacture and mechanical pulp manufacture.

There are many different chemical pulping methods, including kraft, sulfite and semichemical (FAL, 1998a). In the chemical pulp process, wood fibers are isolated by removing the surrounding lignin in the wood raw material. Wood chips are delivered to the mill, washed and screened. Then the chips are heated with water and chemicals to break down the lignin, resulting in long fibers (VDP, 2008). The chips are softened and brightened by impregnation with sodium sulfite, which also aids in fiber separation. The resulting pulp undergoes several stages of refining, screening, cleaning and filtering to remove undesirable particles from the pulp. At this stage, pulp can be bleached using chlorine dioxide, along with other chemicals. After bleaching, the pulp is mechanically dewatered using filters and roll presses. The final pulp drying operation involves circulating hot air over the pulp in a series of columns (VDP, 2008).

Mechanical pulping is a process in which fibers are physically separated from the wood raw material (VDP, 2008). Mechanical pulp production includes groundwood pulp production and refiner mechanical pulp production. Because data on refiner mechanical pulp production, which uses a disc refiner to break down wood chips, are not available, the data for mechanical pulp represent only the stone groundwood process. In the groundwood pulp production process, pulp is produced by pressing blocks of wood against an abrasive rotating stone surface. Few to no chemicals are used in this process (FAL, 1998a).

Corrugated containerboard is produced by gluing a fluted corrugating medium between two linerboards. Corrugated containers are typically 68 percent linerboard and 32 percent corrugating medium by weight. Both the linerboard and corrugating medium typically contain recycled content.

RMAM processes for corrugated containers include roundwood harvesting,¹⁹ wood residues production, limestone mining, salt mining, caustic soda production, sulfur production, sodium sulfate mining and processing, sulfuric acid production, unbleached virgin kraft paper production, old corrugated container collection, recycled medium and linerboard production, semichemical paper production, soda ash production, starch adhesives, corrugated container manufacture and folding box manufacture (FAL, 1998a).

Approximately 12 percent of newsprint is composed of continuously recycled pulp from recovered newspapers. The majority of newsprint pulp is from virgin pulp. The virgin pulp is made from approximately 70 percent mechanical pulp and 30 percent chemical pulp. RMAM processes involved in the production of newsprint include roundwood harvesting, wood residues production, salt mining, caustic soda and chlorine production, sodium chlorate production, limestone mining, sulfur production, bleached chemical pulp manufacture, mechanical pulp manufacture, newsprint production and ink manufacture. Approximately 53 percent of wood delivered to paper mills comes from trees harvested specifically for wood pulp production, while the remainder comes from wood residues generated by lumber production or other wood processing operations. After the wood is pulped, pulps are mixed and combined with water in the stock storage chest to form a suspension. This suspension is mechanically dewatered and pressed using wire mesh, synthetic felt and vacuum boxes. Once dry, the paper is softened, smoothed and wound onto a large, bulk size reel, or parent roll. Any broke, or scrap generated in the papermaking process, is collected to be repulped (FAL, 1998a).

Office paper manufacture involves the following RMAM processes: roundwood harvesting, wood residues production, salt mining, caustic soda and chlorine production, sodium chlorate production, limestone mining, sulfur production, mechanical pulp manufacture, bleached virgin kraft pulp production and paper production. Office paper production involves draining the dilute pulp suspension onto a finely woven plastic or wire mesh belt. Draining and pressing the fiber web between hard machine rolls removes approximately 98 percent of the excess water. Final excess water is evaporated using steam-heated drums. The paper is then wound onto rolls. The rolls are then cut and packaged into reams²⁰ (FAL, 1998a).

Paper used in magazines/third-class mail is composed of a mix of mechanically and chemically pulped paper, which has then been treated to give it a shiny appearance. This treatment involves coating the raw paper with substances including pigments, binders and sealing coats. The paper is further smoothed through a process called the “supercalender,” where the paper runs between several rollers of varying hardness and material, making the paper smooth and glossy through an “ironing effect” (VDP, 2008). Phone books and textbooks are bound books with covers. Phone books are made with mechanical pulp, similar to newspapers. Textbooks are made with chemical pulp, similar to office paper.

The RMAM calculation in WARM also incorporates “retail transportation,” which is the average emissions from truck, rail, water and other-modes transportation required to transport paper products 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). Transportation emissions from the retail point to the consumer are not included in WARM. The energy and GHG emissions from retail transportation are presented in Exhibit 3-8. The number of miles traveled is

¹⁹ Harvested logs, with or without bark. Roundwood may be round, spilt or roughly squared (FAO, 1997).

²⁰ The life-cycle process description of office paper provided in FAL (1998a) is inclusive of winding the paper onto rolls after the drying section, but does not include the final step of cutting and packing into reams.

obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and mode-specific fuel use is from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998a).

Exhibit 3-8: Retail Transportation Energy Use and GHG Emissions for Paper Products

Material	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors (MTCO ₂ E/ Short Ton)
Corrugated Containers	675	0.73	0.05
Magazines/Third-Class Mail	257	0.28	0.02
Newspaper	257	0.28	0.02
Office Paper	257	0.28	0.02
Phone Books	546	0.59	0.04
Textbooks	546	0.59	0.04

3.4 MATERIALS MANAGEMENT METHODOLOGIES

WARM models four materials management alternatives for paper products: source reduction, recycling, combustion, and landfilling. Source reduction, recycling, and combustion result in negative emissions (net emission reductions) for all nine paper products and mixed paper categories, while landfilling results in negative emissions for three of the nine products. As shown in Exhibit 3-7, source reducing paper products is the most beneficial management strategy overall.

WARM also calculates an emission factor for producing paper products from “virgin” inputs. For all paper products except corrugated containers, virgin production is from 100 virgin inputs. Corrugated containers, however, are rarely manufactured from 100 percent virgin inputs. Exhibit 3-9 shows the range of recycled content used for manufacturing paper products (FAL, 2003a). Since the minimum recycled content for corrugated containers is 9.8 percent, “virgin” corrugated cardboard as referred to in the rest of this chapter is assumed to contain 9.8 percent recycled inputs.

Exhibit 3-9: Typical Paper Products Recycled Content Values in the Marketplace

Material	Recycled Content Minimum	Recycled Content Maximum
Corrugated Containers	9.8%	75%
Magazines/Third-Class Mail	0.0%	30%
Newspaper	0.0%	60%
Office Paper	0.0%	35%
Phone Books	0.0%	10%
Textbooks	0.0%	15%

The current mix of recycled and virgin inputs used for manufacturing each paper product is provided in Exhibit 3-10. The emission factors for source reduction and recycling are affected by the mix of inputs used for the manufacturing process. The emission factors for paper products produced from the current mix of virgin and recycled inputs are calculated using a weighted average of virgin and recycled paper products production data, based on the values in Exhibit 3-10 (FAL, 2003a).

Exhibit 3-10: Current Mix of Inputs for Paper Products Manufacturing

Material	% of Current Production from Recycled Inputs	% of Current Production from "Virgin" Inputs
Corrugated Containers	35%	65%
Magazines/Third-Class Mail	4%	96%
Newspaper	23%	77%
Office Paper	4%	96%
Phone Books	0%	100%
Textbooks	4%	96%
Mixed Paper (general)	23%	77%
Mixed Paper (primarily residential)	25%	75%
Mixed Paper (primarily from offices)	10%	90%

3.4.1 Source Reduction

Source reduction activities reduce the quantity of paper products manufactured, reducing the GHG emissions associated with making the material and managing the post-consumer waste. Printing on both sides of office paper is one example of source reduction for paper products. For more information on source reduction in general, see the [Source Reduction](#) chapter.

Exhibit 3-11 provides the breakdown of the GHG emissions factors for source reduction of paper 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 energy, transportation and non-energy process GHG emissions. Producing paper products results in GHG emissions from energy consumption in manufacturing processes and transportation, as well as non-energy-related CO₂ emissions in the production of lime from limestone.

Carbon storage. Reducing the quantity of paper products manufactured results in increased forest carbon stocks from marginal changes in the demand for virgin pulpwood. For more information, see the [Forest Carbon Storage](#) chapter.

Exhibit 3-11: Source Reduction Emission Factors for Paper Products (MTCO₂E/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
Corrugated Containers	-0.87	-0.84	-4.73	-7.26	-5.60	-8.10
Magazines/Third-Class Mail	-1.64	-1.64	-6.96	-7.26	-8.60	-8.90
Newspaper	-1.82	-2.01	-2.95	-3.83	-4.77	-5.84
Office Paper	-1.01	-0.99	-6.96	-7.26	-7.97	-8.25
Phone Books	-2.38	-2.38	-3.83	-3.83	-6.22	-6.22
Textbooks	-2.11	-2.11	-6.96	-7.26	-9.07	-9.37
Mixed Paper (general)	-1.19	-1.22	-5.56	-7.26	-6.75	-8.48
Mixed Paper (primarily residential)	-1.19	-1.21	-5.46	-7.26	-6.65	-8.47
Mixed Paper (primarily from offices)	-1.40	-1.43	-6.56	-7.26	-7.96	-8.69

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

3.4.1.1 Developing the Emission Factor for Source Reduction of Paper Products

To calculate the avoided GHG emissions for paper products, EPA first looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 3-12 shows the results for each component and the total GHG emission factors for source reduction of paper products. More information on each component making up the final emission factor is provided in the remainder of this section. The methodology for estimating emissions from paper products manufactured from recycled materials is discussed in the Recycling section (3.4.2).

Exhibit 3-12: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Paper Products (MTCO₂E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Corrugated Containers ^a	0.69	0.15	0.01	0.84
Magazines/Third-Class Mail	1.62	0.02	–	1.64
Newspaper	1.95	0.06	–	2.01
Office Paper	0.95	0.02	0.03	0.99
Phone Books	2.34	0.04	–	2.38
Textbooks	2.07	0.04	–	2.11

– = Zero emissions.

^a “Virgin” corrugated containers include a minimum recycled content of 9.8 percent; see section 3.4.

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

To calculate this factor, EPA obtained an estimate of the amount of energy, by fuel type, required to acquire and produce one short ton of each paper product, in Btu (RTI, 2004). Next, we multiplied the fuel consumption (in Btu) by the fuel-specific carbon content as outlined by EPA (2015b). The sums of the resulting GHG emissions by fuel type comprise the total process energy GHG emissions from all fuel types used in paper production. The process energy used to produce paper products and the resulting emissions are shown in Exhibit 3-13.

Exhibit 3-13: Process Energy GHG Emissions Calculations for Virgin Production of Paper Products

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	25.13	0.69
Magazines/Third-Class Mail	32.99	1.62
Newspaper	39.92	1.95
Office Paper	37.01	0.95
Phone Books	39.61	2.34
Textbooks	35.07	2.07

Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for paper products production. The methodology for estimating these emissions is the same as used for process energy emissions. Based on estimated transportation energy by fuel type (RTI, 2004), EPA calculates the total emissions using fuel-specific carbon coefficients (EPA, 2015b). Transportation energy also includes “retail transportation,” as described in section 3.3. The transportation energy used to produce paper products and the resulting emissions are shown in Exhibit 3-14.

Exhibit 3-14: Transportation Energy Emissions Calculations for Virgin Production of Paper Products

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	1.31	0.10
Magazines/Third-Class Mail	NA	–
Newspaper	0.50	0.04
Office Paper	NA	–
Phone Books	NA	–
Textbooks	NA	–

NA = Not applicable.

– = Zero emissions.

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 3-8.

