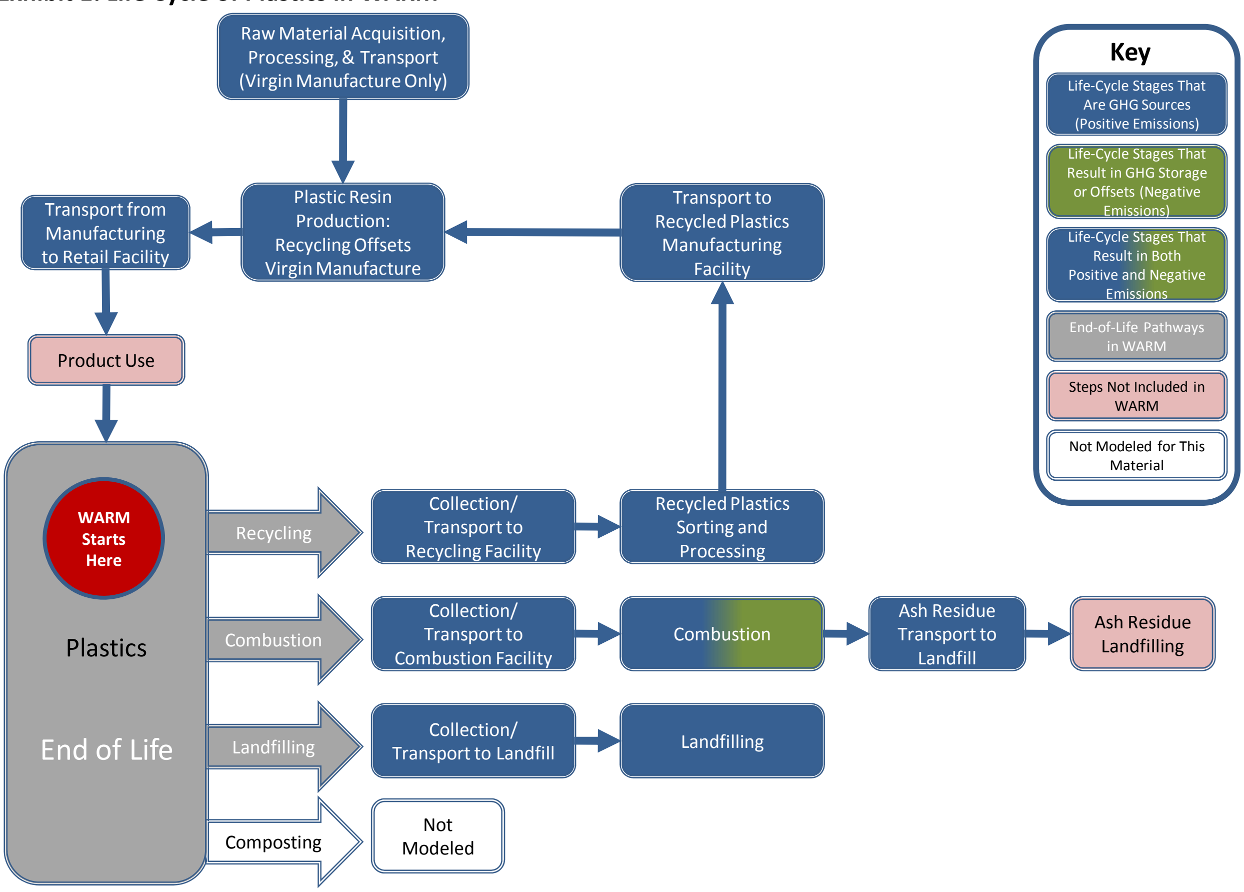
PLASTICS

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 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 Introduction & 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 1: Life Cycle of Plastics in WARM



Plastics included in WARM are high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET). According to the EPA report, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2008,* these three plastics accounted for nearly half of all plastic waste generated in 2008 (EPA, 2009). These three plastics were chosen for WARM because the most comprehensive and complete data were available from a consistent source only for these plastics. Note 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. 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 each of the plastic types in the recovery stream, as shown in column (f) of Exhibit 2. Further discussion on the end uses of these plastics is provided below.

Exhibit 2: Plastic Waste Generation and Recovery in the United States, 2008

(a) Type of Product	(b) Generation (Short Tons)	(c) % of Total Generation	(d) Recovery (Short Tons)	(e) % of Total Recovery	(f) Relative Prevalence in Recovery Stream	(g) Recovery Rate (%)
HDPE	5,350,000	17.8%	570,000	26.9%	35.0%	10.7%
LDPE	5,880,000	19.6%	330,000	15.6%	20.2%	5.6%
PET	3,740,000	12.4%	730,000	34.4%	44.8%	19.5%
All Plastics	**30,050,000**		**2,120,000**			**7.1%**

Source: EPA (2009).

