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)

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Office of Resource Conservation and Recovery

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GUIDE TO WARM DOCUMENTATION

The documentation provided in this file explains the data, methods, and calculations behind the WARM greenhouse gas (GHG) emission and energy factors. This documentation is the next stage in evolution of the report most recently titled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks, 3rd Edition*, published in 2006. The second edition was published in 2002, while the first edition, titled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, was published in 1998.

The current documentation explains the calculation of emission factors by material type, or group of materials, arranged into individual chapters. EPA also provides chapters addressing each specific materials management practice available in WARM, along with an introductory chapter, a glossary, and additional chapters on special topics like forest carbon storage and energy factors. This chapter-based format, first introduced in 2010, provides more detailed and up-to-date information about the WARM emission factors than was available in the previous report format. In addition, several background documents are available that provide additional useful information pertaining to the WARM emission factors; see the EPA WARM Documentation page for access to background documents.

Below is a brief summary of the WARM documentation chapters available in this file to help in navigating the information contained across the documentation file.

BACKGROUND CHAPTERS

WARM Background and Overview – provides a summary of the materials management context for WARM, the genesis and application of WARM, an introduction to the WARM methodology, a summary of the life-cycle stages modeled in WARM, and the limitations of WARM.

WARM Definitions and Acronyms – defines key terms and acronyms used throughout the documentation chapters.

MANAGEMENT PRACTICE CHAPTERS

Source Reduction – describes the development of material-specific emission factors for source reduction, including types of source reduction, a summary of the GHG implications of source reduction, how to apply WARM's emission factors to specific source reduction strategies, and limitations of the source reduction emission factors.

Recycling – describes the development of material-specific emission factors for recycling, including a discussion of open- and closed-loop recycling, the GHG impact of material losses, calculating the GHG impacts of recycling, the resulting emission factors in WARM, and the limitations of the recycling emission factors.

Composting – describes the development of composting emission factors, including emissions from transportation of materials and turning of compost, fugitive emissions during composting, carbon storage from compost application to soils, the Century model framework and simulations used to develop emission factors, humus formation carbon storage, and the limitations of the composting emission factors.

Combustion – describes the development of material-specific emission factors for combustion, including emissions from waste-to-energy (WTE) facilities, emissions from transportation of waste and ash, estimating utility emissions avoided, avoided emissions due to steel recovery, the resulting emission factors in WARM, and the limitations of the combustion emission factors.

Landfilling – describes the development of material-specific emission factors for landfilling, including carbon stocks and flows in landfills, WARM's approach for estimating emissions from landfills, emissions from transportation to landfills and landfill operation, estimating landfill carbon storage, electric utility GHG emissions avoided, the resulting net GHG emission factors from landfilling, and the limitations of the landfilling emission factors.

SPECIAL TOPIC CHAPTERS

Energy Impacts –describes the methodology for developing energy factors, energy implications for waste management options, how energy factors are applied in WARM, and how energy savings relate to GHG benefits.

Forest Carbon Storage – describes the development of material-specific estimates of changes in forest carbon storage in WARM for paper products and wood products, including a summary of the GHG implications of forest carbon storage, the WARM forest carbon storage methodology, the effect of source reduction and recycling on timber harvests, the effect of changes in timber harvest on forest carbon stocks, changes in the in-use product carbon pool, the net change in carbon storage, and the limitations of the forest carbon storage factors.

MATERIALS CHAPTERS

These chapters describe the methodology used in WARM to estimate streamlined life-cycle GHG emission factors for all materials in WARM, beginning at the waste generation reference point. Materials are organized in the documentation file alphabetically with a chapter for each material type or group of materials. While the content and structure varies to some degree by material type, each chapter includes the life-cycle assessment and emission factor results, the emissions from raw materials acquisition and manufacturing, the development of emission factors for each of the management practice, and the limitations of the emission factors for each material.

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1 WARM BACKGROUND AND OVERVIEW

During the last century, population and economic growth have caused increased consumption of materials such as minerals, wood products and food. Materials consumption continues to accelerate while simultaneously shifting away from renewable materials like agriculture and forestry products toward non-renewable products such as metals and fossil fuel-derived products (EPA, 2009c). Source reduction, reuse and recycling of materials are ways that we can manage materials more sustainably.

Extracting, harvesting, processing, transporting and disposing of these materials result in greenhouse gas (GHG) emissions, in part due to the large amounts of energy required for these life-cycle stages. The U.S. Environmental Protection Agency's (EPA) Waste Reduction Model (WARM), the focus of this documentation, is a tool designed to help managers and policy-makers understand and compare the life-cycle GHG and energy implications of materials management options (recycling, source reduction, landfilling, combustion with energy recovery, and composting) for materials commonly found in the waste stream. By comparing a baseline scenario (e.g., landfilling) to an alternate scenario (e.g., recycling), WARM can assess the energy and GHG implications that would occur throughout the material life cycle.

1.1 Materials Management Context

The United States and the international community are focusing increasingly on a life-cycle materials management paradigm that considers the environmental impacts of materials at all life-cycle stages. Recognition is growing that, since traditional environmental policies focus on controlling "end-of-pipe" emissions, they do not provide a means for systematically addressing environmental impacts associated with the movement of materials through the economy. While "end-of-pipe" policies are often effective in controlling direct pollution, they may result in some environmental impacts being overlooked or shifted from one area of the life cycle to another (EPA, 2009c).

Materials management refers to how we manage material resources as they flow through the economy, from extraction or harvest of materials and food (e.g., mining, forestry, and agriculture), production and transport of goods, use and reuse of materials, and, if necessary, disposal. The EPA 2020 Vision Workgroup defines materials management as "an approach to serving human needs by using/reusing resources most productively and sustainably throughout their life cycles, generally minimizing the amount of materials involved and all the associated environmental impacts" (EPA, 2009c).

The EPA Office of Solid Waste and Emergency Response found that 42 percent of U.S. 2006 GHG emissions were associated with the manufacturing, use and disposal of materials and products (EPA, 2009b). As a result, changing materials management patterns is an important strategy to help reduce or avoid GHG emissions. Reducing the amount of materials used to make products, extending product life spans, and maximizing recycling rates are examples of possible materials management strategies that can significantly reduce GHG emissions (EPA, 2009b).

Private and public entities globally are moving toward life-cycle materials management. For example, the Organisation for Economic Cooperation and Development (OECD) and the Kobe 3R Action Plan (a plan issued by the Group of Eight) have recommended that member countries pay increased attention to life-cycle approaches to material flows. Companies in the metals, cement, agribusiness, food and retail industries are also formulating approaches to increase efficiency and reduce environmental impacts by taking a life-cycle view of materials and processes (EPA, 2009c).

1.2 Genesis and Applications of WARM

1.2.1 History of WARM Development

Recognizing the potential for source reduction and recycling of municipal solid waste (MSW) to reduce GHG emissions, EPA included a source reduction and recycling initiative in the original 1994 U.S. *Climate Change Action Plan.* EPA set an emission reduction goal based on a preliminary analysis of the potential benefits of these activities. It was clear that a rigorous analysis would be needed to gauge more accurately the total GHG emission reductions achievable through source reduction and recycling.

That *all* of the options for managing MSW should be considered also became clear. By addressing a broader set of MSW management options, EPA could gain a more comprehensive picture of the GHG benefits of voluntary actions in the waste sector and assess the relative GHG impacts of various waste management approaches. To this end, EPA launched a major research effort, which resulted in the development of life-cycle GHG and energy factors for materials across several categories (e.g., plastics, metals, wood products), the online GHG and energy calculation tool WARM applying these factors, and accompanying documentation. The first documentation report, entitled *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*, was published in 1998, the second edition in 2002 (retitled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*) and the third edition in 2006 (EPA, 1998, 2002, 2006).

This documentation effort, initiated in 2010, has reorganized the documentation into chapters by material and by process and includes more in-depth descriptions of the WARM emission factors. Whereas the previous documentation reports were structured only around process chapters (i.e., source reduction, recycling, composting, combustion, landfilling), this materials-based structure allows EPA to provide WARM users with more detailed information about the specific materials analyzed in WARM. This information was to a large extent omitted in previous versions of the report. As WARM has grown in popularity, many users have become more interested in the details of the calculations behind specific material emission factors, and EPA hopes that this current documentation approach provides these users with more useful information.

The Model History chapter describes the revisions made to different model versions and the documentation. The model itself has been updated on a regular, near annual, basis to reflect updated statistics on national average electricity generation fuel mix, transmission and distribution losses, coal weighting for electricity generation, electricity generation per fuel type, the carbon content of fuels, landfill methane generation distribution (by type of landfill), landfill gas recovery and flaring rates, and waste generation and recovery rates. In addition, annual updates have often included new material emission factors and other improvements to the analysis (Exhibit 1-1, found in section 1.2.4, provides the dates when materials were added to WARM).

The latest recent versions of WARM have undergone some of the most extensive improvements and additions since the tool’s inception. In WARM Version 13 (released in June 2014), updates include a variety of new material categories and revisions to existing numbers and methodology. The majority of the updates in WARM Version 13 concern the model’s handling of organics, including new source reduction emission factors for food waste, an updated methodology for estimating landfill gas emissions, the inclusion of fugitive gas emissions from composting, and updates to the global warming potential (GWP) values in the model. Changes to other recent versions include the addition of either updated or new emission factors for construction and demolition (C&D) materials, plastics, aluminum cans and ingot, PLA, and carpet; the addition of component-specific decay rates; and increased specificity in the Excel version of WARM with region-specific electricity grid factors and an updated method for estimating landfill gas collection efficiency.

1.2.2 WARM Audience and Related Efforts

The primary application of WARM is to support materials-related decision-making in the context of climate change. By quantifying the climate impacts of materials management decisions, the factors in this report and the tool enable municipalities, companies and other waste- and program-management decision-makers to measure the benefits of their actions. Other EPA decision-support tools such as the Recycled Content Tool (ReCon), Individual WARM (iWARM), Saving Money and Reducing Trash Benefit Evaluation Tool (SMART BET), and the Office Carbon Footprint Tool, rely on WARM energy and emission factors to help users make a wide range of decisions. For example, SMART BET is designed to help local waste managers decide whether unit-based pricing for solid waste management (also known as Pay-As-You-Throw or PAYT) is the right model for their community. SMART BET calculates both cost savings and GHG savings associated with a possible PAYT model using user-defined inputs. The iWARM tool uses life-cycle information from WARM to quantify energy benefits of recycling small quantities of common waste materials by calculating the “run time” of a variety a household appliances (e.g., clothes washer, hairdryer, etc.) using electricity savings from recycling materials. Other applications have included quantifying the GHG reductions from voluntary programs aimed at source reduction and recycling, such as EPA’s WasteWise and Pay-As-You-Throw programs.

Global Warming Potentials

CO_2, CH_4, N_2O and perfluorocarbons (PFCs) are very different gases in terms of their heat-trapping potential. The Intergovernmental Panel on Climate Change (IPCC) has established CO_2 as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of one kilogram (kg) of CO_2 is one. The GWPs of other common GHGs from materials management activities are as follows:

- CH_4 has a GWP of 25, which means that one kg of CH_4 has the same heat-trapping potential as 25 kg of CO_2.
- N_2O has a GWP of 298.
- PFCs are the most potent GHG included in this analysis; GWPs are 7,390 for CF_4 and 12,200 for C_2F_6.

WARM expresses comparative GHG emissions in metric tons of CO_2 equivalents ($MTCO_2e$), which uses the tool of GWP to allow all emissions to be compared on equal terms.

WARM uses GWPs from IPCC(2007).

The international community has shown considerable interest in using the emission factors—or adapted versions—to develop GHG emission estimates for non-U.S. materials management.[1] For example, Environment Canada and Natural Resources Canada employed EPA’s life-cycle methodology and components of its analysis to develop a set of Canada-specific GHG emission factors to support analysis of waste-related mitigation opportunities (Environment Canada, 2005).