Non-energy GHG emissions occur during manufacturing, but are not related to consuming fuel for energy. For corrugated containers and newspaper, non-energy CO₂ emissions are based on data from RTI (2004). For office paper, non-energy CO₂ emissions are based on the original analysis supporting the first edition of this report (ICF, 1994). Exhibit 3-15 shows the components for estimating process non-energy GHG emissions for paper products.

Exhibit 3-15: Process Non-Energy Emissions Calculations for Virgin Production of Paper Products

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	0.01	–	–	–	–	0.01
Magazines/Third-Class Mail	–	–	–	–	–	–
Newspaper	–	–	–	–	–	–
Office Paper	0.03	–	–	–	–	0.03
Phonebooks	–	–	–	–	–	–
Textbooks	–	–	–	–	–	–

– = Zero emissions.

In addition to RMAM emissions, source reduction of paper affects the amount of carbon forest stored in managed forests. By reducing the quantity of paper products manufactured, source reduction reduces the number of trees harvested relative to what would have been harvested without source reducing paper. By preserving trees that would have otherwise been harvested, source reduction increases the amount of carbon stored in the forest. The change in carbon storage per unit of paper source reduction for each paper type is shown in

Exhibit 3-16. For the carbon storage portion of the newspaper emission factor, EPA assumes, in order to be conservative, that the paper was all mechanical pulp. For more information, see the [Forest Carbon Storage](#) chapter.

Exhibit 3-16: Forest Carbon Storage from Source Reduction of Paper Products

(a) Material	(b) Pulp Type	(c) Reduction in Timber Harvest per Unit of Increased Source Reduction (Short Tons Timber/Short Ton of Paper)	(d) Change in Forest C Storage per Unit Reduced Timber Harvest (Metric Tons Forest C/Metric Ton Timber)	(e) Net Change in C Storage per Unit of Increased Source Reduction, 100% Virgin Inputs (MTCO ₂ E/Short Ton) (e = c × d × 0.907)	(f) Percent Virgin Inputs in the Current Mix of Inputs	(g) Net Change in C Storage per Unit of Increased Source Reduction, Current Mix (MTCO ₂ E/Short Ton) (g = e × f)
Corrugated Cardboard	Chemical	2.11	1.04	7.26	65.1%	4.73
Magazines/Third-Class Mail	Chemical	2.11	1.04	7.26	95.9%	6.96
Newspaper	Mechanical	1.11	1.04	3.83	77.0%	2.95
Office Paper	Chemical	2.11	1.04	7.26	95.9%	6.96
Phone Books	Mechanical	1.11	1.04	3.83	100.0%	3.83
Textbooks	Chemical	2.11	1.04	7.26	95.9%	6.96

One metric ton = 0.907 short tons.

3.4.2 Recycling

In order to use pulp recovered from industrial scrap or post-consumer paper products, recovered fiber sources must undergo deinked recovered pulp manufacture. To do this, recovered fiber sources must first be repulped. During this step, large-sized contaminants are separated from the fiber. Smaller-sized contaminants are then screened for removal. If inks are present, a portion of the inks, as well as some coatings and fillers, are washed from the fiber during the screening process. This may be sufficient for some applications, such as combination paperboard. If higher brightness is needed for the final product, additional inks, fillers and coatings are removed using a washing and/or flotation process involving chemical digestion “cooking.” This process results in a significant weight loss of fiber as deinking sludge. The deinked pulp is then dried or partially dried before delivery to a paper mill. Other processes required for recycled paper product production include collection of used paper products, and recycled medium and linerboard production for corrugated containers (FAL, 1998a).

Most paper products are modeled as being recycled in a closed loop (e.g., old newspaper is recycled into new newspaper). Magazines/third-class mail, newspaper, office paper, phone books and textbooks are all assumed to be recycled in a closed-loop cycle. The recycling pathway for these paper types is modeled in Exhibit 3-2.

The three mixed paper types are modeled as being recycled in an open loop. Mixed paper is used in this way because of the quality constraints resulting from a broad mixture of paper types that include newsprint, office paper, coated paper and corrugated containerboard. The pulp fibers obtained from mixed paper are not well-suited for use in producing the materials they were generated from; rather, they are well-suited for lower-grade paper products such as cardboard. For the purposes of this methodology, EPA assumes that 100 percent of the general and residential mixed paper is remanufactured into recycled boxboard. Recycled boxboard is kraft unbleached paperboard that is used for the manufacture of folding cartons and rigid boxes. Although recycled boxboard is modeled as an open-loop recycling pathway in WARM, it is not included as a separate paper type in WARM because it is composed of 100 percent recycled inputs. EPA assumes that mixed paper from offices is remanufactured into tissue paper, which is used in toilet tissue, facial tissue and commercial paper towels. Therefore, the GHG benefits of mixed paper recycling result from the avoided emissions associated with the manufacture of the secondary products (boxboard, tissue paper) that the material is recycled into (since the recycling would affect only the production of the secondary products). To calculate the GHG benefits of recycling mixed paper as outlined in the steps below, EPA compares the difference in emissions associated with manufacturing one ton of each of the secondary products from virgin versus recycled materials, rather than from the mixed paper itself. More information on open-loop recycling is available in the [Recycling](#) chapter. The recycling pathway for the mixed paper types is modeled in Exhibit 3-5.

EPA assumes that corrugated containers are recycled in a partial open loop, where 76 percent of recycled corrugated containers are used to produce boxboard and the remaining 24 percent are used to produce new corrugated containers. For corrugated containers, the results for each of the secondary products (boxboard, corrugated containers) are weighted by the appropriate material-flow distribution to obtain a composite emission factor. The recycling pathway for corrugated containers is modeled in Exhibit 3-1.

A “recycled input credit,” which represents the net change in GHG emissions from process energy, transportation energy and process non-energy sources in recycling paper products relative to virgin production of paper products is calculated for each of the paper products. This is done by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the paper products from virgin inputs. GHG emissions associated with management (i.e., collection,

transportation and processing) of recycled paper products are included in the recycling credit calculation. In addition, there are forest carbon storage benefits associated with recycling. Each component of the recycling emission factor, as provided in Exhibit 3-17, is discussed further below. For more information on recycling in general, see the [Recycling](#) chapter.

Exhibit 3-17: Recycling Emission Factor for Paper Products (MTCO₂E/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)
Corrugated Containers	–	–	-0.00	-0.05	-0.01	-3.06	-3.12
Magazines/Third-Class Mail	–	–	-0.01	–	–	-3.06	-3.07
Newspaper	–	–	-0.70	-0.03	–	-2.02	-2.75
Office Paper	–	–	0.21	–	-0.02	-3.06	-2.86
Phone Books	–	–	-0.62	–	–	-2.02	-2.64
Textbooks	–	–	-0.05	–	–	-3.06	-3.11
Mixed Paper (general)	–	NA	-0.36	-0.11	-0.01	-3.06	-3.53
Mixed Paper (primarily residential)	–	NA	-0.36	-0.11	-0.01	-3.06	-3.53
Mixed Paper (primarily from offices)	–	NA	-0.42	-0.11	0.00	-3.06	-3.59

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.

3.4.2.1 Developing the Emission Factor for Recycling of Paper Products

EPA calculates the GHG benefits of recycling paper products by taking the difference between producing paper products from virgin inputs and producing paper products from recycled inputs, after accounting for material losses that occur during the recycling process. This difference is the “recycled input credit.”

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

Step 1. *Calculate emissions from virgin production of one short ton of paper products.* The GHG emissions from virgin production of paper products are provided in Exhibit 3-13, Exhibit 3-14, and Exhibit 3-15.

Step 2. *Calculate GHG emissions for recycled production of paper products.* Exhibit 3-18, Exhibit 3-19, and

Exhibit 3-20 provide the process, transportation and non-energy process emissions associated with producing recycled paper products. Data on these energy requirements and the associated emissions are from FAL (1998a, 1998b) and are calculated using the same approach as was used for virgin manufacture, explained in section 3.4.1.1.

Exhibit 3-18: Process Energy GHG Emissions Calculations for Recycled Production of Paper Products

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	11.73	0.81
Magazines/Third-Class Mail	31.97	1.60
Newspaper	21.98	1.17
Office Paper	20.12	1.31
Phone Books	22.02	1.43
Textbooks	33.51	1.99
Mixed Paper (general)	11.95	0.66
Mixed Paper (primarily residential)	11.95	0.66
Mixed Paper (primarily from offices)	51.69	2.57

Exhibit 3-19: Transportation Energy GHG Emissions Calculations for Recycled Production of Paper Products

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	0.80	0.06
Magazines/Third-Class Mail	NA	–
Newspaper	0.03	0.00
Office Paper	NA	–
Phone Books	NA	–
Textbooks	NA	–
Mixed Paper (general)	0.23	0.02
Mixed Paper (primarily residential)	0.23	0.02
Mixed Paper (primarily from offices)	0.44	0.03

NA = Not applicable.

– = Zero emissions.

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 3-8

Exhibit 3-20: Process Non-Energy Emissions Calculations for Recycled Production of Paper Products

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
Corrugated Containers	–	–	–	–	–	–
Magazines/Third-Class Mail	–	–	–	–	–	–
Newspaper	–	–	–	–	–	–
Office Paper	–	–	–	–	–	–
Phone Books	–	–	–	–	–	–
Textbooks	–	–	–	–	–	–
Mixed Paper (general)	–	–	–	–	–	–
Mixed Paper (primarily residential)	–	–	–	–	–	–
Mixed Paper (primarily from offices)	0.01	0.00	–	–	–	0.01

– = Zero emissions.

Step 3. Calculate the difference in emissions between virgin and recycled production. To calculate the GHG emissions implications of recycling one short ton of paper products, WARM subtracts the recycled 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 3-21.

Exhibit 3-21: Differences in Emissions between Recycled and Virgin Paper Products Manufacture (MTCO₂E/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs (MTCO ₂ E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO ₂ E/Short Ton)			Difference Between Recycled and Virgin 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
Corrugated Containers	0.69	0.15	0.01	0.81	0.11	–	0.12	-0.04	-0.01
Magazines/Third-Class Mail	1.62	0.02	–	1.60	0.02	–	-0.02	–	–
Newspaper	1.96	0.05	–	1.17	0.02	–	-0.79	-0.03	–
Office Paper	0.95	0.02	0.03	1.31	0.02	–	0.36	–	-0.03
Phone Books	2.34	0.04	–	1.43	0.04	–	-0.91	–	–
Textbooks	2.07	0.04	–	1.99	0.04	–	-0.08	–	–
Mixed Paper (general)	1.04	0.13	0.01	0.66	0.02	–	-0.38	-0.12	-0.01
Mixed Paper (primarily residential)	1.04	0.13	0.01	0.66	0.02	–	-0.38	-0.12	-0.01
Mixed Paper (primarily from offices)	3.04	0.15	0.01	2.57	0.03	0.01	-0.47	-0.12	0.00

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. 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 1 short ton of new material generally is made from 1 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. The difference between virgin and recycled manufacture is multiplied by the product's net retention rate (i.e., material that is not lost during recycling, equal to the inverse of the loss rate) (FAL, 2003b; RTI, 2004), which is calculated as follows:

$$\text{Net Retention Rate for Paper Products} = \text{Recovery Stage Retention Rate} \times \text{Manufacturing Stage Retention Rate}$$

Exhibit 3-22 shows the retention rate calculations for each of the paper products.