HDPE. HDPE is used for a wide variety of products, including milk jugs, 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, 2009).

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 (ICIS, 2010a).

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, and other products (ICIS, 2010b).

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 types of plastics examined here cannot be composted, so composting is not included. As Exhibit 3 illustrates, most of the GHG sources relevant to plastics in this analysis are associated with raw materials acquisition and manufacturing (RMAM).

Exhibit 3: 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** • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy	NA	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled manufacture process energy • Recycled manufacture process non-energy **Offsets** • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy	NA	**Emissions** • Collection and transportation to material recovery facility
Composting	Not applicable because plastics cannot be composted		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related CO_2 and N_2O **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery

NA = Not applicable.

WARM emission factors include all of the GHG sources and sinks outlined in Exhibit 3 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 4 provides the net emission factors for all plastic types under all materials management scenarios. The next sections include more detailed methodology on the derivation of the emission factors.

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

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
HDPE	-1.77	-1.38	NA	1.31	0.04
LDPE	-2.25	-1.67	NA	1.31	0.04
PET	-2.07	-1.52	NA	1.28	0.04
Mixed Plastics	NA	-1.50	NA	1.29	0.04

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

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.

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 are presented in Exhibit 5. Transportation emissions from the retail point to the consumer are not included. The number of miles traveled is obtained from the 2007 *U.S. Census Commodity Flow Survey* (BTS, 2007) and mode-specific fuel use is from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 5: Retail Transportation Energy Use and GHG Emissions

Material/Product	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors ($MTCO_2E$/ Short Ton)
HDPE	521	0.56	0.04
LDPE	521	0.56	0.04
PET	521	0.56	0.04

RTI data also do not include non-process energy. The 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 4.1.

4. MATERIALS MANAGEMENT

WARM models four materials management alternatives for HDPE, LDPE, PET and mixed plastics: source reduction, recycling, landfilling and combustion. 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 6 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 6: Recycled Content Values in Plastics Manufacturing

Product/Material	Recycled Content Minimum (%)	Recycled Content for "Current Mix" in WARM (%)	Recycled Content Maximum (%)
HDPE	–	10%	15%
LDPE	–	4%	15%
PET	–	3%	10%

Source: FAL (2003).
– = Zero percent.

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 4.1, source reduction.

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. For more information on source reduction in general, see the Source Reduction chapter.

Exhibit 7: Source Reduction Emission Factors for Plastics ($MTCO_2E$/Short Ton)

Product/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
HDPE	-1.77	-1.95	NA	NA	-1.77	-1.95
LDPE	-2.25	-2.34	NA	NA	-2.25	-2.34
PET	-2.07	-2.13	NA	NA	-2.07	-2.13

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 sequestration. As discussed in the RMAM section (section 3), the RMAM emissions associated with plastics can be broken down into three emission sources: process energy, transportation energy and non-energy processes. Exhibit 8 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 6. The methodology for estimating emissions from manufacturing plastic from recycled materials is discussed in the next section, Recycling.

As mentioned in section 1, EPA estimates emissions for mixed plastics by weighting emissions for each plastic type by the assumed mix in the waste stream.

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

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
HDPE	1.72	0.04	0.19	1.95
LDPE	2.10	0.04	0.19	2.34
PET	1.98	0.04	0.11	2.13
Mixed Plastics	1.72	0.04	0.19	1.95

Exhibit 9, Exhibit 10, and Exhibit 11 provide the calculations for each source of RMAM emissions: process energy, transportation energy and non-energy processes.

Exhibit 9: Process Energy GHG Emissions Calculations for Virgin Production of Plastics

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
HDPE	28.69	1.72
LDPE	35.26	2.10
PET	32.82	1.98

Exhibit 10: Transportation Energy Emissions Calculations for Virgin Production of Plastics

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
HDPE	NA	NA
LDPE	NA	NA
PET	NA	NA

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

– = Zero emissions.

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

Product/Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Total Non-Energy Emissions ($MTCO_2E$/Short Ton)
HDPE	–	0.01	–	–	–	0.19
LDPE	–	0.01	–	–	–	0.19
PET	0.00	0.01	–	–	–	0.11

– = Zero emissions.

4.2 RECYCLING

WARM models HDPE, LDPE and PET as being recycled in a closed loop, meaning that when these plastics are recovered and recycled, they are recycled back into the same products.[1] The net emission factor for recycling each plastic type is the sum of the factors provided in Exhibit 12. 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 sequestration when

[1] 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).

recycling plastics. Among the three plastic types, LDPE shows the largest GHG benefit when recycled. For more information on recycling in general, refer to the Recycling chapter.