1.2.3 Estimating and Comparing Net GHG Emissions

WARM compares the emissions and offsets resulting from a material in a baseline and an alternative management pathway in order to provide decision-makers with comparative emission results. For example, WARM could be used to calculate the GHG implications of landfilling 10 tons of office paper versus recycling the same amount of office paper.

The general formula for net GHG emissions for each scenario modeled in WARM is as follows:

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[1] Note that waste composition and product life cycles vary significantly among countries. This report may assist other countries by providing a methodological framework and benchmark data for developing GHG emission estimates for their solid waste streams.

Net GHG emissions = Gross manufacturing GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

This equation should only be considered in the context of comparing two alternative materials management scenarios in order to identify the lowest net GHG emissions. The following circumstances influence the net GHG emissions of a material:

- Through *source reduction* (for example, "lightweighting" a beverage can—using less aluminum for the same function), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon is sequestered in forests, through reduced tree harvesting.
- Through *recycling*, the GHG emissions from making an equivalent amount of material from virgin inputs are avoided. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less energy than making the product from virgin inputs.
- *Composting* with application of compost to soils results in carbon storage and small amounts of CH_4 and N_2O emissions from decomposition.
- *Landfilling* results in both CH_4 emissions from biodegradation and biogenic carbon storage. If captured, the CH_4 may be flared, which simply reduces CH_4 emissions (since the CO_2 produced by flaring is biogenic in origin, it is not accounted for in this assessment of anthropogenic emissions). If captured CH_4 is burned to produce energy, it offsets emissions from fossil fuel consumption.
- *Combustion* of waste may result in an electricity utility emissions offset if the waste is burned in a waste-to-energy facility, which displaces fossil-fuel-derived electricity.

1.2.4 Materials Considered in WARM

To measure the GHG impacts of materials management, EPA first decided which materials and products to analyze. EPA surveyed the universe of materials and products found in the solid waste stream and identified those that are most likely to have the greatest impact on GHGs. These determinations were initially based on (1) the quantity generated; (2) the differences in energy use for manufacturing a product from virgin versus recycled inputs; and (3) the potential contribution of materials to CH_4 generation in landfills. Since the initial assessment, many materials have been added. Materials that EPA selects for inclusion in WARM are generally selected based on the three principles above, with the additional criterion that enough data be available to create defensible emission factors. As of June 2014 in which WARM Version 13 was released, WARM included 51 materials, products and mixed categories, as listed in Exhibit 1-1 by category type. Exhibit 1-1 also shows the main sources of virgin and recycled production energy data for each material, the vintage of those data, the year each material was first added to WARM, the percentage each material constitutes of total MSW generated in the United States (to the extent information is available), and whether the recycling process is modeled as open- or closed-loop in WARM (more information on the recycling process is presented in the Recycling chapter). EPA is in the process of gathering and reviewing new life-cycle inventory (LCI) data for several material types to develop updated and new emission factors for WARM.

Exhibit 1-1: Current Materials and Products in WARM, Historical Inclusion, and Source of Data

Material/Product	Year First Added to WARM (updated year if applicable)	Source of Main Process Energy Data	Approximate Year(s) of Current Energy Data[a]	% of MSW Generation by Weight[b]	Open- or Closed-Loop Recycling?[c]
Metals and Glass					
Aluminum Cans	1998 (2012)	PE Americas (2010)	2006	0.5%	Closed
Aluminum Ingot	2012	PE Americas (2010)	2006	NE	Closed
Steel Cans	1998	FAL (1998b)	1990	0.7%	Closed
Copper Wire	2005	Battelle (1975); Kusik and Kenahan (1978); FAL (2002b)	1973–2000	NE	Open
Glass	1998	RTI (2004)	Late 1990s	4.6%	Closed
Plastics					
HDPE (high-density polyethylene)	1998 (2012)	FAL (2011)	2000s	2.2%	Closed
LDPE (low-density polyethylene)	1998 (2012)	FAL (2011)	2000s	2.9%	Closed
PET (polyethylene terephthalate)	1998 (2012)	FAL (2011)	2000s	1.8%	Closed
LLDPE	2012	FAL (2011)	2000s	NE	Closed
PP	2012	FAL (2011)	2000s	NE	Closed
PS	2012	FAL (2011)	2000s	NE	Closed
PVC	2012	FAL (2011)	2000s	NE	Closed
Paper and Wood					
Corrugated Containers	1998	RTI (2004)	Late 1990s	11.8%	Both
Magazines/Third-Class Mail	2001	RTI (2004)	Late 1990s	2.0%	Closed
Newspaper	1998	RTI (2004)	Late 1990s	3.3%	Closed
Office Paper	1998	RTI (2004)	Late 1990s	1.9%	Closed
Phone Books	2001	RTI (2004)	Late 1990s	NE	Closed
Textbooks	2001	RTI (2004)	Late 1990s	NE	Closed
Dimensional Lumber	1998	FAL (1998c)	Mid 1990s	3.8%	Closed
Medium-Density Fiberboard	1998	FAL (1998c)	Mid 1990s	NE	Closed
Organics					
Food Waste	2014	NA	NA	14.5%	NA
Food Waste (meat only)	2015	NA	NA	IE	NA
Food Waste (non-meat)	2014	NA	NA	IE	NA
Beef	2015	Battagliese et al. (2013)	2011	IE	NA
Poultry	2015	Pelletier (2008, 2010)	Late 2000s	IE	NA
Grains	2014	LCA Digital Commons (2012)	2000s	IE	NA
Bread	2014	Espinoza-Orias (2011)	2011	IE	NA
Dairy Products	2014	Thoma et al. (2010)	2008	IE	NA
Fruits and Vegetables	2014	Luske (2010) UC Davis (multiple)	Late 2000s	IE	NA
Yard Trimmings	1998	NA	NA	13.5%	NA
Grass	2001	NA	NA	IE	NA
Leaves	2001	NA	NA	IE	NA
Branches	2001	NA	NA	IE	NA

Material/Product	**Year First Added to WARM (updated year if applicable)**	**Source of Main Process Energy Data**	**Approximate Year(s) of Current Energy Data**[a]	**% of MSW Generation by Weight**[b]	**Open- or Closed-Loop Recycling?**[c]
PLA	2012	NatureWorks, LLC (2010)	2009	NE	NA
Mixed Categories					
Mixed Paper (general)	1998	Virgin: FAL (1998a), RPTA (2003) Recycled: RPTA (2003)	Virgin: 1996; Recycled: early 2000s	NE	Open
Mixed Paper (primarily residential)	1998	FAL (1998a)	1996	NE	Open
Mixed Paper (primarily from offices)	1998	FAL (1998a)	1996	NE	Open
Mixed Metals	2002	NA	NA	4.0%	NA
Mixed Plastics	2001	NA	NA	8.8%	NA
Mixed Recyclables	1998	NA	NA	NE	NA
Mixed Organics	2001	NA	NA	NE	NA
Mixed MSW	2001	NA	NA	NE	NA
Composite Products					
Carpet[d]	2004 (2012)	FAL (2002a); Realff (2011)	2000s	1.5%	Open
Personal Computers[d]	2004	FAL (1998b)	1973–2001	0.8%	Open
Construction and Demolition (C&D)					
Clay Bricks	2004	Athena Sustainable Materials Institute (1998)	Mid-late 1990s	NA	NA
Concrete[d]	2004	U.S. Census Bureau (1997),Wilburn and Goonan (1998)	1997	NA	Open
Fly Ash	2004	IPCC (1996), PCA (2003), Nisbet et al. (2000)	Early 2000s	NA	Open
Tires[d]	2006	Athena Sustainable Materials Institute (2000), Atech Group (2001), EIA (2009), Corti and Lombardi (2004)	Early 2000s	1.2%	Open
Asphalt Concrete[d]	2010	U.S. Census Bureau (1997), Athena Sustainable Materials Institute (2001), U.S. Census Bureau (2001), Environment Canada (2005),	Early 2000s	NA	Closed

Material/Product	Year First Added to WARM (updated year if applicable)	Source of Main Process Energy Data	Approximate Year(s) of Current Energy Data[a]	% of MSW Generation by Weight[b]	Open- or Closed-Loop Recycling?[c]
		Levis (2008), NREL (2009)			
Asphalt Shingles[d]	2010	Athena Sustainable Materials Institute (2000), Cochran (2006), CMRA (2007)	Early 1990s	NA	Open
Drywall[d]	2010	Venta (1997); recycling data from WRAP (2008)	Virgin: 1997; Recycled: 2008	NA	Both
Fiberglass Insulation	2010	Lippiatt (2007), Enviros Consulting (2003) for glass cullet production	Mid 2000s	NA	NA
Vinyl Flooring[d]	2010	ECOBILAN (2001), FAL (2007), Lippiatt (2007), Ecoinvent Centre (2008)	2007	NA	NA
Wood Flooring[e]	2010	Bergman and Bowe (2008), Hubbard and Bowe (2008), Bergman (2010)	Late 2000s	NA	NA

NA = Not applicable.

NE = Not estimated.

IE = Included elsewhere.

[a] Note that years are approximate because each source draws on a variety of data sources from different years.

[b] Source for percent generation data is EPA (2014).

[c] Closed-loop recycling indicates a recycling process where end-of-life products are recycled into the same product. Open-loop recycling indicates that the products of the recycling process (secondary product) are not the same as the inputs (primary material).

[d] Indicates composite product.

[e] Wood flooring also falls under the Paper and Wood category.

There are generally two overarching waste categories under which material types listed in Exhibit 1-1 fall. Municipal solid waste generally includes metals and glass, plastics, paper and wood, organics, mixed categories and composite products. These materials are household, commercial, institutional and light industrial waste collected and managed by a municipality. The construction and demolition materials are materials that are produced during construction, renovation or demolition of structures and include clay bricks, concrete, fly ash, tires, asphalt concrete, asphalt shingles, drywall, fiberglass insulation, vinyl flooring and wood flooring. EPA’s interest in C&D materials is the result of a growing interest in environmentally friendly or “green” building practices, including reusing and recycling the impressive quantities of C&D debris that are generated each year. In 2008, 143.5 million tons of C&D waste were generated (Waste Business Journal, 2009). One major difference between waste management for C&D materials versus MSW materials is that C&D materials are typically disposed of in landfills created specifically for C&D waste that do not accept MSW waste. C&D and MSW landfills differ in several ways, including in the design and operation requirements of the landfills. From the GHG perspective, the most significant difference between the two landfill types is that C&D landfills generally do not have the landfill methane capture systems that are common at MSW landfills. Thus, the methane that is produced in C&D landfills is eventually released directly to the atmosphere.

The MSW materials listed in Exhibit 1-1 constitute more than 75 percent, by weight, of MSW, as shown in the fifth column of Exhibit 1-1. Several materials, including most C&D materials, were not included in the waste characterization report cited here, so the utility of this percent estimate is limited.[2] The definitions of the each of the WARM materials included in Exhibit 1-1 are summarized below in Exhibit 1-2.

Exhibit 1-2: WARM Material Definitions

WARM Material	WARM Data Source Definition
Aluminum Cans	Aluminum cans represent cans produced out of sheet-rolled aluminum ingot.
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. It can serve as a proxy for certain aluminum materials such as electrical transmission and distribution wires, other electrical conductors, some extruded aluminum products, aluminum product cuttings, joinings and weldings, and consumer durable products such as home appliances, computers, and electronics.
Steel Cans	Steel cans represent 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).
Copper Wire	Copper wire is used in various applications, including power transmission and generation lines, building wiring, telecommunication, and electrical and electronic products.
Glass	Glass represents glass containers (e.g., soft drink bottles and wine bottles).
HDPE	HDPE (high-density polyethylene) is usually labeled plastic code #2 on the bottom of the container, and refers to a plastic often used to make bottles for milk, juice, water and laundry products. It is also used to make plastic grocery bags.
LDPE	LDPE (Low-density polyethylene), usually labeled plastic code #4, is often used to manufacture plastic dry cleaning bags. LDPE is also used to manufacture some flexible lids and bottles.
PET	PET (Polyethylene terephthalate) is typically labeled plastic code #1 on the bottom of the container. PET is often used for soft drink and disposable water bottles, but can also include other containers or packaging.
LLDPE	LLDPE (linear low-density polyethylene) 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
PP	PP (Polypropylene) 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
PS	GPPS (General Purpose Polystyrene) 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.
PVC	PVC (Polyvinyl Chloride) 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
PLA	Polylactic acid or PLA is a 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
Corrugated Containers	Corrugated container boxes made from containerboard (liner and corrugating medium) used in packaging applications.