Exhibit 3-22: Paper Products Retention Rate Calculation

Material	Recovery Stage Retention Rate	Manufacturing Stage Retention Rate	Net Retention Rate
Corrugated Containers	100.0%	93.5%	93.5%
Magazines/Third-Class Mail	95.0%	70.9%	67.4%
Newspaper	95.0%	94.3%	89.5%
Office Paper	91.0%	65.6%	59.7%
Phone Books	95.0%	71.4%	67.9%
Textbooks	95.0%	69.4%	66.0%

Step 5. Calculate the net change in carbon storage associated with recycling paper products. These adjusted credits are then combined with the estimated forest carbon sequestration from recycling paper products to calculate the final GHG emission factor for recycling. EPA estimates forest carbon

storage in paper products, involving two parameters, as explained in the [Forest Carbon Storage](#) chapter. The two parameters are:

- The change in timber harvests resulting from increased recycling of paper products and
- The change in forest carbon storage as a result of a reduction in timber harvests.

The net change in carbon storage for mechanical and chemical pulp papers is shown in Exhibit 3-23. For the carbon storage portion of the newspaper factor, it was assumed that the paper was all mechanical pulp. Since paper products are non-durable goods, WARM does not consider changes in the in-use product carbon pool, as these products have shorter lifetimes (typically less than three years) and the carbon contained within these goods cycles out of the in-use pool over a relatively short period. For more information on forest carbon storage and each component of the overall factor, see the [Forest Carbon Storage](#) chapter.

Exhibit 3-23: Net Change in Carbon Storage per Unit of Increased Paper Product Recycling

(a) Pulp Type Recycled	(b) Reduction in Timber Harvest per Unit of Increased Recycling (Short Tons Timber/Short Ton of Wood)	(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 Paper Product Recycling (MTCO ₂ E/Short Ton)	(e) Net Change in C Storage per Unit of Increased Paper Product Recycling (MTCO ₂ E/Short Ton) (e = b × c × 0.907 + d)
Mechanical Pulp	0.58	1.04	NA	2.02
Chemical Pulp	0.89	1.04	NA	3.06

Step 6. Calculate the net GHG emission factor for recycling paper products. The recycling credit calculated in Step 4 is added to the estimated forest carbon sequestration from recycling paper products calculated in Step 5 to calculate the final GHG emission factor for paper products, as shown in Exhibit 3-17.

3.4.3 Composting

Composting is not included as a materials management pathway for paper products. Although paper products are composted, 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 paper would have at a composting site, including whether the GHG emissions/sequestration would be altered or whether the carbon/nitrogen ratio would be affected.

3.4.4 Combustion

Combusting paper products results in emissions of both carbon dioxide (CO₂) and nitrous oxide (N₂O). Because carbon in paper products is considered to be biogenic,²¹ CO₂ emissions from combustion are not considered in WARM. The N₂O emissions, however, are included in WARM's GHG emission factors for paper products. Transporting paper products to combustion facilities also results in GHG emissions from the combustion of fossil fuels in vehicles. Finally, electricity produced from waste combustion energy recovery is used to offset the need for electricity production at power plants,

²¹ WARM assumes that biogenic CO₂ emissions are balanced by CO₂ captured by re-growth of the plant sources of the material. Consequently, these emissions are excluded from net GHG emission factors in WARM.

consequently reducing the power sector's consumption of fossil fuels. WARM takes this into account by calculating an avoided utility emission offset.²²

Exhibit 3-24 provides the breakdown of each paper product's emission factor into these components. For additional information on combustion in WARM, see the [Combustion](#) chapter.

Exhibit 3-24: Components of the Combustion Net Emission Factor for Paper Products (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO ₂ from Combustion ^a	N ₂ O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Corrugated Containers	–	0.01	–	0.04	-0.56	–	-0.51
Magazines/Third-Class Mail	–	0.01	–	0.04	-0.41	–	-0.37
Newspaper	–	0.01	–	0.04	-0.63	–	-0.58
Office Paper	–	0.01	–	0.04	-0.54	–	-0.49
Phone Books	–	0.01	–	0.04	-0.63	–	-0.58
Textbooks	–	0.01	–	0.04	-0.54	–	-0.49
Mixed Paper (general)	–	0.01	–	0.04	-0.56	–	-0.51
Mixed Paper (primarily residential)	–	0.01	–	0.04	-0.55	–	-0.51
Mixed Paper (primarily from offices)	–	0.01	–	0.04	-0.51	–	-0.47

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

– = Zero emissions.

^a CO₂ emissions from combustion of paper products are assumed to be biogenic and are excluded from net emissions.

Exhibit 3-25 provides the calculation for the avoided utility emissions. EPA uses three data elements to estimate the avoided electric utility CO₂ 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 paper products to delivered electricity,²³ and (3) the electric utility CO₂ emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants. For more information on combustion in general, see the [Combustion](#) chapter.

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

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity (MTCO ₂ E/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted (MTCO ₂ E/Short Ton) (e = b × c × d)
Corrugated Containers	14.1	17.8%	0.221	0.56
Magazines/Third-Class Mail	10.5	17.8%	0.221	0.41

²² The utility offset credit is calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, since it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

²³ EPA used a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, 1997), an MSW heat content of 10 million Btu per short ton, and a 5 percent transmission and distribution loss rate.

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity (MTCO ₂ E/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted (MTCO ₂ E/Short Ton) (e = b × c × d)
Newspaper	15.9	17.8%	0.221	0.63
Office Paper	13.6	17.8%	0.221	0.54
Phone Books	15.9	17.8%	0.221	0.63
Textbooks	13.6	17.8%	0.221	0.54

3.4.5 Landfilling

When paper products are landfilled, anaerobic bacteria slowly degrade the materials, producing CH₄ and CO₂ over time. Because paper is derived from sustainably harvested sources of wood in the United States, CO₂ emissions are not counted, as they are biogenic and would be produced through natural decomposition in forests. CH₄ emissions, however, are included in WARM's emission factors, since the CH₄ is emitted as a result of placing the paper in a landfill, making the CH₄ a human-caused (i.e., anthropogenic) source of GHG emissions. In addition to CO₂ and CH₄ emissions, some of the carbon in landfilled paper remains stored in the landfill because paper products are not completely decomposed by anaerobic bacteria. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation. WARM also considers transportation of paper products to the landfill, which results in anthropogenic CO₂ emissions due to the combustion of fossil fuels in vehicles and landfilling equipment. Exhibit 3-26 provides the landfilling emission factors for paper products, broken down into these components. More information on the development of the emission factor is provided in the remainder of this section. For more information on landfilling in general, see the [Landfilling](#) chapter.

From a waste management perspective, landfilling some materials—including newspaper and phone books—results in net storage (i.e., carbon storage exceeds CH₄ plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present. At the other extreme, office paper and textbooks result in net emissions regardless of landfill gas collection and recovery practices.

Exhibit 3-26: Landfilling Emission Factors for Paper Products (MTCO₂E/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)
Corrugated Containers	—	0.02	1.05	-0.11	-0.72	0.23
Magazines/Third-Class Mail	—	0.02	0.48	-0.05	-0.85	-0.39
Newspaper	—	0.02	0.40	-0.05	-1.19	-0.82
Office Paper	—	0.02	1.49	-0.18	-0.12	1.22
Phonebooks	—	0.02	0.40	-0.05	-1.19	-0.82
Textbooks	—	0.02	1.49	-0.18	-0.12	1.22
Mixed Paper (general)	—	0.02	0.93	-0.11	-0.72	0.13
Mixed Paper (primarily residential)	—	0.02	0.90	-0.10	-0.76	0.07
Mixed Paper (primarily from offices)	—	0.02	0.88	-0.10	-0.64	0.17

Note: The emission factors for landfill CH₄ presented in this table are based on national-average rates of landfill gas capture and energy recovery. Avoided CO₂ emissions from energy recovery are calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, since it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills. Negative values denote GHG emission reductions or carbon storage.

— = Zero emissions.

3.4.5.1 Developing the Emission Factor for Landfilling of Paper Products

WARM calculates CH₄ emission factors for landfilled materials based on the CH₄ collection system 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 energy recovery, and (3) landfills that collect LFG and recover energy by combusting it to generate electricity. WARM does not model direct use of landfill gas for process heat. 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 CH₄ is not captured, is flared without energy recovery, or is combusted onsite for energy recovery.^{24, 25} The Landfill CH₄ column of Exhibit 3-26 presents emission factors based on the national average of LFG collection usage.

The Excel version of WARM allows users to select landfill gas collection scenarios and component-specific decay rates based on different assumed moisture contents of the landfill. The tables in this section show typical landfill gas collection practices, assuming national average moisture conditions that represent a weighted average of precipitation received at landfills in the United States (EPA, 2015b). For further explanation, see the [Landfilling](#) chapter.

Exhibit 3-27 depicts the specific emission factors for each landfill gas collection type. Overall, landfills that do not collect LFG produce the most CH₄ emissions.

Exhibit 3-27: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills (MTCO₂E/Short Ton)

(a) Material	(b) Net GHG Emissions from CH ₄ Generation			(c) Net Landfill Carbon Storage	(d) GHG Emissions from Transport -ation	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation			Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Corrugated Containers	2.36	1.14	0.75	-0.72	0.02	1.66	0.45	0.06
Magazines/ Third-Class Mail	1.08	0.46	0.36	-0.85	0.02	0.25	-0.37	-0.46
Newspaper	0.94	0.43	0.28	-1.19	0.02	-0.23	-0.75	-0.89
Office Paper	3.50	1.61	1.05	-0.12	0.02	3.40	1.51	0.95
Phone Books	0.94	0.43	0.28	-1.19	0.02	-0.23	-0.75	-0.89
Textbooks	3.50	1.61	1.05	-0.12	0.02	3.40	1.51	0.95
Mixed Paper (general)	2.14	1.00	0.67	-0.72	0.02	1.44	0.30	-0.03
Mixed Paper (primarily residential)	2.07	0.97	0.65	-0.76	0.02	1.33	0.23	-0.09

²⁴ Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of this report, the assumption was that all gas for energy recovery was combusted onsite.

²⁵ For the year 2013, an estimated 13 percent of landfill CH₄ was generated at landfills with landfill gas recovery systems and flaring, while 72 percent was generated at landfills with gas collection and energy recovery systems (EPA, 2015b).

(a) Material	(b) Net GHG Emissions from CH ₄ Generation			(c) Net Landfill Carbon Storage	(d) GHG Emissions from Transport -ation	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation			Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Mixed Paper (primarily from offices)	2.03	0.91	0.64	-0.64	0.02	1.42	0.29	0.02

Note: Negative values denote GHG emission reductions or carbon storage.

WARM calculates landfill carbon storage from paper products based on laboratory test data on the ratio of carbon storage per short ton of paper landfilled. This estimate uses data from Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013). These studies provide estimates for newsprint, corrugated containers, and office paper. An average of coated paper and office paper is used as a proxy for magazines/third-class mail, newsprint is used as a proxy for phonebooks, and office paper is used as a proxy for textbooks. Exhibit 3-28 provides the landfill carbon storage calculation used in WARM.

Exhibit 3-28: Calculation of the Carbon Storage Factor for Landfilled Paper Products

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (g C/Dry g)	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Storage to Wet Weight (g C/Wet g) (d = b × c)	(e) Amount of Carbon Stored (MTCO ₂ E per Wet Ton)
Corrugated Containers	0.26	83%	0.22	0.72
Magazines/Third-Class Mail	0.28	92%	0.25	0.85
Newspaper	0.41	87%	0.36	1.19
Office Paper	0.04	91%	0.04	0.12
Phonebooks ^b	0.41	87%	0.36	1.19
Textbooks ^c	0.04	91%	0.04	0.12

^a Based on estimates in Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013).