Exhibit 12: Recycling Emission Factor for Plastics ($MTCO_2E$/Short Ton)

Product/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)
HDPE	–	–	-1.23	0.00	-0.15	–	-1.38
LDPE	–	–	-1.53	0.00	-0.15	–	-1.67
PET	–	–	-1.44	0.00	-0.08	–	-1.52

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.

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 recycled production of plastic. Exhibit 13 and Exhibit 14 provide the calculations for GHG emissions from manufacturing each plastic type from 100 percent recycled materials. Exhibit 15 provides the differences between virgin and recycling plastics manufacture that account for the recycled input credits in Exhibit 12.

Exhibit 13: Process Energy GHG Emissions Calculations for Recycled Production of Plastics

Product/Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
HDPE	4.17	0.13
LDPE	4.17	0.13
PET	4.17	0.13

Exhibit 14: Transportation Energy GHG Emissions Calculations for Recycled Production of Plastics

Product/Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
HDPE	0.08	0.01
LDPE	0.08	0.01
PET	0.08	0.01

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

Exhibit 15: Differences in Emissions between Recycled and Virgin Plastics Manufacture ($MTCO_2E$/Short Ton)

Product/ Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
HDPE	1.72	0.04	0.19	0.13	0.05	–	-1.59	0.01	-0.19
LDPE	2.10	0.04	0.19	0.13	0.05	–	-1.97	0.01	-0.19
PET	1.98	0.04	0.11	0.13	0.05	–	-1.85	0.01	-0.11

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

4.1 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.

4.2 COMBUSTION

Because plastic is made from fossil fuels, its combustion is considered an anthropogenic source of carbon emissions. Nitrous oxide (N_2O) emissions can also occur from incomplete combustion of waste but, since the plastic considered here does not contain any nitrogen, there are no N_2O 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 16 provides the emission factors for combusting each plastic type and their components.

Exhibit 16: Components of the Combustion Net Emission Factor for Plastics ($MTCO_2E$/Short Ton)

Product/Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
HDPE	–	0.03	2.79	–	-1.51	–	1.31
LDPE	–	0.03	2.79	–	-1.51	–	1.31
PET	–	0.03	2.04	–	-0.79	–	1.28

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

CO_2 emissions from combusting plastic depend on the carbon content of the plastic and the amount of carbon that is converted to CO_2 during the combustion process. Exhibit 17 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 CO_2 during combustion, which EPA estimates to be 98 percent; and the final resulting CO_2 emissions from combusting each plastic type.

Exhibit 17: Plastics CO_2 Combustion Emission Factor Calculation

Product/Material	Carbon Content (%)	Carbon Converted to CO_2 during Combustion (%)	Combustion CO_2 Emissions ($MTCO_2E$/Short Ton)
HDPE	86%	98%	2.79
LDPE	86%	98%	2.79
PET	63%	98%	2.04

Creating energy from waste at WTE facilities offsets part of the required energy production of utility companies. Exhibit 18 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 18: Utility GHG Emissions Offset from Combustion of Plastics

(a) Material/Product	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
HDPE	37.4	17.8%	0.23	1.51
LDPE	37.4	17.8%	0.23	1.51
PET	19.4	17.8%	0.23	0.79

4.1 LANDFILLING

WARM considers the methane (CH_4) emissions, transportation-related CO_2 emissions and carbon storage that will result from landfilling. Because plastics do not contain biodegradable carbon, they do not generate CH_4 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 CO_2 emissions from the combustion of fossil fuels in truck transport. Exhibit 19 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 19: Landfilling Emission Factors for Plastics ($MTCO_2E$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Sequestration	Net Emissions (Post-Consumer)
HDPE	–	0.04	–	–	–	0.04
LDPE	–	0.04	–	–	–	0.04
PET	–	0.04	–	–	–	0.04

– = Zero emissions.

5. LIMITATIONS

EPA is currently developing more up-to-date emission factors for HDPE, LDPE and PET based on data from Franklin Associates' *Revised Final Report: Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Precursors* (FAL, 2007). Based on preliminary work, EPA expects the emission factors for HDPE, LDPE and PET to decrease due to increases in manufacturing efficiencies. Additionally, EPA plans to develop emission factors for linear low-density polyethylene (LLDPE), polypropylene (PP), general-purpose polystyrene (GPPS) and polyvinyl chloride (PVC), which together account for more than 20 percent of plastic waste generation (EPA, 2009).

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