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[2] Note that these data are based on national averages. The composition of solid waste varies locally and regionally.

WARM Material		WARM Data Source Definition
Magazines/Third-Class Mail		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. This category represents coated paper produced from mechanical pulp.
Newspaper		Newspaper represents uncoated paper made from 70% mechanical pulp and 30% chemical pulp. For the carbon sequestration portion of the factor, it was assumed that the paper was all mechanical pulp.
Office Paper		Office paper represents paper made from uncoated bleached chemical pulp.
Phone Books		Phone books represent telephone books that are made from paper produced from mechanical pulp.
Textbooks		Textbooks represent books made from paper produced from chemical pulp.
Dimensional Lumber		Lumber includes wood used for containers, packaging, and building and includes crates, pallets, furniture and dimensional lumber like two-by-fours.
Medium-Density Fiberboard		Fiberboard is a panel product that consists of wood chips pressed and bonded with a resin. Fiberboard is used primarily to make furniture.
Food Waste		Food waste consists of uneaten food and wasted prepared food from residences, commercial establishments such as grocery stores and restaurants, institutional sources such as school cafeterias, and industrial sources such as factory lunchrooms. This emission factor contains a weighted average of the largest food waste components in the waste stream, including beef, poultry, grains, dairy products, fruits and vegetables.
Food Waste (meat only)		"Food waste (meat only)" is a weighted average of the two meat food type emission factors in WARM: beef and poultry. The weighting is based on the relative shares of these two categories in the U.S. food waste stream
Food Waste (non-meat)		"Food waste (non-meat)" is a weighted average of the three non-meat food type emission factors developed in WARM: grains, fruits and vegetables, and dairy products. The weighting is based on the relative shares of these three categories in the U.S. food waste stream
Beef		Beef represents the upstream emissions and energy associated with the production of beef cattle in the United States, including the upstream energy and emissions associated with feed production.
Poultry		Poultry describes the upstream emissions and energy associated with the production of broiler chicken (i.e., domesticated chickens raised specifically for meat production), including the upstream energy and emissions associated with feed production.
Grains		Grains consists of a weighted average of the relative amounts of grain products in the municipal waste stream, consisting of wheat flour, corn and rice.
Bread		Bread consists of the upstream emissions and energy associated with wheat flour production, as well as the additional energy used to bake it into bread.
Dairy Products		Dairy Products consists of a weighted average of the emissions associated with nearly the entire dairy product waste stream, including milk, cheese, ice cream, and yogurt.
Fruits and Vegetables		Fruits and Vegetables represents the average fresh fruits and vegetable components of food waste, consists of a weighted average of the six most common fruits and vegetables in the municipal waste stream, including apples, bananas, melons, oranges, potatoes, and tomatoes.
Yard Trimmings		Yard trimmings are assumed to be 50% grass, 25% leaves, and 25% tree and brush trimmings (EPA, 2013, p. 56) from residential, institutional and commercial sources.
Mixed Paper	General Definition	Mixed paper is assumed to be 24% newspaper, 48% corrugated cardboard, 8% magazines, and 20% office paper (Barlaz, 1998).
	Residential Definition	Residential mixed paper is assumed to be 23% newspaper, 53% corrugated cardboard, 10% magazines and 14% office paper (Barlaz, 1998).
	Office Definition	Office mixed paper is assumed to be 21% newspaper, 5% corrugated cardboard, 36% magazines and 38% office paper (Barlaz, 1998).
Mixed Metals		Mixed metals are made up of a weighted average of 35% aluminum cans and 65% steel cans.
Mixed Plastics		Mixed plastics are made up of a weighted average of 39% HDPE and 61% PET plastic.
Mixed Recyclables		Mixed recyclables are made up of a weighted average of approximately 1% aluminum cans, 3% steel cans, 6% glass, 1% HDPE, 2% PET, 54% corrugated cardboard, 7% magazines/third-class mail, 11% newspaper, 8% office papers, <1% phonebooks, <1% textbooks, and 5% dimensional lumber. See those definitions for details.

WARM Material	WARM Data Source Definition
Mixed Organics	Mixed organics are made up of a weighted average based on 52% food waste and 48% yard trimmings. See those definitions for details.
Mixed MSW	Mixed MSW (municipal solid waste) comprises the waste materials typically discarded by households and collected by curbside collection vehicles; it does not include white goods (e.g., refrigerators, toasters) or industrial waste.
Carpet	Carpet represents nylon broadloom residential carpet containing face fiber, primary and secondary backing, and latex used for attaching the backings.
Personal Computers	PCs are made up of a central processing unit (CPU) and a cathode ray tube (CRT) monitor. The components of the CPU and monitor include steel housing, internal electric components, the CRT, plastic casing and circuit boards. In addition to these valuable components, PCs contain lead, brominated flame retardants and other potentially hazardous chemicals.
Clay Bricks	Bricks are produced by firing materials such as clay, kaolin, fire clay, bentonite, or common clay and shale. The majority of the bricks produced in the United States are clay. In WARM, clay brick source reduction is considered to be the reuse of full bricks rather than the grinding and reusing of broken or damaged brick.
Concrete	Concrete is a high-volume building material produced by mixing cement, water, and coarse and fine aggregates. In WARM, concrete is assumed to be recycled into aggregate, so the GHG benefits are associated with the avoided emissions from mining and processing aggregate.
Fly Ash	Fly ash is a byproduct of coal combustion that is used as a cement replacement in concrete.
Tires	Scrap tires are tires that have been disposed of by consumers and have several end uses in the U.S. market, including as a fuel, in civil engineering, and in various ground rubber applications such as running tracks and molded products.
Asphalt Concrete	Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust or powder.
Asphalt Shingles	Asphalt shingles are typically made of a felt mat saturated with asphalt. Fiberglass shingles are composed of asphalt cement (22% by weight), a mineral stabilizer like limestone or dolomite (25%), and sand-sized mineral granules/aggregate (38%), in addition to the fiberglass felt backing (15%) (CMRA, 2007).
Drywall	Drywall, also known as wallboard, gypsum board or plaster board, is manufactured from gypsum plaster and a paper covering.
Fiberglass Insulation	Fiberglass insulation is produced from a blend of sand, limestone, soda ash and recycled glass cullet, which accounts for about 40% of the raw material inputs.
Vinyl Flooring	All vinyl flooring is composed of polyvinyl chloride (PVC) resin, along with additives such as plasticizers, stabilizers, pigments and fillers.
Wood Flooring	Virgin hardwood flooring is produced from lumber. Coatings and sealants can be applied to wood flooring in “pre-finishing” that occurs at the manufacturing facility, or onsite.

1.3 Introduction to WARM Methodology

1.3.1 A Streamlined Life-Cycle Inventory

Source reduction, recycling, composting, combustion and landfilling are all materials management options that provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous practices from a GHG perspective, a material-specific comparison of all available materials management options clarifies where the greatest GHG benefits can be obtained for particular materials. A material-specific comparison can help waste managers and policy-makers identify the best options for GHG reductions through materials management.

EPA determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs and environmental releases associated with manufacturing, using, transporting and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

WARM does not provide a full LCA, as EPA wanted the tool to be transparent, easy to access and use, and focused on providing decision-makers with information on climate change impacts, namely GHG and energy implications. WARM's streamlined LCA is limited to an inventory of GHG emissions and sinks and energy impacts. This study did not assess human health impacts, or air, water or other environmental impacts that do not have a direct bearing on climate change. WARM also simplifies the calculation of emissions from points in the life cycle that occur before a material reaches end of life.

1.3.2 Assessing GHG Flux Associated with Material Life-Cycle Stages

The streamlined LCA used in WARM depends on accurately assessing the GHG and energy implications of relevant life-cycle stages. The GHG implications associated with materials differ depending on raw material extraction requirements and how the materials are manufactured and disposed of at end of life. WARM evaluates the GHG emissions associated with materials management based on analysis of three main factors: (1) GHG emissions throughout the life cycle of the material (including the chosen end-of-life management option); (2) the extent to which carbon sinks are affected by manufacturing, recycling and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing electric utility emissions.

The life cycle of a material or product includes the following primary life-cycle stages: (1) extraction and processing of raw materials; (2) manufacture of products; (3) transportation of materials and products to markets; (4) use by consumers; and (5) end-of-life management. GHGs are emitted from (1) the pre-consumer stages of raw materials acquisition and manufacturing, and (2) the post-consumer stage of end-of-life management.

WARM does not include emissions from the use phase of a product's life, since use does not have an effect on the waste management emissions of a product. Since the design and results of WARM include the difference between the baseline and the alternative waste management scenarios that show the GHG savings from different treatment options, emissions from the use phase are the same in both the baseline and alternative scenarios; therefore, emissions from the use phase are excluded and all tables and analyses in this report use a "waste generation" reference point.

Materials management decisions can reduce GHGs by affecting one or more of the following:

- *Energy consumption* (specifically combustion of fossil fuels) and the resulting GHG emissions associated with material extraction, manufacturing, transporting, using, and end-of-life management of the material or product .[3]
- *Non-energy-related manufacturing emissions*, such as the carbon dioxide (CO_2) released when limestone used in steel manufacturing is converted to lime, or the perfluorocarbons (PFCs) generated during the aluminum smelting process.
- *Methane (CH_4) emissions from decomposition* of organic materials in landfills.
- *CO_2 and nitrous oxide (N_2O) emissions* from waste combustion.

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[3] Depending on the material/product type; however, the use phase is not included in WARM, as discussed in the previous paragraph.

- *Carbon sequestration and storage*, which refer to natural or manmade processes that remove carbon from the a*tmosphere and store it f*or long periods or permanently.

The first four mechanisms *add* GHGs to the atmosphere and contribute to climate change. The fifth—carbon storage—*reduces* GHG concentrations. Forest growth is one mechanism for sequestering carbon; if more biomass is grown than is removed (through harvest or decay), the amount of carbon stored in trees increases.

Each combination of material or product type and materials management option will have different implications for energy consumption, GHG emissions and carbon storage. This is because the upstream (raw materials acquisition, manufacturing and forest carbon sequestration) and downstream (recycling, composting, combustion and landfilling) characteristics of each material and product are different. Section 1.3.2 gives an overview of how WARM analyzes each of the upstream and downstream stages in the life cycle. The GHG emissions and carbon sinks are described in detail and quantified for each material in the material-specific chapters.

1.3.2.1 Waste Generation Reference Point

One important difference between WARM and other life-cycle analyses is that WARM calculates emission impacts from a waste generation reference point, rather than a raw materials extraction reference point. Raw materials extraction is the point at which production of the material begins, which is why many life-cycle analyses choose this reference point. However, WARM uses the waste generation point (the moment that a material is discarded) because in WARM, the GHG benefits measured result from the choice of one waste management path relative to another. WARM does capture upstream emissions and sinks, but only when at least one of the practices being compared is recycling or source reduction, as these are the only instances where the choice of a materials management practice will affect upstream emissions.

To apply the GHG emission factors developed in this report, one must compare a baseline scenario with an alternate scenario. For example, one could compare a baseline scenario, where 10 tons of office paper are landfilled, to an alternate scenario, where 10 tons of office paper are recycled.