^b Newspaper used as a proxy.

^c Office Paper used as a proxy.

3.4.6 Anaerobic Digestion

Because of the nature of paper product components, WARM does not include an emission factor for the anaerobic digestion of paper products.

3.5 LIMITATIONS

Aside from the limitations associated with the forest carbon storage estimates as described in the [Forest Carbon Storage](#) chapter, the following limitations are associated with the paper products emission factors:

The emission factors associated with producing and recycling paper products are representative of manufacturing processes in the mid-1990s, and may have changed since the original life-cycle information was collected; depending upon changes in manufacturing process, such as efficiency improvements, fuel inputs and compositional changes, energy use and GHG emissions from virgin and recycled production of these products may have increased or decreased.

Composting is not included as a materials management pathway due to a lack of information on the GHG implications of composting paper products. The composting factor in WARM, described in the

Composting chapter, assumes a generic compost mix, rather than looking at materials in isolation. There are no quantifiable data to measure the effect of adding paper to a compost pile. However, EPA is planning to further investigate this topic, to enable better assessments of composting emission factors for paper products.

The energy content (by weight) and landfill carbon storage for phone books and textbooks are assumed to be the same as those for newspaper and office paper, respectively, while in fact they may be different, since phone books and textbooks include covers and binding materials. EPA does not expect that this difference would have a large influence on the combustion or landfilling emission factors.

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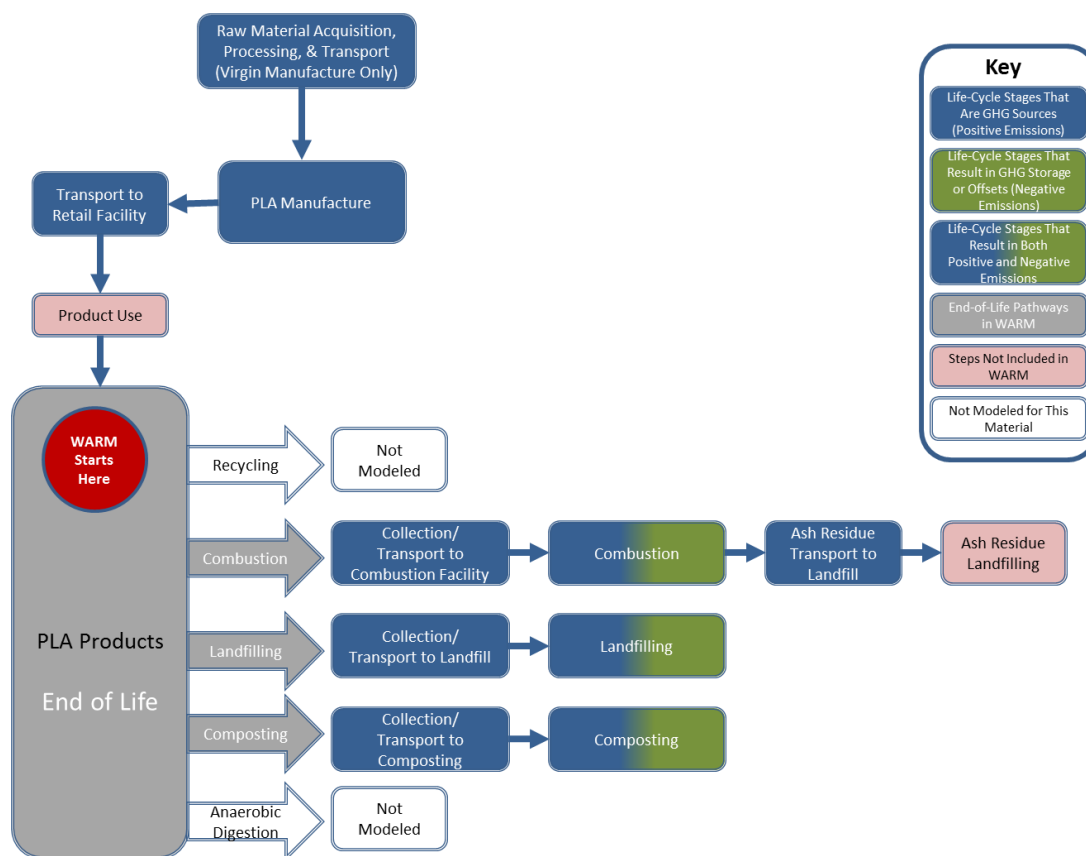
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4 POLYLACTIDE (PLA) BIOPOLYMER

4.1 INTRODUCTION TO WARM AND PLA

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for Natureworks' Ingeo polylactide (PLA) biopolymer resin, beginning at the waste generation reference point. Due to the large number of end applications for PLA (e.g., food containers, bottles and other consumer products) and the lack of data specific to the United States, EPA models all PLA in resin form only and does not include final processes that convert the resin into products. The WARM GHG emission factors are used to compare the net emissions associated with this biopolymer in the following four materials management options: source reduction, composting, landfilling, and combustion.²⁶ The rest of this module provides details on these materials management options as life-cycle pathways for PLA. Exhibit 4-1 shows the general outlines of materials management pathways for PLA 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](#), [Landfilling](#), and [Combustion](#), see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHG emissions. 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 PLA in WARM



²⁶ As discussed in this chapter, life-cycle data for recycling PLA are not available and thus EPA cannot represent the recycling pathway in WARM.

In recent years, there has been a push towards manufacturing “greener alternatives” for consumer products and packaging; bio-based materials are being developed for constructing materials such as containers and packaging products. Polylactic acid or PLA is one such biopolymer that is constructed from renewable agricultural products (e.g., corn) and is being used for a wide range of products such as rigid packaging and folding boxes, disposable cups, cutlery, bottles, films, carpet, apparel, and personal hygiene products. Although there are a number of different types of biopolymers, for example Poly-3-hydroxybutyrate-co-3-hydroxyoctanoate (PHBO), EPA is currently only modeling the PLA biopolymer material type in WARM due to life-cycle data availability. Additionally, there are several different grades of PLA biopolymer used to manufacture a wide variety of products. The emission factors developed for WARM have been developed using life-cycle inventory data specifically for thermoplastic resin (i.e., 2002D and 2003D) that can be extruded for use in various applications, including fresh food packaging and service ware. EPA did not obtain life-cycle information about the additional PLA grades (e.g., 3001D, 4043D, 7001D or 7032D) to develop appropriate GHG emission factors for these biopolymer grades.²⁷ Note that the data provided by NatureWorks and used to create the GHG emission factors for WARM only represents Ingeo polylactide (PLA) resin production by NatureWorks LLC in Blair, Nebraska. However, considering that there are no direct competitors to NatureWorks that operate a fully industrial-scale PLA manufacturing plant in the United States, these data are considered representative of U.S. PLA production. In WARM, the definition of PLA is shown below:

PLA. PLA is a versatile thermoplastic biopolymer constructed entirely from annually renewable agricultural products, e.g., corn, and used in manufacturing fresh food packaging and food service ware such as rigid packaging, food containers, disposable plastic cups, cutlery, and plates (U.S. LCI, 2010a).

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.²⁸ 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. The upstream manufacturing process for PLA is summarized in section 4.3. For further information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

The overall life-cycle energy associated with manufacturing PLA from virgin inputs is given in Exhibit 4-2. Life-cycle data for recycling PLA are not available and this practice is not common in the US. Therefore, we cannot represent the recycling pathway in WARM. In addition, WARM does not include anaerobic digestion as a materials management pathway for PLA.

Exhibit 4-2: Life-Cycle Energy Associated with Manufacture (with 100% Virgin and 100% Recycled Inputs)

Material	Virgin Manufacture		Recycled Manufacture	
	Process Energy per Ton Made from Virgin Inputs (Million Btu)	Transportation Energy per Ton Made from Virgin Inputs (Million Btu)	Process Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)
PLA	29.99	0.17	NA	NA

NA = Not applicable.

²⁷ A list of the various PLA grades can be found here: <http://www.natureworkslc.com/Technical-Resources.aspx>

²⁸ 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.

As Exhibit 4-3 illustrates, most of the GHG sources relevant to PLA in this analysis fall under the raw materials acquisition and manufacturing and end-of-life sections of the life cycle. The source reduction pathway has the largest emission factor for PLA since upstream manufacturing emissions are significant. PLA contains biogenic carbon but does not generate CH₄ emissions when landfilled because it stores carbon. Therefore, the emissions associated with landfilling PLA include only transportation- and landfill-equipment-related emissions.

Exhibit 4-3: PLA GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for PLA	GHG Sources and Sinks Relevant to PLA		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Offsets <ul style="list-style-type: none"> • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy • Transport of PLA to point of sale 	NA	NA
Recycling	Not applicable since data for recycling of PLA (in the United States) does not exist		
Composting	NA	Offsets E. Increase in soil carbon storage	Emissions F. Transport to compost facility G. Compost machinery
Combustion	NA	NA	Emissions H. Transport to WTE facility
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> • Transport to landfill • Landfilling machinery Offsets <ul style="list-style-type: none"> • Landfill carbon storage
Anaerobic Digestion	Not Modeled in WARM		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 4-3 and calculates net GHG emissions per short ton of PLA generated for each materials management alternative as shown in Exhibit 4-4. For additional discussion on the detailed methodology used to develop these emission factors, see sections 4.3 and 4.4.

Exhibit 4-4: Net Emissions for PLA under Each Materials Management Option (MTCO₂E/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
PLA	-2.09	NA	-0.15	-0.65	-1.64	NA

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

NA = Not applicable.

*Due to unavailable data, it is assumed that the current mix of PLA is 100% virgin inputs

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 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. For example, in PLA manufacture, CO₂ emissions occur during production of calcium hydroxide from conversion of calcium carbonate into calcium oxide.

The RMAM calculation in WARM also incorporates “retail transportation,” which includes the average truck, rail, water and other-modes transportation emissions required to transport these PLA products from the manufacturing facility to the retail/distribution point. The energy and GHG emissions from retail transportation are presented in Exhibit 4-5. Transportation emissions from the retail point to the consumer are not included. The number of miles traveled and mode-specific fuel use 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, 1998c), respectively. The “plastics and rubber” commodity type in the Commodity Flow Survey is used as a proxy for PLA.

Exhibit 4-5: Retail Transportation Energy Use and GHG Emissions

Material	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emission Factors (MTCO ₂ E per Short Ton of Product)
PLA	497	0.539	0.040

The total RMAM emissions for PLA manufacture are shown in the section on source reduction. The net emission factor for source reduction of PLA includes RMAM “upstream” emissions.

PLA manufacture involves production of the following materials in a step-by-step process – corn, dextrose, lactic acid, lactide and polymer production. Corn production involves harvesting and drying of corn and its transportation to a corn wet mill (CWM). At the CWM, the starch is separated from the corn kernel and hydrolyzed using enzymes to obtain dextrose. This unrefined dextrose solution is sent to an adjacent fermentation facility via a pipeline for fermentation into lactic acid. The fermentation process produces crude lactic acid by combining dextrose with other materials including microbes. The addition of some calcium hydroxide, to maintain pH balance, and sulfuric acid in the end, to acidify the lactic acid, results in precipitation of gypsum. The purified lactic acid is polymerized to form polylactide polymer through removal of water in a continuous condensation process and catalytic conversion of the lactic acid into lactide (a cyclic dimer). Finally, this lactide is distilled and polymerized. Polymer pellets are the final product of this manufacturing process. (U.S. LCI, 2010a)

The GHG emissions associated with embedded carbon (either biogenic or non-biogenic) are not considered part of the RMAM emissions. Since WARM uses a materials management perspective, the GHG emissions associated with embedded carbon are incorporated within the various waste management scenarios (i.e., source reduction, recycling, landfilling, composting, or combustion) according to the relative amount of biogenic carbon that is ultimately stored and non-biogenic carbon that is eventually released at end-of-life.

4.4 MATERIALS MANAGEMENT

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 4-3 and calculates net GHG emissions per short ton of PLA input. Landfilling, composting, source reduction and combustion are the four materials management options used to manage PLA. Source reduction and landfilling have the lowest net emission factors among the various materials management options for PLA.

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 post-consumer waste are avoided. As discussed above, under the measurement convention used in this analysis, source reduction results in negative raw material and manufacturing GHG emissions (i.e., it avoids emissions attributable to production) and zero end-of-life management GHG emissions. For more information, please refer to the [Source Reduction](#) chapter.

The biogenic carbon emissions associated with the growth of the plant sources in the production of PLA are assumed to be net zero during source reduction of PLA. WARM assumes that carbon in biogenic sources was originally removed from the atmosphere by photosynthesis, and under natural conditions, would cycle back to the atmosphere due to degradation processes. Unlike other bio-based materials such as paper and wood materials where WARM assumes that source reduction of these products increases the amount of carbon stored in forests by reducing the amount of wood harvested in forests, the implications for growing annual crops used to produce PLA is unclear and highly uncertain. Most likely, source reducing the manufacture of PLA would result in the underlying input corn crop being harvested for other purposes. Since the corn crops are annual crops, unharvested crops would eventually decay and release the biogenic carbon back to the atmosphere. Therefore, it is unlikely that any additional biogenic carbon would be stored. Thus, the biogenic carbon emissions associated with source reducing PLA are considered net zero.

Exhibit 4-6 presents the inputs to the source reduction emission factor for both current mix of inputs and 100 percent virgin inputs manufacture of PLA. Due to unavailable data, it is assumed that the current mix of PLA is 100% virgin inputs. Please see the [Source Reduction](#) chapter for more information.

Exhibit 4-6: Source Reduction Emission Factors for PLA (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs*	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Sequestration for Current Mix of Inputs	Forest Carbon Sequestration for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs*	Net Emissions for 100% Virgin Inputs
PLA	-2.09	-2.09	NA	NA	-2.09	-2.09

NA = Not applicable.

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 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.

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

4.4.1.1 Developing the Emission Factor for Source Reduction of PLA

To calculate the avoided GHG emissions for PLA, EPA first looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 4-7 shows the results for each component and the total GHG emission factors for source reduction of PLA.

Exhibit 4-7: Raw Material Acquisition and Manufacturing Emission Factor for Source Reduction of Virgin Production of PLA (MTCO₂E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
PLA	1.81	0.05	0.22	2.09

Process Energy: To calculate this factor, EPA obtained an estimate of the amount of energy required to acquire and produce one short ton of PLA, in Btu. Next, we determined the fuel mix that comprises this Btu estimate (U.S. LCI, 2010b), mainly electricity from the grid and natural gas combusted in industrial equipment and boilers, and then multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. The appropriate emissions profile for electricity consumption is calculated by using the electricity factor representative of the West-North Central grid mix from eGRID because PLA is developed at one main production facility in Nebraska, which draws electricity from the West-North Central grid.

The sums of the resulting GHG emissions by fuel type comprise the total process energy GHG emissions, including both CO₂ and CH₄, from all fuel types used in PLA production. The process energy used to produce PLA and the resulting emissions are shown in Exhibit 4-8.

Exhibit 4-8: Process Energy GHG Emissions Calculations for Virgin Production of PLA

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
PLA	29.99	1.82

Transportation Energy: Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for PLA production. The methodology for estimating these emissions is the same as that used for process energy emissions. All transport is reported as taking place via diesel-powered combination truck. Hence, EPA calculates the total emissions by applying the carbon coefficient for diesel to the transportation fuel use (U.S. LCI, 2010b). The calculations for estimating the transportation energy emission factor are shown in Exhibit 4-9.

Exhibit 4-9: Transportation Energy Emissions Calculations Virgin Production of PLA

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
PLA	0.17	0.01

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 4-5.

Non-energy Process: Non-energy GHG emissions occur during manufacturing but are not related to the consumption of fuel for energy. For example, there are N₂O emissions associated with offgassing from fertilizer production and application in corn production. Also, non-energy CO₂ emissions are emitted in calcium hydroxide production in the conversion of calcium carbonate into calcium oxide during upstream production. According to NatureWorks (EPA, 2010b), all of the nitrous oxide (N₂O) and 30 percent of the total CO₂ emitted are non-energy emissions, and the CH₄ emissions are mainly energy related.²⁹ Hence, the appropriate proportion of total CO₂ and all of the N₂O output per short ton of PLA produced as provided in U.S. LCI database (U.S. LCI, 2010b) is assigned to non-energy process emissions. Exhibit 4-10 shows the components for estimating process non-energy GHG emissions for PLA.

²⁹ According to responses received from NatureWorks (EPA 2010b) all of the N₂O is released during crop production and is hence considered non-energy process emissions.

Exhibit 4-10: Process Non-Energy Emissions Calculations for Source Reduction of Virgin Production of PLA

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions (MTCO ₂ E/Short Ton)
PLA	0.11	NA*	—	—	0.00	0.22

* CH₄ emissions are not accounted for here since these are associated with energy use which is captured in the energy emissions for process energy use.

— = Zero emissions.

4.4.2 Recycling

Although the NatureWorks' PLA website³⁰ indicates that PLA can be recycled indefinitely with virtually no use of virgin polymer for remanufacture, no life-cycle emission factor for recycling was developed as recycling data are currently unavailable. Also, the infrastructure for recycling PLA in the United States is still developing (due to economic and technological issues) and therefore is not a common waste management practice.

4.4.3 Composting

The net composting emission factor is calculated as the sum of emissions from transportation to compost facility, processing of compost, and the carbon storage resulting from compost application. Transportation of PLA to the central composting site results in nonbiogenic CO₂ emissions.³¹ In addition, during the composting process the compost is mechanically turned, and the operation of this equipment results in non biogenic CO₂ emissions. Additionally, microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH₄ and N₂O gas, a net contributor to the GHG emissions associated with the composting pathway (for more information on fugitive emissions, please refer to the Composting chapter). Exhibit 4-11 details these components for PLA.

PLA is biogenic and according to the NatureWorks' PLA website³², fully biodegrades within 45 days. Hence, it is assumed to have the same composting life-cycle emission factor as other biogenic materials in WARM. For additional information on composting in WARM, see the Composting chapter. Exhibit 4-11 shows the two emission sources and one emission sink resulting from the composting of organics.

Exhibit 4-11: Components of the Composting Net Emission Factor for Organics

Composting of Post-Consumer Material (GHG Emissions in MTCO ₂ E/Short Ton)						
Material Type	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Composting	Compost CO ₂	Compost CH ₄ and N ₂ O	Soil Carbon Storage	Net Emissions (Post- Consumer)
PLA	NA	0.02	—	0.07	-0.24	-0.15

³⁰ <http://www.natureworkslc.com/The-Ingeo-Journey/End-of-Life-Options/Recycling.aspx>

³¹ Transportation emissions from delivery of finished compost from the composting facility to its final destination were not counted.

³² <http://www.natureworkslc.com/The-Ingeo-Journey/End-of-Life-Options/Composting.aspx>

4.4.3.1 Emissions from Collection and Transport

Transportation energy emissions occur when fossil fuels are combusted to collect and transport yard trimmings and food scraps to a composting facility, and then to operate the composting equipment that turns the compost. 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 2015). The NREL emission factor assumes a diesel, short-haul truck which are detailed in Exhibit 4-12.

Exhibit 4-12: Emissions Associated with Transporting and Turning Compost

	Diesel Fuel Required to Collect and Transport One Ton (million Btu) ^a	Diesel Fuel Required to Turn the Compost Piles (million Btu) ^a	Total Energy Required for Composting (million Btu)	Total CO ₂ Emissions from Composting (MTCO ₂ E)
PLA	0.37	0.22	0.59	0.02

^a Based on estimates found on Table I-17 on page I-32 of FAL (1994).

4.4.3.2 Carbon Storage Associated with Composting

WARM currently assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils (the "soil carbon restoration" effect)³³ and carbon stored in non-reactive humus compounds (the "increased humus formation" effect).³⁴ The carbon values from the soil carbon restoration effect are scaled according to the percentage of compost that is passive, or non-reactive, which is assumed to be 52 percent (Cole, 2000). The weighted soil restoration value is then added to the increased humus formation effect in order to estimate the total sequestration value associated with composting. The inputs to the calculation are shown in Exhibit 4-13.

Exhibit 4-13: Soil Carbon Effects as Modeled in Century Scenarios (MTCO₂E/Short Ton of Organics)

Scenario	Soil Carbon Restoration			Increased Humus Formation	Net Carbon Flux ^a
	Unweighted	Proportion of C that is Not Passive	Weighted estimate		
Annual application of 32 tons of compost per acre	-0.04	48%	-0.07	-0.17	-0.24

^a The net carbon flux sums each of the carbon effects together and represents the net effect of composting a short ton of yard trimmings in MTCO₂E.

4.4.3.3 Net Composting Emission Factor

The nonbiogenic CO₂ emissions from transportation, collection and compost turning are added to the compost carbon sink in order to calculate the net composting GHG emission factors for each organics type. WARM estimates that the net composting GHG factor for all compostable organic materials is the same for all sources of compost.

4.4.4 Combustion

This study's general approach was to estimate (1) gross emissions of CO₂ and N₂O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the

³³ EPA evaluated the soil carbon restoration effect using Century, a plant-soil ecosystems model that simulates long-term dynamics of carbon, nitrogen, phosphorous and sulfur in soils. For more information, see the [Composting](#) chapter.

³⁴ EPA evaluated the increased humus formation effect based on experimental data compiled by Dr. Michael Cole of the University of Illinois. These estimates accounted for both the fraction of carbon in the compost that is considered passive and the rate at which passive carbon is degraded into CO₂. For more information, see the [Composting](#) chapter.

combustor to a landfill), (2) CO₂ emissions avoided due to displaced electric utility generation, and (3) CO₂ emissions avoided due to recovery and recycling of ferrous metals at the combustor. To obtain an estimate of the net GHG emissions from MSW combustion, the value for GHG emissions avoided is subtracted from the direct GHG emissions. Exhibit 4-14 provides the emission factors related to combusting of PLA.

Exhibit 4-14: Components of the Combustion Net Emission Factor for PLA (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO ₂ from Combustion	N ₂ O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
PLA	–	0.01	–	–	-0.66	–	-0.65

Note: Negative emissions indicate GHG benefits.

– = Zero emissions.

Because this study considers a material from end of life, RMAM emissions are considered to be zero for this materials management pathway. Since there is no nitrogen content in PLA, we assume no N₂O emissions from combustion. There are also no emissions avoided due to steel recovery.