1.3.3 Emissions Sources and Sinks in WARM

As discussed above, EPA focused on aspects of the life cycle that have the potential to emit GHGs as materials are converted from raw resources to products and then to waste. Exhibit 1-3 describes the steps in the material life cycle modeled in WARM at which GHGs are emitted, carbon sequestration is affected, and electric utility energy is displaced. As shown, EPA examined the potential for these effects at the following points in a material's life cycle:

- Raw material acquisition and manufacturing (fossil fuel energy and other emissions, and changes in forest carbon sequestration);
- Carbon sinks in forests and soils (forest carbon storage associated with reduced tree harvest from source reduction and recycling, soil carbon storage associated with application of compost); and
- End-of-life management (CO_2 emissions associated with composting, nonbiogenic CO_2 and N_2O emissions from combustion, and CH_4 emissions from landfills); these emissions are offset to some degree by carbon storage in soil and landfills, as well as by avoided utility emissions from energy recovery at combustors and landfills.
- At each point in the material life cycle, EPA also considered transportation-related energy emissions.

Estimates of GHG emissions associated with electricity used in the raw materials acquisition and manufacturing steps are based on the nation's current mix of energy sources, including fossil fuels, hydropower and nuclear power. However, when estimating GHG emission reductions attributable to electric utility emissions avoided from landfill gas capture or waste-to-energy at combustion facilities, the electricity use displaced by waste management practices is assumed to be from non-baseload power plants to represent the marginal electricity emissions offset. EPA did not analyze the GHG emissions typically associated with consumer use of products because the purpose of the analysis is to evaluate one materials management option relative to another. EPA assumed that the energy consumed during use would be approximately the same whether the product was made from virgin or recycled inputs. In addition, energy use at this life-cycle stage is small (or zero) for all materials studied except personal computers.

Exhibit 1-3 shows how GHG sources and sinks are affected by each waste management strategy. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing; (2) results in an increase in forest carbon sequestration for certain materials; and (3) does not result in GHG emissions from waste management .[4] The sum of emissions (and sinks) across all steps in the life cycle represents net emissions for each material management strategy.

Exhibit 1-3: Components of Net Emissions for Various Materials Management Strategies

Materials Management Strategies	**GHG Sources and Sinks Modeled in WARM**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Decrease in GHG emissions, relative to the baseline of manufacturing with the current industry average mix of virgin and recycled inputs	**Offsets** • Increase in forest carbon sequestration (for paper and wood products) due to avoided harvesting	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled manufacture process energy and non-energy **Offsets** • Transport of raw materials and products • Virgin manufacture process energy and non-energy		**Emissions** • Transport to recycling facility and sorting of recycled materials at material recovery facility (MRF)
Composting[a]	NA[b]	**Offsets** • Increase in soil carbon storage from application of compost to soils	**Emissions** • Transport to compost facility • Equipment use at compost facility • CH_4 and N_2O emissions during composting
Combustion	**Emissions**	NA	**Emissions** • Transport to WTE facility

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[4] The source reduction techniques the EPA researchers analyzed involve using less of a given product—e.g., by making aluminum cans with less aluminum ("lightweighting"); double-sided rather than single-sided photocopying; or reuse of a product. EPA did not analyze source reduction through material substitution (except in the special case of fly ash)—e.g., substituting plastic boxes for corrugated paper boxes. For a discussion of source reduction with material substitution, see the Source Reduction chapter.

Materials Management Strategies	GHG Sources and Sinks Modeled in WARM		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
	• Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs		• Combustion-related non-biogenic CO_2 and N_2O **Offsets** • Avoided electric utility emissions due to WTE • Avoided steel manufacture from steel recovery at WTE for combusted materials including steel cans, mixed metals, mixed recyclables, PCs, tires and mixed MSW
Landfilling	**Emissions** • Baseline process and transportation emissions due to manufacture with the current mix of virgin and recycled inputs	NA	**Emissions** • Transport to landfill • Equipment use at landfill • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas to energy • Landfill carbon storage

NA = Not Applicable.

[a] Includes composting of food waste and yard trimmings.

[b] No manufacturing transportation GHG emissions are considered for composting of food waste and yard trimmings because these materials are not considered to be manufactured.

CO_2 Emissions from Biogenic Sources

The United States and all other parties to the United Nations Framework Convention on Climate Change (UNFCCC) agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. In 2006, the Intergovernmental Panel on Climate change (IPCC) updated a set of inventory methods that it had first developed in 1996 to be used as the international standard (IPCC (1996); IPCC (2006)). The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO_2 emissions from biogenic sources. For many countries, the treatment of CO_2 flux from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis and, under natural conditions, it would cycle back to the atmosphere eventually as CO_2 due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability.

For processes with CO_2 emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO_2 that was originally removed by photosynthesis. In this case, the CO_2 emissions are *not* counted. (For purposes of this analysis, biogenic materials are paper and wood products, yard trimmings and food discards.) On the other hand, CO_2 emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH_4 emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH_4 would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH_4 formation.

Note that this approach does not distinguish between the timing of CO_2 emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO_2, whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor) is inconsequential.

1.4 Summary of the Life-Cycle Stages Modeled In WARM

1.4.1 GHG Emissions and Carbon Sinks Associated with Raw Materials Acquisition and Manufacturing

Raw inputs are needed to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is required to obtain or extract these material inputs.

The inputs for *manufacturing* considered in this analysis are (1) energy and (2) either virgin raw materials or recycled materials.[5]

When a material is source reduced, GHG emissions associated with raw material acquisition, producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. Since many materials are manufactured from a mix of virgin and recycled inputs, the quantity of virgin material production that is avoided is not always equal to the quantity of material source reduced. To estimate GHG emissions associated with source reduction, WARM uses a mix of virgin and recycled inputs (referred to throughout the documentation as "the current mix"), based on the national average for that material. For example, in source reducing 100 tons of aluminum cans, WARM models that only 32 tons of virgin aluminum manufacture are avoided, because the current mix for aluminum is 32 percent virgin inputs and 68 percent recycled inputs. WARM also assumes that source reduction of paper and wood products increases the amount of carbon stored in forests by reducing the amount of wood harvested. See the Source Reduction process chapter for further information on calculation of offsets resulting from source reduction.

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[6] Each of these emission sources is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper and wood products. For more information on forest carbon sequestration associated with source reduction of paper and wood products, see the Forest Carbon Storage chapter.

1.4.1.1 Process Energy GHG Emissions

Process energy GHG emissions consist primarily of CO_2 emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO_2 emissions from combustion of biomass are not counted as GHG emissions. (See "CO_2 Emissions from Biogenic Sources" text box in section 1.3.3.)

The majority of process energy CO_2 emissions result from the direct combustion of fuels, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport fuels to the place where they are used. Thus, indirect CO_2 emissions from "precombustion energy" are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the resulting CO_2 emissions are also counted.

To estimate process energy GHG emissions, EPA first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu) and the fuel mix (e.g., diesel oil, natural gas, fuel oil). Next, emission factors for each type of fuel were used to convert fuel consumption to GHG emissions based on fuel combustion carbon coefficients per fuel type (EPA, 2011). As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

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[5] Water is also often a key input to manufacturing processes, but is not considered here because it does not have direct GHG implications.

[6] For some materials (plastics, magazines/third-class mail, office paper, phone books, and textbooks), the transportation data EPA received were included in the process energy data. For these materials, EPA reports *total* GHG emissions associated with process and transportation in the "process energy" estimate. The transportation energy estimate therefore only includes emissions from transport from the point of manufacture to a retail facility.

The fuel mixes used in these calculations reflect the material-specific industry average U.S. fuel mixes for each manufacturing process. However, it is worth noting that U.S. consumer products (which eventually become MSW) increasingly come from overseas, where the fuel mixes may differ. For example, China relies heavily on coal and generally uses energy less efficiently than does the United States. Consequently the GHG emissions associated with the manufacture of a material in China may be higher than they would be for the same material made in this country. In addition, greater energy is likely to be expended on transportation to China than on transportation associated with domestic recycling. However, such analysis is beyond the scope of this model, which focuses only on domestic production, transportation, consumption and disposal.

1.4.1.2 Process Non-Energy GHG Emissions

Some GHG emissions occur during the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process non-energy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or $CaCO_3$), and the manufacture of lime results in CO_2 emissions. In some cases, process non-energy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used.

1.4.1.3 Transportation Energy GHG Emissions

Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fossil fuels used to (1) transport raw materials and intermediate products during the manufacturing stage and (2) transport the finished products from the manufacturing facilities to the retail/distribution point.

The estimates of transportation energy emissions for transportation of raw materials to the manufacturing or fabrication facility are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing one short ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation as represented in the industry average life-cycle inventory data.

The estimates of GHG emissions from transporting manufactured products or materials from the manufacturing point to the retail/distribution point are calculated using information from the U.S. Census Bureau, along with the Bureau of Transportation Statistics. These agencies conducted a Commodity Flow Survey that determined the average distance typical commodities were shipped in the United States, and the percentage of each of the various transportation modes that was used to ship these commodities (U.S. Census Bureau, 2003). However, there is large variability in the shipping distance and modes used, and so transportation emission estimates given here are somewhat uncertain.

The final step of the analysis applies fuel combustion carbon coefficients for each fuel type from the U.S. Inventory in order to convert fuel consumption to GHG emissions (EPA, 2011).

1.4.1.4 Carbon Storage, Carbon Sequestration and Carbon Stocks

This analysis includes carbon sequestration and storage when relevant to materials management practices. Carbon storage is the prevention of the release of carbon to the atmosphere. In the context of WARM, this storage can occur in living trees, in undecomposed biogenic organic matter (wood, paper, yard trimmings, food waste) in landfills, or in undecomposed biogenic organic matter in soils due to compost amendment.

Carbon sequestration is the transfer of carbon from the atmosphere to a carbon pool, where it can be stored if it is not rereleased to the atmosphere through decay or burning. Carbon sequestration occurs when trees or other plants undergo photosynthesis, converting CO_2 in the atmosphere to carbon in their biomass. As forests grow, they absorb atmospheric CO_2 and store it. When the rate of uptake exceeds the rate of release, carbon is said to be sequestered. In this analysis, EPA considers the impact of waste management on forest carbon storage. The amount of carbon stored in forest trees is referred to as a forest's carbon stock. WARM models carbon storage, sequestration and stocks at several points in the life-cycle analysis, as detailed below:

- Forest carbon storage *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling "get credit" for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not. See the Source Reduction and Recycling process chapters for more information on this modeling analysis.
- Although source reduction and recycling are associated with forest carbon storage, the application of compost to degraded soils enhances soil carbon storage. The Composting process chapter details the modeling approach used to estimate the magnitude of carbon storage associated with composting.
- Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. See the Landfilling process chapter for further information on carbon storage in landfills.

1.4.2 GHG Emissions and Carbon Sinks Associated with Materials Management

As shown in Exhibit 1-3, depending on the material, WARM models up to four post-consumer materials management options, including recycling, composting, combustion, and landfilling. WARM also models source reduction as an alternative materials management option. This section describes the GHG emissions and carbon sinks associated with each option.

1.4.2.1 Recycling

When a material is recycled, this analysis assumes that the recycled material replaces the use of virgin inputs in the manufacturing process. This approach is based on the assumption that demand for new materials/products and demand for recycled materials remains constant. In other words, increased recycling does not cause more (or less) material to be manufactured than would have otherwise been produced. In WARM, each ton of recycled material would displace the virgin material that would have been produced in the absence of recycling. EPA recognizes that, in reality, there may be a relationship between recycling and demand for products with recycled content since these products may become cheaper as the supply of recycled materials increases. However, for the purpose of simplicity in WARM, EPA assumed that increased recycling does not change overall demand for products.