Emissions from Transportation of Waste. For the CO₂ emissions from transporting waste to the combustion facility, EPA used emission factors from NREL's US Life Cycle Inventory Database (USLCI) (NREL 2015). The NREL emission factor assumes a diesel, short-haul truck. For the handling of the ash from the combustion facility to a landfill, EPA used an estimate of 12.6 lbs CO₂ per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO₂ per ton of mixed MSW to MTCO₂E per ton of mixed MSW. WARM assumes that transportation of PLA uses the same amount of energy as transportation of mixed MSW.

Avoided Utility Emissions. Most WTE plants in the United States produce electricity and only a few cogenerate electricity and steam (EPA, 2006). In this analysis, EPA assumes that the energy recovered with PLA combustion would be in the form of electricity, as shown in Exhibit 4-15. The exhibit shows emission factors for mass burn facilities (the most common type of WTE plant). EPA used three data elements to estimate the avoided electric utility CO₂ 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 MSW to delivered electricity, and (3) the electric utility CO₂ emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

For PLA, we can calculate the amount of GHG avoided using the national average non-baseload factor for utility generated electricity based on the energy content of PLA. According to the NatureWorks' PLA website³⁵, the Ingeo PLA contains 8,368 Btu/pound. At a combustion efficiency of roughly 18 percent at mass burn combustion facilities, this translates into avoided CO₂ emissions of 0.68 MTCO₂E/short ton of PLA combusted as shown below.

³⁵ <http://www.natureworkslc.com/The-Ingeo-Journey/End-of-Life-Options/Incineration.aspx>

Exhibit 4-15: Utility GHG Emissions Offset from Combustion of PLA

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity (MTCO ₂ E/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted (MTCO ₂ E/Short Ton) (e = b × c × d)
PLA	16.74	17.8%	0.15	0.45

Source: NatureWorks, LLC (2010a).

To estimate the gross GHG emissions per ton of PLA combusted, EPA adds transportation CO₂ emissions to the avoided utility emissions in order to calculate the net GHG emission factor. As shown in Exhibit 4-15 WARM estimates that combustion of PLA results in a net emissions reduction.

4.4.5 Landfilling

The landfilling emissions factor is calculated as the sum of emissions from transportation of waste to the landfill and operation of landfill equipment, methane emissions from degradation of biogenic carbon in the landfill, avoided GHG emissions from landfill methane capture and subsequent energy recovery, and the carbon storage resulting from undecomposed carbon remaining in landfills. According to NatureWorks (2011a), PLA does not biodegrade in landfill conditions. However, other biopolymers such as poly(3-hydroxybutyrate-co-3-hydroxyoctanoate) (PHBO) (C₁₃H₂₁O₄) have been shown to degrade in landfills so it is important not to use PLA as a proxy for other biopolymers (Levis and Barlaz 2011). For Ingeo PLA, the percentage of sequestered biogenic carbon remains steady at close to 100 percent for the 2002D PLA product even after four months in simulated landfill conditions.³⁶ This is similar to petroleum-based polyethylene (PE) plastic resin. Therefore, landfill CH₄ emissions in the landfilling pathway are determined to be zero for PLA.³⁷ Accordingly, there are no avoided CO₂ emissions from landfill gas recovery for energy.

However, we can calculate the amount of biogenic carbon stored in the landfill based on the CO₂ sequestered via photosynthesis in corn production. The “inputs from nature” in the US LCI Database PLA spreadsheet accounts for “CO₂ taken from air during corn production and stored in polymer”. We have translated this information into the assumed “biogenic carbon content” of the PLA (Exhibit 4-16).

Exhibit 4-16: Biogenic Carbon Content of PLA³⁸

(a) CO ₂ , biogenic, uptake by corn used to manufacture PLA (kg CO ₂ /kg PLA)	(b=a*0.907) CO ₂ , biogenic, uptake by corn used to manufacture PLA (short ton CO ₂ /short ton PLA)	(c = b *(12/44)) Carbon stored within PLA (short ton Carbon/short ton PLA)	(d) Biogenic Carbon Content (percent per short ton PLA)
1.94	1.76	0.48	48%

The only emissions associated with landfilling for PLA relate to transporting PLA waste to the landfills and moving waste around in the landfills. Transportation of waste and the use of landfilling equipment results in anthropogenic CO₂ emissions, due to the combustion of fossil fuels in the vehicles

³⁶ <http://www.natureworkslc.com/The-Ingeo-Journey/End-of-Life-Options/Landfill.aspx>

³⁷ It was determined that assuming zero degradation in landfill conditions for the PLA Ingeo 2002d is valid and supported by experimental results.

³⁸ In response to the *Preliminary Review of NatureWorks polylactide biopolymer (PLA) LCI Data* memo (EPA, 2010) prepared by ICF, NatureWorks responded that the “net CO₂ uptake is 1.833 kg CO₂/kg PLA” which implies that Carbon content of PLA is 50% (EPA 2010b).

used. For further information please refer to the chapter on Landfilling. Exhibit 4-17 provides the net emission factor for landfilling of PLA.

Exhibit 4-17: Landfilling Emission Factors for PLA (MTCO₂E/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)
PLA	–	0.02	–	–	-1.66	-1.64

4.4.6 Anaerobic Digestion

Because of the nature of PLA components, WARM does not include an emission factor for the anaerobic digestion of PLA.

4.5 LIMITATIONS

In developing and reviewing the life-cycle emission factors for all the materials management pathways, it is clear that source reduction and landfilling result in net GHG benefits for PLA. This can also be seen in Exhibit 4-3. Landfilling appears to be a particularly attractive option because of the assumption that 100 percent of the biogenic carbon is stored in landfills. Source reduction is the only materials management strategy that results in more GHG benefits than landfilling (due to avoided PLA production).

A few key limitations and uncertainties of this analysis include the following:

High landfill carbon storage: For this analysis EPA assumes 100 percent landfill carbon storage for PLA. Limited lab testing by NatureWorks indicated that the biogenic carbon of only one of the PLA products (Ingeo 2002d - thermoforming) is fully stored in a landfill, while the other two (Ingeo 4032 D and 4060D – film) show a decrease in carbon storage under accelerated landfill conditions. Since the WARM analysis mainly considers thermoforming products in the waste stream, discussion with NatureWorks determined that assuming zero degradation in landfills for the PLA Ingeo 2002d is valid and supported by experimental results. However, this assumption may be conservative since PLA may break down over time, especially under accelerated conditions. Thus, the GHG benefits of landfilling PLA may be lower than currently calculated.

Currently unavailable recycling data: Data relevant to the recycling materials management pathway for PLA are lacking. EPA will consider incorporating the recycling pathway for PLA in the future should the necessary data become available.

4.6 REFERENCES

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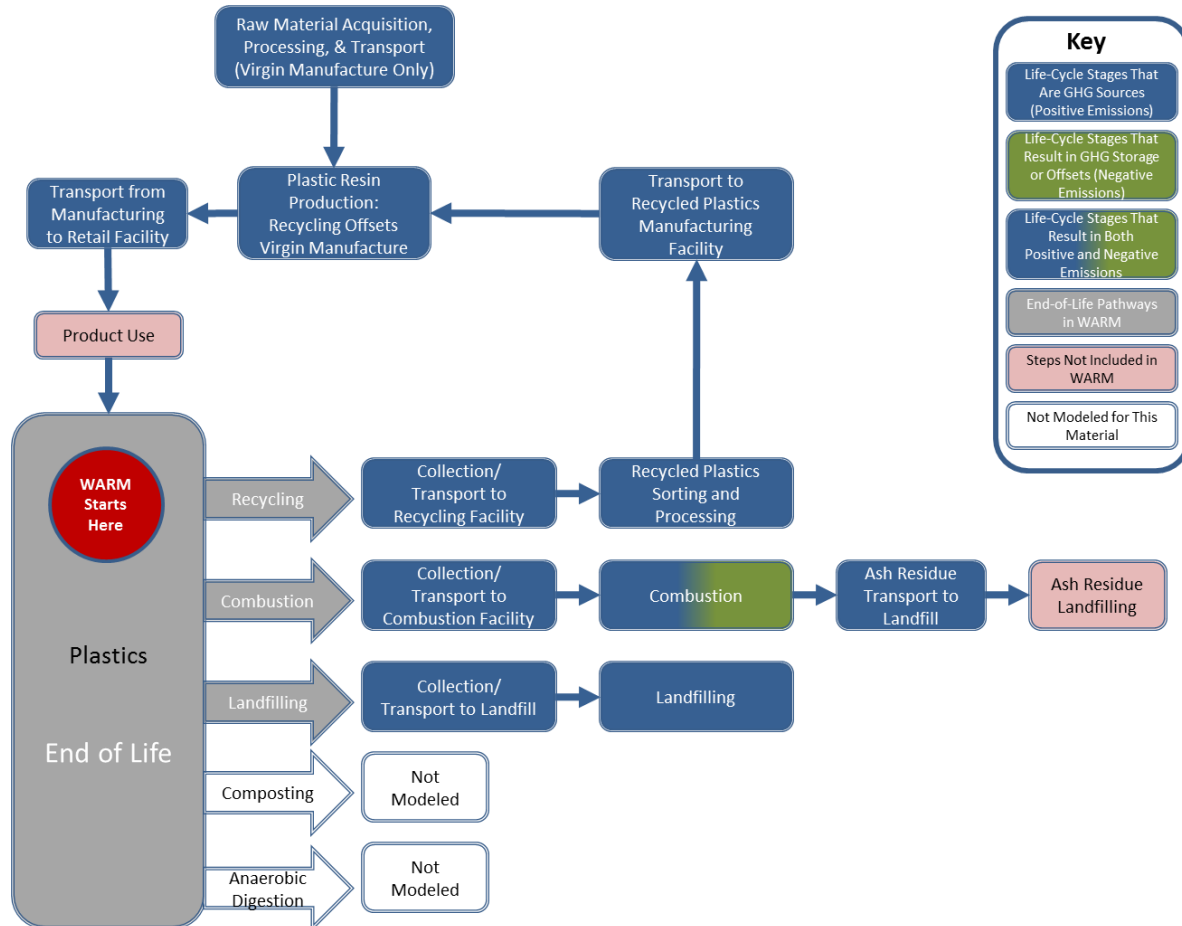
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5 PLASTICS

5.1 INTRODUCTION TO WARM AND PLASTICS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for various plastics, beginning at the waste generation reference point. The WARM GHG emission factors are used to compare the net emissions associated with management of plastics in the following four materials management alternatives: source reduction, recycling, landfilling, and combustion (with energy recovery). Exhibit 5-1 shows the general outline of materials management pathways for plastics 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](#), [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.

Exhibit 5-1: Life Cycle of Plastics in WARM³⁹



Plastics included in WARM are high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyethylene terephthalate (PET), linear low-density polyethylene (LLDPE), polypropylene (PP), general purpose polystyrene (PS), and polyvinyl chloride (PVC).³⁹ According to the EPA report, *Advancing Sustainable Materials Management: Facts and Figures 2013*, these seven plastics accounted

³⁹ Due to LCI data limitations, the recycling pathway is only available for HDPE and PET plastic resins.

for over eighty-seven percent of the plastic waste generated in 2013 (EPA, 2015). These plastics were chosen for WARM because they represent plastics commonly found in the MSW stream and comprehensive and complete data were available from a consistent source for these plastics (FAL, 2011a; FAL, 2011b). Due to the large number of end applications for plastics (e.g., bags, bottles and other consumer products) and the lack of data specific to the United States, EPA models all plastics in resin form only and does not include final processes that convert the resins into plastic products. According to PlasticsEurope, which has conducted life-cycle inventories on some plastics end applications such as HDPE bottles, the majority of the energy and emissions associated with the production of various plastics applications is due to the production of the resin itself (PlasticsEurope, 2005).