The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material with 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates associated with curbside collection losses and remanufacturing losses) with 100 percent virgin inputs. The GHG emissions associated with manufacturing a material with 100 percent recycled inputs includes the process of collecting and transporting the recyclables used in remanufacture. EPA did not consider GHG emissions at the MSW management stage because the recycled material is diverted from waste management facilities (i.e., landfills or combustion facilities).[7] If the product made from the recycled material is later composted, combusted or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material. The Recycling chapter discusses the process in further detail.

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process where end-of-life products are recycled back into the same product (e.g., a recycled aluminum can becomes a new aluminum can). Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data. For materials recycled in an open loop, the products of the recycling process differ from the inputs. In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products into which the material is recycled.

The materials modeled as open-loop recycling processes in WARM are: mixed paper, corrugated containers (partial open-loop) copper wire, carpet, personal computers, concrete, tires, fly ash, asphalt shingles and drywall (partial open-loop).[8, 9] For more detail on the recycling pathways for particular materials or products, see the material-specific chapter. For more information on recycling, see the Recycling process chapter.

1.4.2.2 Source Reduction

In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting waste minimization or source reduction. Source Reduction refers to any change in the design, manufacture, purchase or use of materials or products (including packaging) that reduces the amount of material entering the waste collection and disposal system. Source reduction conserves resources and reduces GHG emissions. The avoided GHG emissions are based on raw material acquisition and manufacturing processes for the industry average current mix of virgin and recycled inputs for materials in the marketplace.[10] There are no emissions from end-of-life management because it is assumed that a certain amount of material or product was never produced in the first place.

1.4.2.3 Composting

WARM models composting as resulting in both carbon storage and minimal CO_2 emissions from transportation and mechanical turning of the compost piles. Composting also results in CO_2 emissions from the decomposition of source materials, which include leaves, brush, grass, food waste and newspaper. However, as described in the text box on "CO_2 Emissions from Biogenic Sources," the biogenic CO_2 emitted from these materials during composting is not counted toward GHG emissions. Composting also produces small amounts of CH_4 and N_2O (due to anaerobic decomposition during composting), which vary depending on the carbon and nitrogen ratios of the waste being composted.

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[7] The EPA researchers did not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

[8] Note that corrugated is modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated is closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

[9] Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

[10] Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.

Because recent literature indicated that these fugitive emissions occurred even in well-managed compost piles, these emissions were added into WARM version 13. Composting does result in increased soil carbon storage due to the effects of compost application on soil carbon restoration and humus formation. For more information on GHG flux resulting from composting, see the Composting process chapter.

1.4.2.4 Combustion

When materials are combusted at waste-to-energy facilities, GHGs in the form of CO_2 and N_2O are emitted. Nonbiogenic CO_2 emitted during combustion (i.e., CO_2 from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO_2 (i.e., CO_2 from paper products) is not. WARM assumes that the combustion pathway involves only waste-to-energy facilities that produce electricity. This electricity substitutes for utility-generated electricity and therefore the net GHG emissions are calculated by subtracting the electric utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described further in the Combustion chapter.

1.4.2.5 Landfilling

When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4. Some of the organic matter never decomposes at all; instead, the carbon becomes stored in the landfill. Landfilling of metals and plastics does not result in CH_4 emissions or carbon storage.

At some landfills, virtually all of the CH_4 produced is released to the atmosphere. At others, CH_4 is captured for flaring or combustion with energy recovery (e.g., electricity production). Almost all of the captured CH_4 is converted to CO_2, but is not counted in this study as a GHG because it is biogenic. With combustion of CH_4 for energy recovery, emission factors reflect the electric utility GHG emissions avoided. Regardless of the fate of the CH_4, the landfill carbon storage associated with landfilling of some organic materials is accounted for. GHG emissions and carbon sinks from landfilling are described in the Landfilling chapter.

1.4.2.1 Forest Carbon Storage

See section 1.4.1.4 for discussion.

1.4.2.2 Avoided Electric Utility GHG Emissions Related to Waste

Waste that is used to generate electricity (either through waste combustion or recovery and burning of CH_4 from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuels to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions. When gas generated from decomposing waste at a landfill is combusted for energy, GHG emissions are reduced from the landfill itself, and from avoided fossil fuel use for energy.

1.4.3 Temporal Aspects of Emission Factors in WARM

The emission factors used by WARM represent the full life-cycle changes in GHG emissions resulting from an alternative end-of-life management practice relative to the current, or baseline practice. Certain components of these life-cycle GHG emission factors, however, do not occur immediately following end-of-life management of a material, but over a longer period of time. For example, for paper, yard waste and food waste materials, not all of the GHG reductions occur within the same year of recycling: a portion of the reduction in GHG emissions results from avoided methane emissions from landfills and increased carbon storage in soils and forests. These emission reductions, resulting from the avoided degradation of organic materials into methane in landfills and the accumulation of carbon in forests, can occur over a timeframe of years to decades.

Consequently, WARM correctly accounts for the full range of GHG emission benefits from alternative waste management practices, but it does not explicitly model the timing of GHG reductions from these practices. Therefore, since WARM is a tool that describes the full life-cycle benefits of alternative waste management pathways, it is not appropriate to directly compare the benefits of alternative waste management as modeled through WARM with traditional GHG Inventory reports, which quantify GHG emissions from different sectors on an annual basis. This section explains the temporal components of WARM's emission factors, and explains how WARM considers these timing issues.

1.4.3.1 Temporal Components of WARM

The GHG emissions that occur throughout a materials management pathway can be released instantaneously or over a period of time. For example, while combustion instantaneously releases GHGs, the energy used to transport materials releases GHGs over the course of the trip, and materials decomposing in landfills may release methane for decades. Four main parts of the life-cycle GHG emissions and sinks calculated by WARM occur over time: (1) landfill methane emissions, (2) landfill carbon storage, (3) forest carbon sequestration and storage, and (4) soil carbon storage from compost. All four temporal components are relevant to management of organic materials such as paper and other wood products, food waste and yard trimmings.

- <u>Landfill Methane Emissions:</u> When placed into a landfill, a fraction of the carbon within organic materials degrades into methane emissions. The quantity and timing of methane emissions released from the landfill depends upon at least four factors: (1) how much of the original material decays into methane (varies from material to material), (2) how readily the material decays, (3) landfill moisture conditions (wetter leading to faster decay), and (4) landfill gas collection practices. Food waste and yard trimmings degrade within 20 to 30 years; materials with slower decay rates, such as paper and wood products, release a sizable fraction of their ultimate methane emissions after 30 years.
- <u>Landfill Carbon Storage</u>: The fraction of carbon in organic materials that does not degrade into landfill gas is permanently stored in the landfill. Consequently, the amount of carbon stored in the landfill over time is affected by how much of the original material decays into landfill gas, and the speed (or rate) at which the material decays.
- <u>Forest Carbon Sequestration and Storage</u>: Recycling or "source reducing" wood products offsets the demand for virgin wood. Trees that would otherwise be harvested are left standing in forests. In the short term, this reduction in harvest increases carbon storage in forests; over the longer-term, some of this additional carbon storage decreases as forest managers adjust by planting fewer new trees in managed forests. Results from USDA Forest Service models suggest that the forest carbon storage benefit is long-term, lasting at least for several decades (EPA, 2006, p. 41). WARM's life-cycle perspective includes several timing issues involving complex economic relationships that affect the market for wood products (e.g., change in demand for virgin wood, adjustment in harvest practices and change in forest management in response to tree harvesting) relevant to carbon storage and release.
- <u>Soil Carbon Storage</u>: The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO_2 flux during decomposition of organic matter). When compost is applied to soils, a portion of the carbon in the compost remains un-

decomposed for many years and acts as a carbon sink. While research into the mechanisms and magnitude of carbon storage is ongoing by EPA, WARM currently assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. Although the carbon storage rate declines with time after initial application, the life-cycle perspective in WARM assumes that the carbon stored in compost after a 10-year period is stable in the long term.

Evaluating the timing of GHG emissions from waste management practices involves a high level of uncertainty. For example, the timing of methane emissions from and carbon storage in landfills depends upon uncertain and variable parameters such as the ultimate methane yield and rate of decay in landfills; evaluating forest carbon storage involves complex economic relationships that affect the market for wood products and the management of sustainably harvested forests. In addition to the four components described above, timing issues may also apply to process energy and non-energy emissions from raw material acquisition and manufacturing, transportation and other activities. Timing issues for these components could depend upon factors such as how quickly markets respond to changes in demand for virgin materials given increases in recycling.

EPA designed WARM as a tool for waste managers to use to compare the full, life-cycle GHG benefits of alternative waste management pathways. Its strength as a tool is due to the relatively simple framework that distills complicated analyses of the life-cycle energy and GHG emissions implications of managing materials into a user-friendly spreadsheet model. The purpose of WARM, therefore, is to capture the full life-cycle benefits of alternative waste management practices rather than model the timing of GHG emissions or reductions.

This is fundamentally different from GHG inventories that quantify GHG emissions from different sectors on an annual basis. GHG inventories, in contrast, are used to establish baselines, track GHG emissions and measure reductions over time. The annual perspective of inventories, however, changes depending upon the timeframe used to evaluate GHG emissions, offering a narrow—and sometimes incomplete—picture of the full life-cycle benefits of materials management options. In contrast, the life-cycle view is exactly the perspective that WARM is designed to communicate. As a result, WARM's emission factors cannot be applied to evaluate reductions from annual GHG inventories because they do not necessarily represent annual reductions in emissions (i.e., emission reductions that occur within the same calendar year).

1.5 Limitations

When conducting this analysis, EPA used a number of analytical approaches and numerous data sources, each with its own limitations. In addition, EPA made and applied assumptions throughout the analysis. Although these limitations would be troublesome if used in the context of a regulatory framework, EPA believes that the results are sufficiently accurate to support their use in decision-making and voluntary programs. Some of the major limitations include the following:

- The manufacturing GHG analysis is based on estimated industry averages for energy usage, and in some cases the estimates are based on limited data. In addition, EPA used values for the average GHG emissions per ton of material produced, not the marginal emission rates per incremental ton produced. In some cases, the marginal emission rates may be significantly different.
- The forest carbon sequestration analysis deals with a very complicated set of interrelated ecological and economic processes. Although the models used represent the state-of-the-art in forest resource planning, their geographic scope is limited. Because of the global market for forest products, the actual effects of paper recycling would occur not only in the United States

but in Canada and other countries. Other important limitations include: (1) the model assumes that no forested lands will be converted to non-forest uses as a result of increased paper recycling; and (2) EPA uses a point estimate for forest carbon sequestration, whereas the system of models predicts changing net sequestration over time. Forest carbon sequestration is discussed further in the Forest Carbon Storage chapter.

- The composting analysis considers a small sampling of feedstocks and a single compost application (i.e., agricultural soil). The analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and their impacts on carbon storage.
- The combustion analysis uses national average values for several parameters; variability from site to site is not reflected in the estimate.
- The landfill analysis (1) incorporates some uncertainty on CH_4 generation and carbon sequestration for each material type, due to limited data availability; and (2) uses estimated CH_4 recovery levels for the year 2012 as a baseline.
- Every effort has been made to tailor WARM to the conditions found in the United States, including, where possible, production processes, fuel mixes and other underlying factors. Therefore, the results can only be considered applicable to the United States, and caution should be used in applying or extrapolating them to other countries.

EPA cautions that the emission factors in WARM should be evaluated and applied with an appreciation for the limitations in the data and methods, as described further at the end of each chapter.

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2 WARM DEFINITIONS AND ACRONYMS

2.1 Definitions

Aerobic	Occurring in the presence of free oxygen.
Anaerobic	Occurring in the absence of free oxygen.
Anthropogenic	Derived from human activities.
Baseload electricity	An estimate of the electricity produced from plants that are devoted to the production of baseload electricity supply. Baseload plants are the production facilities used to meet continuous energy demand, and produce energy at a constant rate. Plants that run at over 80% capacity are considered “baseload” generation; a share of generation from plants that run between 80% and 20% capacity is also included based on a “linear relationship.”
Biogenic	Of non-fossil, biological origin.
C&D landfill	A landfill designed for and accepting only construction and demolition materials.
Carbon offset	Emission savings or storage that can be considered to cancel out emissions that would otherwise have occurred. For example, electricity produced from burning landfill gas is considered to replace electricity from the grid, leading to a carbon offset because landfill gas production and combustion results in lower GHG emissions than grid electricity production from fossil fuels.
Carbon sequestration	The removal of carbon (usually in the form of carbon dioxide) from the atmosphere, by plants or by technological means.
Carbon storage	Prevention of the release of carbon to the atmosphere by its storage in living plants (e.g., trees) and undecayed and unburned dead plant material (e.g., wood products, biogenic materials in landfills).
Cellulose	A polysaccharide that is the chief constituent of all plant tissues and fibers.
Closed-loop recycling	A *recycling* process in which the primary product type is remanufactured into the same product type. (e.g., Aluminum cans recycled into aluminum cans.)
Combustion	A waste management strategy in which the waste material is burned. Waste-to-energy combustion facilities are set up to produce useful heat and/or electricity.
Combustion emissions	Emissions from combustion adjusted based on regional avoided utility emission factors.

Composting	A waste management strategy in which aerobic microbial decomposition transforms biogenic material such as food scraps and yard trimmings into a stable, humus-like material (compost).
Demanufacturing	Disassembly and recycling of obsolete consumer products such as computers, electronic appliances, and carpet into their constituents in order to recover the metal, glass, plastic, other materials, and reusable parts.
Downstream emissions	Emissions that occur at life-cycle stages after use: e.g., waste management.
Embedded energy	The energy contained within the raw materials used to manufacture a product. For example, the embedded energy of plastics is due to their being made from petroleum. Because petroleum has an inherent energy value, the amount of energy that is saved through plastic recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input.
Emission factor	Greenhouse gas emission in metric tons of carbon dioxide equivalent per short ton of material managed.
End-of-life pathways	The end-of-life management strategies available in WARM: recycling, composting, combustion, and landfilling. Sometimes source reduction is included in this phrase, although source reduction does not occur at end of life.
Energy content	The inherent energy of a material. For example, the amount of energy in a plastic potentially available for release during combustion.
Forest carbon sequestration	As forests grow, they absorb atmospheric CO_2 and store it. When the rate of uptake exceeds the rate of release, carbon is said to be sequestered. See also carbon sequestration and carbon storage.
Fugitive Emissions	During the composting process, microbial activity decomposes waste into a variety of compounds, whose composition depends on many factors, including the original nutrient balance and composition of the waste, the temperature and moisture conditions of the compost, and the amount of oxygen present in the pile. In WARM, this process is refers to the generation of small amounts of CH_4 and N_2O.
Hemicellulose	Constituent of plant materials that is a polysaccharide, easily hydrated, and easily decomposed by microbes.
Inorganic	1. Not referring to or derived from living organisms. 2. In chemistry, any compound not containing carbon (with a few exceptions).

Landfill carbon storage	Biogenic materials in a landfill are not completely decomposed by anaerobic bacteria, and some of the carbon in these materials is stored. Because this carbon storage would not normally occur under natural conditions (virtually all of the organic material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastic that remains in the landfill is not counted as stored carbon, because it is of fossil origin.
Landfilling	A waste management strategy involving the anaerobic decomposition of organic substrates producing CH_4 and CO_2.
Leachate	Liquid that percolates through waste material in a landfill picking up contaminants from the waste material. Landfill leachate must be collected and properly disposed of to avoid transferring the contaminants to groundwater
Life-cycle assessment	An accounting method that evaluates and reports the full life-cycle inputs and outputs (including GHG emissions) associated with the raw materials extraction, manufacturing or processing, transportation, use, and end-of-life management of a good or service.
Loss rate	The amount of recovered material that is lost during the recycling process, relative to the total amount of collected material. The inverse of the retention rate.
Materials (or waste) management strategy	One of the five strategies in WARM: source reduction, recycling, composting, combustion, and landfilling.
Methanogenic	Biologically producing methane.
MSW landfill	A landfill designed for and accepting only municipal solid waste.
Non-baseload electricity	An estimate of the marginal electricity produced from plants that are more likely to respond to incremental changes in electricity supply and demand based on their capacity factor. All power plants with capacity factors below 20% are considered "non-baseload". Plants that run at over 80% capacity are considered “baseload” generation and not considered the “non-baseload”; a share of generation from plants that run between 80% and 20% capacity is included based on a “linear relationship”.
Open-loop recycling	A *recycling* process in which the primary product is remanufactured into other products that are different from the original primary product. (e.g., carpet recycled into molded auto parts).
Organic	1. Referring to or derived from living organisms. 2. In chemistry, any compound containing carbon (with a few exceptions).

Partial-open-loop recycling	A *recycling* process in which a portion of the primary product type is remanufactured into the same product type, while the remaining portion is recycled into other product types. e.g., corrugated containers are recycled into both corrugated containers and paperboard.
Personal Computer	For WARM's purposes, a PC is composed of a CPU, consisting of housing (mostly steel) and internal electronic components, and a cathode ray tube (CRT) monitor, consisting of the CRT, plastic case, and circuit boards. The peripheral equipment (e.g., keyboards, external cables, printers) are not included in WARM's analysis.
Post-consumer emissions	Emissions that occur after a consumer has used a product or material: generally, waste management emissions.
Post-consumer recycling	Materials or finished products that have served their intended use and have been diverted or recovered from waste destined for disposal, having completed their lives as consumer items. In contrast, pre-consumer recycling is material (e.g., from within the manufacturing process) that is recycled before it reaches the consumer.
Pre-combustion emissions	The GHG emissions that are produced by extracting, transporting, and processing fuels that are in turn consumed in the manufacture of products and materials.
Process energy emissions	Emissions from energy consumption during the acquisition and manufacturing processes
Process non-energy emissions	Emissions occurring during manufacture that are not associated with energy consumption, e.g., perfluorocarbons (PFCs) are emitted during the production of aluminum.
Recovery	The collection of used materials for recycling. Generally recovered materials are taken from the point of use to a materials recovery facility (MRF).
Recycled input credit	WARM calculates the recycled input credit by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of material from virgin inputs.
Recycling	Recovering and reprocessing usable products that might otherwise become waste.
Retail transport emissions	The typical emissions from truck, rail, water, and other-modes of transportation required to transport materials or products from the manufacturing facility to the retail/distribution point.
Retention rate	The amount of recovered material that is transformed into a recycled product, relative to the total amount of collected material. The inverse of the loss rate.

Source reduction	Any change in the design, manufacture, purchase, or use of materials or products that reduces or delays the amount or toxicity of material entering waste collection and disposal. These practices include lightweighting, double-sided copying, and material reuse. It is also possible to source reduce one type of material by substituting another material.
Transportation emissions	Emissions from energy used to transport materials, including transport of manufactured product to retail/distribution point.
Upstream emissions	Emissions that occur at life-cycle stages prior to use: e.g., raw materials acquisition, manufacturing, and transportation.
Waste-to-energy facility	Municipal solid waste incinerator that converts heat from combustion into steam or electricity

2.2 Acronyms

AF&PA	American Forest and Paper Association
BBP	benzyl butyl phthalate
Btu	British thermal unit
C	carbon
C_2F_6	hexafluoroethane
$CaCO_3$	limestone
CaO	lime
CF_4	tetrafluoromethane
CH_4	methane
CO_2	carbon dioxide
DINP	diisononyl phthalate
EF	emission factor
eGRID	U.S. EPA's Emissions & Generation Resource Integrated Database
EPA	U.S. Environmental Protection Agency
FAL	Franklin Associates, Ltd.
FC	forest carbon
FRA	Forest Resources Association
GHG	greenhouse gas
GWP	global warming potential
HDPE	high-density polyethylene
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
kWh	kilowatt-hour
lb	pound
LCA	life cycle assessment
LCI	life cycle inventory

LDPE	low-density polyethylene
LFG	landfill gas
MDF	medium-density fiberboard
MRT	mean residence time
MSW	municipal solid waste
MTCE	metric tons carbon equivalent
$MTCO_2e$	metric tons carbon dioxide equivalent
N	nitrogen
N_2O	nitrous oxide
NAPAP	North American Pulp and Paper
NREL	National Renewable Energy Laboratory
PET	polyethylene terephthalate
PRC	paper recovery
PVC	polyvinyl chloride
PWH	pulpwood harvest
RDF	refuse-derived fuel
RMAM	raw materials acquisition and manufacturing
USDA	U.S. Department of Agriculture
USDA-FS	U.S. Department of Agriculture, Forest Service
VCT	vinyl composition tile
VOC	volatile organic compound
WARM	Waste Reduction Model
WTE	waste-to-energy

3 SOURCE REDUCTION

This chapter describes the development of material-specific emission factors for source reduction in EPA's Waste Reduction Model (WARM). Source reduction, or waste prevention, refers to practices that reduce the amount of materials entering the waste stream, including changes in the design, manufacture, purchase or use of materials. This document provides examples of source reduction and a summary of how EPA estimates the GHG benefits from source reduction of materials.

3.1 Types of Source Reduction

Source reduction can result from any activity that reduces the amount of a material or agricultural input needed and therefore used to make products or food.[11] Some specific examples of source reduction practices are:

- Redesigning products to use fewer materials (e.g., lightweighting, material substitution).
- Reusing products and materials (e.g., a refillable water bottle).
- Extending the useful lifespan of products.
- Avoiding using materials in the first place (e.g., reducing junk mail, reducing demand for uneaten food).

In addition to the activities above, there are limited circumstances where the emission factors can be used to estimate GHG benefits of substituting one material or product for another material or product. Section 3.3.2 presents considerations for estimating the GHG effects of material substitution.

3.2 A Summary of the GHG Implications of Source Reduction

When a material is source reduced, GHG emissions associated with producing the material and/or manufacturing the product and managing the post-consumer waste are avoided. Consequently, source reduction provides GHG emission benefits by: (1) avoiding the "upstream" GHGs emitted in the raw material acquisition, manufacture or production and transport of the source-reduced material; (2) increasing the amount of carbon stored in forests (when wood and paper products are source reduced); and (3) avoiding the downstream GHG emissions from waste management.

Because many materials are manufactured from a mix of virgin and recycled inputs, the quantity of virgin material production that is avoided is not always equal to the quantity of material source reduced. Therefore, to estimate GHG emissions associated with source reduction, WARM uses a mix of virgin and recycled inputs, based on the national average for each material. However, WARM also allows users to evaluate the benefits of source reducing materials manufactured from 100-percent virgin inputs, instead of a mix of virgin and recycled inputs. For some materials, such as food waste and some wood products, it is either not possible or very uncommon to use recycled inputs during material production, so WARM always assumes material production using 100 percent virgin inputs.

WARM assumes that source reduction of paper and wood products increases the amount of carbon stored in forests by reducing the amount of wood harvested. For more information on the calculations that went into creating the forest carbon storage offset, see the Forest Carbon Storage chapter.