WARM also calculates emission factors for a mixed plastics category, based on the relative prevalence of HDPE and PET plastics in the recovery stream based on the recovery amounts shown in EPA's *Advancing Sustainable Materials Management: Facts and Figures 2013* (EPA, 2015).⁴⁰ Further discussion on the end uses of these plastics is provided below.

HDPE. HDPE is used for a wide variety of products, including bottles, packaging containers, drums, automobile fuel tanks, toys and household goods. It is also used for packaging many household and industrial chemicals such as detergents and bleach and can be added into articles such as crates, pallets or packaging containers (ICIS, 2011a).

LDPE. LDPE is used mainly for film applications in packaging, such as poultry wrapping, and in non-packaging, such as trash bags. It is also used in cable sheathing and injection moulding applications (ICIS, 2011a).

LLDPE. LLDPE is used in high-strength film applications. Compared to LDPE, LLDPE's chemical structure contains branches that are much straighter and closely aligned, providing it with a higher tensile strength and making it more resistant to puncturing or shearing (ICIS, 2011a).

PET. The largest use for PET is for synthetic fibers, in which case it is referred to as polyester. PET's next largest application is as bottles for beverages, including water. It is also used in electrical applications and packaging (ICIS, 2011b).

PP. PP is used in packaging, automotive parts, or made into synthetic fibres. It can be extruded for use in pipe, conduit, wire, and cable applications. PP's advantages are a high impact strength, high softening point, low density, and resistance to scratching and stress cracking. A drawback is its brittleness at low temperatures (ICIS, 2011c).

PS. PS has applications in a range of products, primarily domestic appliances, construction, electronics, toys, and food packaging such as containers, produce baskets, and fast food containers (ICIS, 2011d).

PVC. PVC is produced as both rigid and flexible resins. Rigid PVC is used for pipe, conduit, and roofing tiles, whereas flexible PVC has applications in wire and cable coating, flooring, coated fabrics, and shower curtains (ICIS, 2011e).

⁴⁰ The mixed plastics is only based on HDPE and PET plastics because these are the plastic types for which information on recycling energy use and GHG emissions is currently available.

5.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

The life-cycle perspective in WARM starts at the point of waste generation—the point at which a material is discarded—and only considers upstream (i.e., material acquisition and manufacturing) GHG emissions for two of the four end-of-life materials management decisions, recycling and source reduction. For more information on evaluating upstream emissions, see the chapters on [Recycling](#) and [Source Reduction](#).

WARM includes emission factors for source reduction, recycling, landfilling, and combustion with energy recovery for this material group. The recycling pathway is currently only available for HDPE and PET plastic resins. Life-cycle inventory data for other recycled plastic resins is not yet available, and some plastics (e.g., PVC) are not widely recycled in practice (EPA, 2015). The types of plastics examined here cannot be composted or anaerobically digested, so composting and anaerobic digestion are not included. As Exhibit 5-2 illustrates, most of the GHG sources relevant to plastics in this analysis are associated with raw materials acquisition and manufacturing (RMAM).

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

Materials Management Strategies for Plastics	GHG Sources and Sinks Relevant to Plastics		
	Sources of Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	Sources of End-of-Life Management GHGs
Source Reduction	Offsets <ul style="list-style-type: none"> Transport of raw materials and products Virgin manufacture process energy Virgin manufacture process non-energy 	NA	NA
Recycling*	Emissions <ul style="list-style-type: none"> Transport of recycled materials Recycled manufacture process energy Recycled manufacture process non-energy Offsets <ul style="list-style-type: none"> Transport of raw materials and products Virgin manufacture process energy Virgin manufacture process non-energy 	NA	Emissions <ul style="list-style-type: none"> Collection and transportation to material recovery facility
Composting	Not applicable because plastics cannot be composted		
Combustion	NA	NA	Emissions <ul style="list-style-type: none"> Transport to WTE facility Combustion-related CO₂ and N₂O Offsets <ul style="list-style-type: none"> Avoided utility emissions
Landfilling	NA	NA	Emissions <ul style="list-style-type: none"> Transport to landfill Landfilling machinery
Anaerobic Digestion	Not applicable because plastics cannot be anaerobically digested		

NA = Not applicable.

* The recycling pathway is only available for HDPE and PET plastics currently due to LCI data limitations.

WARM emission factors include all of the GHG sources and sinks outlined in Exhibit 5-2 and calculate net GHG emissions per short ton of plastics inputs. In all cases, source reduction and recycling of plastics provide GHG savings when compared to landfilling and combustion. Exhibit 5-3 provides the net emission factors for all plastic types under all materials management scenarios.⁴¹ The next sections include more detailed methodology on the derivation of the emission factors.

Exhibit 5-3: Net Emissions for Plastics under Each Materials Management Option (MTCO₂E/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
HDPE	-1.47	-0.87	NA	1.25	0.02	NA
LDPE	-1.80	NA	NA	1.25	0.02	NA
PET	-2.20	-1.12	NA	1.23	0.02	NA
LLDPE	-1.58	NA	NA	1.25	0.02	NA
PP	-1.55	NA	NA	1.25	0.02	NA
PS	-2.50	NA	NA	1.62	0.02	NA
PVC	-1.95	NA	NA	0.65	0.02	NA
Mixed Plastics	-1.92	-1.02	NA	1.23	0.02	NA

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

NA = Not applicable.

5.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

Plastic resins are made from derivatives of petroleum and natural gas. The first step in plastic manufacture is the acquisition of derivatives from refined petroleum and natural gas, which results in process energy and non-energy GHG emissions from the extraction and refining of petroleum and natural gas. The petroleum and/or natural gas are then transported to plastic manufacturers, which results in transportation GHG emissions. Once the manufacturers have the appropriate inputs, the two main processes in plastic manufacture are cracking and processing.

Cracking. Hydrocarbons from refined petroleum and natural gas are heated to extremely high temperatures during the cracking process to break down the larger molecules into smaller hydrocarbons such as ethylene and propylene.

Processing. During the processing phase, the simpler hydrocarbon molecules are made into chains called polymers, which are then combined in different variations to make plastic resins with different characteristics.

The plastic resin is then made into products through various processes such as extrusion blow molding (e.g., PET in soda bottles) and injection molding (e.g., HDPE crates). Note again that, due to the large number of end applications for plastics (e.g., bags, bottles and other consumer products) and the lack of data specific to the United States, EPA models HDPE, LDPE and PET as resin form. Energy data for RMAM of the three plastic resins in WARM come from RTI (2004), which provides energy data on both virgin and recycled plastic resin production.

⁴¹ In versions of WARM prior to version 13, source reduction of mixed material categories (e.g., metals, plastic, and paper) was not activated because mixed categories are not an individual product and therefore cannot be directly source reduced. The source reduction pathway for plastics, however, has been activated since general efficiency improvements and reduction strategies that affect plastics use broadly may result in source reduction across the mixed plastics category. In some cases, WARM users may not have information on exactly which types of plastics are being reduced, and may therefore wish to approximate changes using the mixed category.

The RMAM calculation in WARM also incorporates “retail transportation,” which includes the average truck, rail, water and other-modes transportation emissions required to transport plastics 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 for all plastic resins are presented in Exhibit 5-4. Transportation emissions from the retail point to the consumer are not included. The number of miles traveled is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and mode-specific fuel use is from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 5-4: 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 ₂ E/ Short Ton)
All Plastics	497	0.54	0.04

RMAM non-process energy data was based on FAL (2011a).⁴² Emissions associated with non-combustion-related processes (such as methane emissions from the chemical reaction to produce ethylene) are included in the WARM analysis. Non-energy process emissions from natural gas pipelines and the processing of natural gas that is used to produce steam in the manufacturing stage are also included in the overall RMAM emissions for these plastics. Further discussion on developing the RMAM emissions for each plastic type is provided in section 5.4.1.

5.4 MATERIALS MANAGEMENT

WARM models three materials management alternatives for HDPE, LDPE, PET, LLDPE, PP, PS, and PVC: source reduction, landfilling, and combustion. WARM also models a fourth materials management alternative, recycling, for HDPE and PET. For source reduction and recycling, net emissions depend not only on the management practice but also on the recycled content of the plastic. Plastics can be manufactured from 100 percent virgin inputs but are often manufactured from a combination of virgin and recycled materials. As a result, WARM models emission factors for each plastic as produced from 100 percent virgin material and from a “current mix” of virgin and recycled material. (Both options are available only in the downloadable version of WARM. The online version of WARM only models emissions factors for the “current mix.”) Exhibit 5-5 presents the variation in recycled content found in plastics in the United States, including what WARM assumes is the “current mix” of virgin and recycled content in most plastic today.

Exhibit 5-5: Recycled Content Values in Plastics Manufacturing

Material	Recycled Content Minimum (%)	Recycled Content for “Current Mix” in WARM (%)	Recycled Content Maximum (%)
HDPE	—	10%	15%
LDPE ^a	—	—	—
PET	—	3%	10%

Source: FAL (2003).

— = Zero percent.

^a The recycling pathway is only available for HDPE and PET plastics currently due to LCI data limitations.

⁴² Non-process energy emissions are equivalent to “process” emissions in FAL (2011a and 2011b). Non-process energy emissions include non-energy CO₂ emissions produced from non-biogenic (i.e., fossil) feedstocks, methane, and nitrous oxide. The emission factors do not include emissions of methyl bromide, methyl chloride, trichloroethane, chloroform, methylene chloride, carbon tetrachloride, CFC 13, or HCFC-22 since these gases together represent less than 0.1 percent of total non-energy process emissions.

The emission factors associated with source reduction are estimated for both for 100 percent virgin material and the “current mix” as detailed in the section 5.4.1, source reduction.

5.4.1 Source Reduction

When plastic is source reduced (i.e., less plastic is made), GHG emissions associated with manufacturing the plastic are avoided. As a result, emissions from RMAM are negative (representing GHG savings), as shown in Exhibit 6. The methodology for calculating the source reduction emission factors is outlined in this section. As mentioned in section 5.1, EPA estimates the emissions for the source reduction of mixed plastics by weighting the emissions for HDPE and PET by their relative shares in the waste stream. For more information on source reduction in general, see the [Source Reduction](#) chapter.

Exhibit 5-6: Source Reduction Emission Factors for Plastics (MTCO₂E/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
HDPE	-1.47	-1.57	NA	NA	-1.47	-1.57
LDPE	-1.80	-1.80	NA	NA	-1.80	-1.80
PET	-2.20	-2.24	NA	NA	-2.20	-2.24
LLDPE	-1.58	-1.58	NA	NA	-1.58	-1.58
PP	-1.55	-1.55	NA	NA	-1.55	-1.55
PS	-2.50	-2.50	NA	NA	-2.50	-2.50
PVC	-1.95	-1.95	NA	NA	-1.95	-1.95
Mixed Plastics	-1.92	-1.98	NA	NA	-1.92	-1.98

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

NA = Not applicable.

In the case of plastics, source reduction emission factors include only emissions from RMAM because there are no emissions associated with forest carbon storage. As discussed in the RMAM section (section 5.3), the RMAM emissions associated with plastics can be broken down into three emission sources: process energy, transportation energy and non-energy processes.