In order to measure the full GHG impact of source reduction, the user must compare the GHG emissions from source reduction to the GHG emissions of another materials management option. For example, a user could compare the benefits from source reducing one short ton of office paper instead

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[11] The source reduction pathway was added for food waste in June 2014 into WARM Version 13.

of sending the paper to the landfill. This approach enables policy-makers to evaluate, on a per-ton basis, the overall difference in GHG emissions between (1) source reducing one short ton of material, and (2) manufacturing and then managing (post-consumer) one short ton of the same material. For most materials, source reduction has lower GHG emissions than the other materials management options.[12]

3.3 Applying Emission Factors to Specific Source Reduction Strategies

3.3.1 Calculating the Energy and GHG Emissions Benefits of Reuse

The GHG and energy benefits of reusing non-food materials or products multiple times before they are sent for end-of-life management can be modeled using the source reduction pathway in WARM. The process for calculating the GHG and energy benefits of reuse is as follows:

1. Using the downloadable (i.e., Excel-based) version of WARM, run the model using a baseline scenario of landfilling, recycling, combustion or composting (depending on the likely fate of the material or product if it is not reused), and an alternate scenario of source reduction. For example, if the item was originally destined for a landfill and now will be reused, the baseline scenario is landfilling.
2. Select whether the reused material is manufactured from 100-percent virgin inputs or the current mix of virgin and recycled inputs.[13] (The assumption that the material is manufactured from 100-percent virgin inputs indicates an upper bound estimate of the benefits from reuse.)
3. Multiply the GHG emissions reduction result (i.e. "total change in GHG emissions" from WARM) by the number of times the material is reused. The reuse number should equal one less than the number of total uses to account for the production of the initial material.

This methodology for calculating the GHG benefits from reuse is summarized in the following formula. Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors.

$$\text{GHG Benefits of Reuse} = (N - 1) \times (A)$$

Where,

N = Number of total uses

A = GHG benefits of the source reduction (alternate) pathway minus the baseline pathway (i.e., "total change in GHG emissions" from WARM)

For example, consider reusable HDPE plastic crates, weighing 1,000 short tons total, used for transporting bread to a grocery store. Assume that the crates are typically recycled after each use, but could be reused up to 20 times before they are recycled. In order to calculate the GHG benefits of reusing the crates, the user can run WARM using a baseline of recycling 1,000 short tons HDPE and an alternate scenario of source reducing 1,000 short tons HDPE. Assuming that reusing the crates offsets the production of HDPE crates that would otherwise have been manufactured from 100-percent virgin

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[12] The most notable exceptions are for aluminum cans and carpet, where recycling benefits are higher. For aluminum cans, source reduction benefits (for the current mix of inputs) are smaller than recycling benefits. This is because of two factors: (1) the large difference in GHG emissions between virgin and recycled manufacture of aluminum cans and (2) the relatively high recycled content (68 percent) in aluminum cans. In this instance, source reduction is relatively less beneficial because of the high recycled content of a "virgin" can. The discrepancy in the carpet emission factors is due to the open-loop recycling process modeled for carpets (see the Carpet chapter for more details). This issue is discussed further on the WARM FAQ page, available at: http://epa.gov/epawaste/conserve/tools/warm/WARM_faq.html.

[13] Some materials modeled in WARM utilize 100% virgin materials in the "current mix" of inputs. This is in cases where information on the share of recycled inputs used in production is unavailable or is not a common practice.

inputs, WARM's results indicate that source reduction of 1,000 short tons of HDPE crates results in a net emissions reduction of 692 $MTCO_2e$ relative to the baseline recycling scenario.[14]

The GHG benefits should then be multiplied by 19 reuses (i.e., 20 total uses – 1 original use). Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors. In equation form:

GHG Benefits of Reuse = 19 × (source reduction of 1,000 short tons HDPE – recycling of 1,000 short tons HDPE)

100% virgin inputs (upper bound for reductions):

GHG Benefits of Reuse = 19 × (692 $MTCO_2e$) = 13,148 $MTCO_2e$

3.3.2 Calculating the Energy and GHG Emissions Benefits of Material Substitution

The analysis of source reduction is based on an assumption that source reduction is achieved by practices such as lightweighting, double-sided copying and material reuse. However, it is also possible to source reduce one type of material by substituting another material. The GHG impact of this type of source reduction is the net GHG benefits from source reduction of the original material and manufacturing and disposing of the substitute material.

Where both the original material and the substitute material are available in WARM, the GHG impacts of source reduction with material substitution may be estimated as long as users verify that the material production and end-of-life pathways in WARM are representative of the materials involved in the substitution. However, for cases where one of the materials in the substitution pair is not in WARM, a quantitative analysis of source reduction with material substitution is beyond the scope of the emission factors described in this documentation. The large number of materials that could be substituted for the materials available in WARM, and the need for specific information on application of material substitution, make such an analysis prohibitive and highly uncertain.

In the case where both the material being replaced and its substitute are in WARM, the GHG benefits can be estimated as described below. Note that this calculation cannot be run in WARM, because WARM requires the user to have the same material in the baseline and alternate scenarios:

1. Calculate the GHG emissions from manufacturing and end-of-life management of the original material that will be replaced by the substitute material (i.e., the baseline scenario; see equations below for an explanation of this calculation).
2. Calculate the GHG emissions from manufacturing and end-of-life management of the substitute material (i.e., the alternate scenario; see equations below for an explanation of this calculation).
3. Calculate the mass substitution rate. The mass substitution rate is the number of tons of substitute material used per ton of original material. In calculating the mass substitution rate, users should also account for any difference in the number of times that a product made from the original material is used prior to waste management, compared to the number of times a product made from the substitute material will be used prior to waste management.
4. Calculate the net GHG benefits by subtracting the GHG emissions that would have been generated to produce the baseline material from the GHG emissions generated by producing an equivalent amount of the substitute materials.

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[14] If reusing the crates offsets crates that would otherwise have been manufactured from the current mix of virgin and recycled inputs, source reduction of 1,000 short tons HDPE would result in a net emissions reduction of 589 $MTCO_2e$ relative to the baseline recycling scenario.

This basic methodology for calculating the GHG benefits of material substitution is summarized in the following formula. Energy use can be similarly calculated by replacing the GHG emission factors with energy use factors.

$$GHG\ Benefits\ of\ Material\ Substitution = (EF_{alternate\ material} * MS - EF_{baseline\ material})$$

Where,

$EF_{\text{alternate material}}$ = GHG emissions from production and end-of-life management of the substitute material per unit of substitute material

$EF_{\text{baseline material}}$ = GHG emissions from production and end-of-life management of the original material per unit of original material

MS = Material substitution rate = Amount of substitute material required to replace a unit of the original material

Because source reduction GHG emission factors represent the benefits of avoided production of materials, the GHG emissions generated by the production of materials can be calculated by taking the absolute value of WARM's source reduction factors. The energy or GHG emissions from end-of-life management can be calculated using the various end-of-life materials management factors in WARM (e.g., recycling, composting, combustion or landfilling). Consequently, the $EF_{\text{alternative material}}$ and $EF_{\text{baseline material}}$ terms are equal to:

$$EF_{alternate\ material} = -EF_{\text{source reduction},\ alternate\ material} + EF_{end\text{-}of\text{-}life\ management,\ alternate\ material}$$

$$EF_{baseline\ material} = -EF_{source\ reduction,\ baseline\ material} + EF_{end\text{-}of\text{-}life\ management,\ baseline\ material}$$

Where,

$EF_{\text{source reduction}}$ = WARM emission factor for source reduction of the baseline and alternative materials

$EF_{\text{end-of-life management}}$ = WARM emission factor for the end-of-life management practice (recycling, composting, combustion or landfilling) used to manage the baseline and alternative materials

3.4 Limitations

Because the data presented in this chapter were developed using data presented in the raw materials and acquisition section of the Overview chapter (and the Forest Carbon Storage chapter), the limitations discussed there also apply to the values presented here. Other limitations include:

- The source reduction factors for food waste materials are meant to capture the emissions avoided through waste reduction. They are the closest pathway available in WARM to approximate the benefits from food reuse and donation, but they likely overstate the benefits. Applying source reduction factors to donated materials assumes that the donation completely offsets the use of new materials, but this may not be the case. For example, edible food can be donated to feed hungry people, and while this may offset the demand for other food, it is unlikely that the donation will entirely offset the production of an equivalent amount of food. Also, food donations could be reused for other purposes such as feed for livestock, which would instead offset the production of traditional livestock feed. EPA is conducting research into how to address food donation and food waste reuse in WARM.

- WARM allows users to model source reduction for several mixed material types: mixed paper (all types), mixed metals, mixed plastics, food waste, food waste (meat only), and food waste (non-meat). For these mixed material categories, all components can be individually source reduced in WARM and users could reasonably implement activities or purchasing practices that would reduce a representative mix of these materials. The other mixed materials in WARM—mixed recyclables, mixed organics, and mixed MSW—cannot be source reduced because they contain a broader mixture of materials at end-of-life where users could not reasonably implement activities or purchasing practices that reduce demand for all components. Additionally, mixed MSW and mixed organics include waste materials for which there is no source reduction pathway in WARM.
- There may be additional GHG impacts from disposal of industrial wastes, particularly paper sludge at paper mills. Because of the complexity of analyzing these second-order effects and the lack of data, EPA did not include them.

4 RECYCLING

This chapter describes the development of material-specific emission factors for recycling in EPA's Waste Reduction Model (WARM). A discussion of forest carbon storage, an important input in calculating the emission benefits of paper product recycling, is also included in this chapter.

4.1 A Summary of the GHG Implications of Recycling

EPA defines recycling as "the separation and collection of wastes, their subsequent transformation or remanufacture into usable or marketable products or materials, and the purchase of products made from recyclable materials" (EPA, 2012). WARM considers the recycling of post-consumer materials, which are defined as a "material or finished product that has served its intended use and has been diverted or recovered from waste destined for disposal, having completed its life as a consumer item" (EPA, 2014).

Recycling is a process that takes materials or products that are at end of life and transforms them into either (1) the same product or (2) a secondary product (see discussion of open- and closed-loop 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. Consequently, recycling provides GHG reduction benefits in two ways, depending upon the material recycled: (1) it offsets a portion of "upstream" GHGs emitted in raw material acquisition, manufacture and transport of virgin inputs and materials, and (2) it increases the amount of carbon stored in forests (when wood and paper products are recycled).

In calculating the first source of GHG reduction benefits, WARM assumes that recycling materials does not cause a change in the amount of materials that would otherwise have been manufactured. Since the amount of products manufactured stays the same, and the existing demand for recycled content is the same, an increase in recycling leads to a displacement of virgin-sourced materials.

For more information on the second source of GHG reduction benefits that are provided by forest carbon storage, see the Forest Carbon Storage chapter.

4.1.1 Open- and Closed-Loop Recycling

Recycling processes can be broadly classified into two different categories: open-loop and closed-loop recycling. Most of the materials in WARM are modeled in a closed-loop recycling process, where end-of-life products are recycled into the same product. An example of a closed-loop recycling process is recycling an aluminum can back into another aluminum can. Decisions about whether to model materials in an open-loop or closed-loop process are based on how the material is most often recycled and the availability of data.

For materials recycled in an open loop, the products of the recycling process (secondary product) are not the same as the inputs (primary product). In open-loop emission factors, the GHG benefits of material recycling result from the avoided emissions associated with the virgin manufacture of the *secondary* products that the material is recycled into. Open-loop recycling does not account for avoided emissions from manufacturing the primary material, since recycling the recycled material does not displace manufacturing of the primary material. It only displaces manufacturing of the secondary product. For example, personal computers (PCs) are recycled by dismantling the PC and recovering and processing the raw materials it contains for use in secondary products. WARM models the plastics from PCs as being recycled into asphalt, rather than into new computer casings; the other materials in PCs also are recycled into non-PC products. Consequently, WARM calculates the GHG benefit from recycling PCs based on the emissions displaced from extracting and producing these secondary products from virgin inputs, rather than on the emissions displaced from manufacturing an entire new PC. In applying this method, EPA considers only the GHG benefit for one generation of recycling (i.e., future benefits from recycling the secondary products into additional products were not included).

The materials modeled as open-loop recycling processes in WARM are: mixed paper, corrugated containers (partial open-loop),[15] copper wire, carpet, personal computers, concrete, tires, fly ash, asphalt shingles and drywall (partial open-loop).[16] Corrugated containers and drywall are modeled as partial open-loop because the recycling emission factors for these materials are a weighted average of a closed-loop recycling pathway and an open-loop recycling pathway (e.g., 70 percent of recycled corrugated containers are used in production of more corrugated containers, and 30 percent of corrugated containers are recycled into boxboard). Fly ash is a special case: because it is a byproduct rather than a primary product, it would be impossible to recycle into additional primary product. For more detail on any of the materials mentioned, please refer to the material-specific chapter.