Exhibit 5-7 provides the emission estimates by each emission source for plastics made from 100 percent virgin material. In the Excel version of WARM, the user also has the option of selecting source reduction using estimates from the current mix of recycled and virgin material. EPA calculates the RMAM emission factors for the current mix of plastics by weighting the emissions from manufacturing each plastic type from 100 percent virgin material and the emissions from manufacturing each plastic type from 100 percent recycled material by the assumed recycled content shown in Exhibit 5-5. The methodology for estimating emissions from manufacturing plastic from recycled materials is discussed in the next section, Recycling.

Exhibit 5-7: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Plastics (MTCO₂E/Short Ton)

(a) Material	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
HDPE	1.18	0.15	0.20	1.53
LDPE	1.40	0.15	0.21	1.76
PET	1.74	0.07	0.39	2.20
LLDPE	1.14	0.15	0.25	1.54
PP	1.17	0.13	0.21	1.51
PS	1.86	0.15	0.45	2.46
PVC	1.68	0.08	0.14	1.90

Exhibit 5-8, Exhibit 5-9, and Exhibit 5-10 provide the calculations for each source of RMAM emissions: process energy, transportation energy and non-energy processes.

Exhibit 5-8: Process Energy GHG Emissions Calculations for Virgin Production of Plastics

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO ₂ E/Short Ton)
HDPE	23.68	1.18
LDPE	27.77	1.40
PET	28.25	1.74
LLDPE	23.04	1.14
PP	23.62	1.17
PS	35.86	1.87
PVC	30.25	1.68

Exhibit 5-9: Transportation Energy Emissions Calculations for Virgin Production of Plastics

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO ₂ E/Short Ton)
HDPE	2.74	0.15
LDPE	2.79	0.15
PET	1.00	0.07
LLDPE	2.77	0.15
PP	2.36	0.13
PS	2.36	0.15
PVC	1.46	0.08

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 1-6.
 – = Zero emissions.

Exhibit 5-10: Process Non-Energy Emissions Calculations for Virgin Production of Plastics

Material	CO ₂ Emissions (MT/Short Ton)	CH ₄ Emissions (MT/Short Ton)	CF ₄ Emissions (MT/Short Ton)	C ₂ F ₆ Emissions (MT/Short Ton)	N ₂ O Emissions (MT/Short Ton)	Total Non-Energy Emissions (MTCO ₂ E/Short Ton)
HDPE	0.06	0.01	–	–	–	0.20
LDPE	0.07	0.01	–	–	0.00	0.21
PET	0.27	0.00	–	–	–	0.39
LLDPE	0.11	0.01	–	–	0.00	0.25
PP	0.07	0.01	–	–	0.00	0.21
PS	0.30	0.01	–	–	–	0.45
PVC	0.08	0.00	–	–	–	0.14

– = Zero emissions.

5.4.2 Recycling

WARM models HDPE and PET recycling in a closed loop, meaning that when these plastics are recovered and recycled, they are recycled back into the same products.⁴³ Due to LCI data availability, only HDPE and PET recycling are modeled in WARM. The net emission factor for recycling each plastic type is the sum of the factors provided in Exhibit 5-11. As mentioned in section 5.1, EPA estimates the emissions for the recycling of mixed plastics by weighting the emissions for HDPE and PET by their relative shares in the waste stream.

The recycled input credits represent the difference between manufacturing the plastics from 100 percent virgin materials and 100 percent recycled materials. RMAM emissions from the virgin product are included in these recycling credits and, again, there are no emissions associated with forest carbon storage when recycling plastics. Among the two plastic types, PET shows the largest GHG benefit when recycled. For more information on recycling in general, refer to the [Recycling](#) chapter.

Exhibit 5-11: Recycling Emission Factor for Plastics (MTCO₂E/Short Ton)

Material ^a	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit ^a Process Energy	Recycled Input Credit ^b – Transportation Energy	Recycled Input Credit ^b – Process Non- Energy	Forest Carbon Storage	Net Emissions (Post- Consumer)
HDPE	–	–	-0.72	0.02	-0.17	–	-0.87
LDPE	–	–	–	–	–	–	–
PET	–	–	-0.88	0.11	-0.34	–	-1.12
LLDPE	–	–	–	–	–	–	–
PP	–	–	–	–	–	–	–
PS	–	–	–	–	–	–	–
PVC	–	–	–	–	–	–	–
Mixed Plastics	–	–	-0.82	0.07	-0.28	–	-1.02

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

– = Zero emissions.

^a Recycling emission factors are only available for HDPE and PET due to LCI data availability.^b Includes emissions from the initial production of the material being managed.

EPA calculated the difference between emissions from manufacturing 100 percent virgin material and 100 percent recycled material, broken down into the three emission sources to estimate the recycled input credits for process, transportation and non-process emissions that sum to the overall recycling emission factor for each plastic type; however there are no non-energy process emissions for

⁴³ As described in section 1, WARM models plastics in the form of plastic resin and does not incorporate the extrusion of plastic resin into various end applications (e.g., bottles).

recycled production of plastic (FAL, 2011b). Exhibit 5-12 and Exhibit 5-13 provide the calculations for GHG emissions from manufacturing each plastic type from 100-percent recycled materials. Exhibit 3-21 provides the differences between virgin and recycling plastics manufacture that account for the recycled input credits in Exhibit 5-11. Process and transportation energy for recycling HDPE and PET were based on FAL (2011b).

Exhibit 5-12: Process Energy GHG Emissions Calculations for Recycled Production of Plastics

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO ₂ E/Short Ton)
HDPE	5.33	0.35
PET	12.02	0.75

Exhibit 5-13: Transportation Energy GHG Emissions Calculations for Recycled Production of Plastics

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO ₂ E/Short Ton)
HDPE	2.31	0.17
PET	2.60	0.19

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 5-4.

Exhibit 5-14: Differences in Emissions between Recycled and Virgin Plastics Manufacture (MTCO₂E/Short Ton)

Material	Product Manufacture Using 100% Virgin Inputs (MTCO ₂ E/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO ₂ E/Short Ton)			Difference Between Recycled and Virgin 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
HDPE	1.18	0.15	0.20	0.35	0.17	–	-0.83	0.02	-0.20
PET	1.74	0.07	0.39	0.75	0.19	–	-0.99	0.12	-0.39

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

5.4.3 Composting

Because the types of plastics under consideration are not subject to aerobic bacterial degradation, they cannot be composted. As a result, WARM does not consider GHG emissions or storage associated with composting.

5.4.4 Combustion

Because plastic is made from fossil fuels, its combustion is considered an anthropogenic source of carbon emissions. Nitrous oxide (N₂O) emissions can also occur from incomplete combustion of waste but, since the plastic considered here does not contain any nitrogen, there are no N₂O emissions associated with combusting plastic. Also included in the net emission factor for combusting each plastic type are emissions associated with transporting the plastic waste to waste-to-energy (WTE) facilities and emission savings associated with the avoided emissions of burning conventional fossil fuels for utilities. Exhibit 5-15 provides the emission factors for combusting each plastic type and their components.

Exhibit 5-15: Components of the Combustion Net Emission Factor for Plastics (MTCO₂E/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO ₂ from Combustion	N ₂ O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
HDPE	–	0.01	2.79	–	-1.58	–	1.23
LDPE	–	0.01	2.79	–	-1.57	–	1.24
PET	–	0.01	2.04	–	-0.84	–	1.21
LLDPE	–	0.01	2.79	–	-1.57	–	1.23
PS	–	0.01	2.79	–	-1.57	–	1.23
PP	–	0.01	3.01	–	-1.42	–	1.60
PVC	–	0.01	1.25	–	-0.62	–	0.64
Mixed Plastics	–	0.01	2.32	–	-1.12	–	1.22

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

CO₂ emissions from combusting plastic depend on the carbon content of the plastic and the amount of carbon that is converted to CO₂ during the combustion process. Exhibit 5-16 provides the carbon content of each plastic type modeled in WARM based on its chemical composition; combustion oxidation, or the amount of carbon converted to CO₂ during combustion, which EPA estimates to be 98 percent; and the final resulting CO₂ emissions from combusting each plastic type.

Exhibit 5-16: Plastics CO₂ Combustion Emission Factor Calculation

Material	Carbon Content (%)	Carbon Converted to CO ₂ during Combustion (%)	Combustion CO ₂ Emissions (MTCO ₂ E/Short Ton)
HDPE	86%	98%	2.79
LDPE	86%	98%	2.79
PET	63%	98%	2.04
LLDPE	86%	98%	2.79
PP	86%	98%	2.79
PS	92%	98%	3.01
PVC	38%	98%	1.25
Mixed Plastics	72%	98%	2.33

Creating energy from waste at WTE facilities offsets part of the required energy production of utility companies. Exhibit 5-17 provides the calculation of utility emissions offsets for plastic combustion by plastic type based on the energy content of each plastic, the combustion system's efficiency, and the emission factor based on the national grid mix associated with a similar amount of energy produced from conventional sources.

Exhibit 5-17: Utility GHG Emissions Offset from Combustion of Plastics

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility- Generated Electricity (MTCO ₂ E/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted (MTCO ₂ E/Short Ton) (e = b × c × d)
HDPE	40.0	17.8%	0.20	1.44
LDPE	39.8	17.8%	0.20	1.44
PET	21.2	17.8%	0.20	0.77
LLDPE	39.9	17.8%	0.20	1.44
PP	39.9	17.8%	0.20	1.44
PS	36.0	17.8%	0.20	1.30
PVC	15.8	17.8%	0.20	0.57

5.4.5 Landfilling

WARM considers the methane (CH₄) emissions, transportation-related CO₂ emissions and carbon storage that will result from landfilling. Because plastics do not contain biodegradable carbon, they do not generate CH₄ and are not considered to store any carbon when landfilled. The only emissions associated with landfilling plastics are from transportation to the landfill and moving waste in the landfill. Transportation of waste materials results in CO₂ emissions from the combustion of fossil fuels in truck transport. Exhibit 5-18 provides the net emission factor and its components for landfilling each plastic type. For further information on landfilling in general, refer to the [Landfilling](#) chapter.

Exhibit 5-18: Landfilling Emission Factors for Plastics (MTCO₂E/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)
HDPE	—	0.02	—	—	—	0.02
LDPE	—	0.02	—	—	—	0.02
PET	—	0.02	—	—	—	0.02
LLDPE	—	0.02	—	—	—	0.02
PP	—	0.02	—	—	—	0.02
PS	—	0.02	—	—	—	0.02
PVC	—	0.02	—	—	—	0.02
Mixed Plastics	—	0.02	—	—	—	0.02

— = Zero emissions.

5.4.6 Anaerobic Digestion

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

5.5 LIMITATIONS

The plastic emission factors presented in this chapter are subject to the following limitations and caveats:

- All processes are only representative of plastic resins and do not include final conversion to plastic products (e.g., recycled PET data does not include solid stating to convert the resin to a bottle-ready state) (FAL, 2011b, p. 2-16).

- The underlying LCI data used to develop these emission factors did not include materials, such as catalysts, pigments, or additives that totaled less than one percent of the net process inputs (FAL 2011a, p. 1-24; 2011b p. 1-14).
- For recycled data, transportation is calculated assuming a truck weight-constrained basis, which is consistent with other waste transportation processes modeled in WARM.
- Virgin non-energy process GHG emissions from CO₂ emissions produced from non-biogenic (i.e., fossil) feedstocks, methane, and nitrous oxide are included. The emission factors do not include emissions of methyl bromide, methyl chloride, trichloroethane chloroform, methylene chloride, carbon tetrachloride, CFC 13, or HCFC-22 since these gases together represent less than 0.1 percent of total non-energy process emissions.

5.6 REFERENCES

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