4.1.2 Material 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 (i.e., at collection and at the materials recovery facility) or in the manufacturing stage. Consequently, more than one short ton of material must be recovered and processed to produce one short ton of new material from the recycling process. Material losses are quantified and translated into loss rates. In this analysis, EPA used estimates of loss rates provided by Franklin Associates, Limited (FAL, 2003), for steel, dimensional lumber and medium-density fiberboard (the same materials for which FAL's energy data were used, as described in the Source Reduction chapter). Loss rates for a number of other materials were based on data compiled by EPA's Office of Research and Development (ORD) and the Research Triangle Institute (RTI, 2004). Material-specific sources were consulted for the remaining materials. These values are shown in Exhibit 4-1.

Exhibit 4-1: Loss Rates for Recovered Materials

(a) Material	(b) % of Recovered Materials Retained in the Recovery Stage	(c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage	(d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c)	(e) Data Source[a]
Aluminum Cans	100	0.93	0.93	RTI, 2004
Aluminum Ingot	100	0.93	0.93	Aluminum cans used as proxy
Steel Cans	100	0.98	0.98	FAL, 2003
Copper Wire	82	0.99	0.81	FAL, 2003
Glass	90	0.98	0.88	FAL, 2003; RTI, 2004
HDPE	92	0.93	0.86	FAL, 2011
PET	95	0.94	0.89	FAL, 2011
Corrugated Containers	100	0.93	0.93	FAL, 2003; RTI, 2004
Magazines/Third-Class Mail	95	0.71	0.67	FAL, 2003; RTI, 2004

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[15] Note that corrugated containers are modeled using a partial open-loop recycling process. Roughly 70 percent of the recycled corrugated containers are closed-loop (i.e., replaces virgin corrugated) and 30 percent is open-loop (i.e., replaces boxboard).

[16] Most recycled drywall is used for a variety of agricultural purposes, but can also be recycled back into new drywall. Approximately 20 percent of recycled drywall is closed-loop (i.e., replaces virgin drywall) and 80 percent is open-loop (i.e., used for agricultural purposes).

(a) Material	(b) % of Recovered Materials Retained in the Recovery Stage	(c) Short Tons of Product Made per Short Ton of Recycled Inputs In the Manufacturing Stage	(d) Short Tons of Product Made per Short Ton Recovered Materials (d = b × c)	(e) Data Source[a]
Newspaper	95	0.94	0.90	FAL, 2003; RTI, 2004
Office Paper	91	0.66	0.60	FAL, 2003; RTI, 2004
Phone Books	95	0.71	0.68	FAL, 2003; RTI, 2004
Textbooks	95	0.69	0.66	FAL, 2003; RTI, 2004
Dimensional Lumber	88	0.91	0.80	FAL, 2003
Medium-Density Fiberboard	88	0.91	0.80	FAL, 2003
Personal Computers	100	0.71[c]	0.71	FAL, 2002b
Concrete	100	1.00	1.00	See note d
Fly Ash	100	1.00	1.00	See note d
Tires	90	0.86	0.78	Corti & Lombardi, 2004
Asphalt Concrete	100	1.00	1.00	Levis 2008[d]
Asphalt Shingles	100	0.07	0.93	Berenyi, 2007
Drywall	100	1.00	1.00	WRAP, 2008

[a] Franklin Associates, Ltd. (FAL) provided data for column (b), while the Research Triangle Institute (RTI) provided data for column (c).

[b] A 0.5% loss rate was assumed for molded products from carpet recycling, based on data provided by FAL (2002a). No loss was assumed for the carpet pad/cushion and carpet backing. Since molded products make up 25% of the materials recovered from recycling carpet, the loss rate was weighted by this percentage to calculate the overall amount of material retained: (100% - 0.05% × 25%)/100 = 1.00.

[c] Weighted average of the materials that personal computers are assumed to be recycled into in an open-loop recycling process; i.e., asphalt, steel sheet, lead bullion, cathode ray tube (CRT) glass, copper wire and aluminum sheet.

[d] Due to the nature of the recycling process for fly ash and concrete, these materials are collected and recycled on a ton-per-ton basis, offsetting the production of portland cement and virgin aggregates, respectively.

[e] Loss rates for recycling asphalt concrete are less than 1% by mass. Since the recovered asphalt concrete is extremely valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high.

Explanatory notes: The value in column (b) accounts for losses such as recovered newspapers that were unsuitable for recycling because they were too wet. Column (c) reflects process waste losses at the manufacturing plant or mill. Column (d) is the product of the values in columns (b) and (c).

4.1.3 Calculating the GHG Impacts of Recycling

WARM assesses the GHG emission implications of recycling from the point of waste generation (i.e., starting at the point when the material is collected for recycling) through the point where the recycled material or product has been manufactured into a new product for use. This includes all of the GHG emissions associated with collecting, transporting, processing and recycling or manufacturing the recycled material into a new product for use. To account for the emissions associated with virgin manufacture, WARM calculates a “recycled input credit” by assuming that the recycled material avoids—or offsets—the upstream GHG emissions associated with producing the same amount of material from virgin inputs.

The approach for calculating the recycled input credit depends upon whether the material is recycled in a closed- or open-loop process. GHG emission reductions associated with closed-loop manufacture using recycled inputs are calculated by taking the difference between (1) the GHG emissions from manufacturing a material (accounting for loss rates) from 100-percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material from 100-percent virgin inputs.

For open-loop recycling processes, the emission reductions are calculated by taking the difference between (1) the GHG emissions from manufacturing a secondary product from 100-percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the secondary product (accounting for loss rates) from 100-percent virgin inputs.

The methodology for estimating resource acquisition and manufacturing emissions is described in the WARM Background and Overview chapter. There are separate estimates for manufacturing process emissions for virgin inputs and recycled inputs, and transportation for virgin inputs and recycled inputs. For details on the components of the manufacturing process and transportation inputs, see the WARM Background and Overview chapter.

The recycling GHG emission factors are provided in the chapters corresponding to each individual material modeled in WARM. These GHG emission factors represent the GHG emissions associated with recycling each material into a new product for use, minus a GHG emission offset for avoiding the manufacture of an equivalent amount of the product from virgin inputs.

In evaluating the relative GHG reduction benefits of recycling compared to an existing materials management practice (i.e., evaluating the benefits of recycling relative to source reduction, composting, combustion or landfilling), the recycling GHG emission factors developed in WARM must be compared against the corresponding emission factors for the existing management practice. For example, to evaluate the GHG emission reductions from recycling one short ton of aluminum cans instead of sending the same quantity to the landfill, the GHG emission factor for landfilling one short ton of aluminum cans must be subtracted from the recycling emission factor for aluminum cans. Please see the WARM Background and Overview chapter for additional explanation of the comparative aspect of WARM emission factors.

4.2 Results

The national average results of this analysis are shown in Exhibit 4-2. The net GHG emission reductions from recycling of each material are shown in column (f). As stated earlier, these estimates of net GHG emissions are expressed for recycling in absolute terms, and are not values relative to another waste management option, although they must be used comparatively, as all WARM emission factors must be. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

Exhibit 4-2: Emission Factor for Recycling ($MTCO_2e$/Short Ton of Material Recovered)

(a) Material	(b) Recycled Input Credit:[a] Process Energy	(c) Recycled Input Credit:[a] Transportation Energy	(d) Recycled Input Credit:[a] Process Non-Energy	(e) Forest Carbon Storage	(f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e)
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	0.00	–	-1.81
Copper Wire	-4.67	-0.06	0.00	–	-4.72
Glass	-0.12	-0.02	-0.14	–	-0.28
HDPE	-0.71	–	-0.17	–	-0.88
LDPE	NA	NA	NA	NA	NA
PET	-0.88	0.09	-0.34	0.00	-1.13
LLDPE	NA	NA	NA	NA	NA

(a) Material	(b) Recycled Input Credit:[a] Process Energy	(c) Recycled Input Credit:[a] Transportation Energy	(d) Recycled Input Credit:[a] Process Non-Energy	(e) Forest Carbon Storage	(f) GHG Reductions from Using Recycled Inputs Instead of Virgin Inputs (f = b + c + d + e)
PP	NA	NA	NA	NA	NA
PS	NA	NA	NA	NA	NA
PVC	NA	NA	NA	NA	NA
PLA	NA	NA	NA	NA	NA
Corrugated Containers	-0.003	-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
Dimensional Lumber	0.07	0.01	–	-2.53	-2.46
Medium-Density Fiberboard	0.05	0.02	–	-2.53	-2.47
Food Waste	NA	NA	NA	NA	NA
Food Waste (meat only)	NA	NA	NA	NA	NA
Food Waste (non-meat)	NA	NA	NA	NA	NA
Beef	NA	NA	NA	NA	NA
Poultry	NA	NA	NA	NA	NA
Grains	NA	NA	NA	NA	NA
Bread	NA	NA	NA	NA	NA
Fruits and Vegetables	NA	NA	NA	NA	NA
Dairy Products	NA	NA	NA	NA	NA
Yard Trimmings	NA	NA	NA	NA	NA
Grass	NA	NA	NA	NA	NA
Leaves	NA	NA	NA	NA	NA
Branches	NA	NA	NA	NA	NA
Mixed Paper					
Mixed Paper (general)	-0.36	-0.11	-0.01	-3.06	-3.53
Mixed Paper (primarily residential)	-0.36	-0.11	-0.01	-3.06	-3.53
Mixed Paper (primarily from offices)	-0.42	-0.11	-0.001	-3.06	-3.59
Mixed Metals	-3.03	-0.04	-1.31	–	-4.38
Mixed Plastics	-0.81	0.06	-0.28	–	-1.03
Mixed Recyclables	-0.22	-0.03	-0.07	-2.50	-2.83
Mixed Organics	NA	NA	NA	NA	NA
Mixed MSW	NA	NA	NA	NA	NA
Carpet	-1.41	-0.01	-0.94	–	-2.36
Personal Computers	-1.59	-0.04	-0.88	–	-2.51
Clay Bricks	NA	NA	NA	NA	NA
Concrete	-0.001	-0.01	–	–	-0.01
Fly Ash	-0.42	–	-0.45	–	-0.87
Tires	-0.46	0.07	–	–	-0.39
Asphalt Concrete	-0.03	-0.05	–	NA	-0.08
Asphalt Shingles	-0.11	0.01	–	NA	-0.09
Drywall	0.01	0.02	–	–	0.03
Fiberglass Insulation	NA	NA	NA	NA	NA
Vinyl Flooring	NA	NA	NA	NA	NA
Wood Flooring	NA	NA	NA	NA	NA

NA = Not applicable. For the plastic resin material types, only HDPE and PET recycling are modeled in WARM due to LCI data availability.
– = Zero emissions.

Note that totals may not add due to rounding, and more digits may be displayed than are significant. Negative values denote GHG emission reductions or carbon storage.

[a] Material that is recycled after use is then substituted for virgin inputs in the production of new products. This credit represents the difference in emissions that results from using recycled inputs rather than virgin inputs. The credit accounts for loss rates in collection, processing and remanufacturing. Recycling credit is based on closed- and open-loop recycling, depending on material.

4.3 Limitations

The data presented in this document involve GHG emissions associated with the raw materials and acquisition of materials; therefore, the limitations related to raw materials and acquisition for specific material types are provided in respective material type chapters. Other limitations are as follows:

- The recycling results are reported in terms of GHG emissions per short ton of material collected for recycling. Thus, the emission factors incorporate assumptions on loss of material through collection, sorting and remanufacturing. There is uncertainty in the loss rates: some materials recovery facilities and manufacturing processes may recover or use recycled materials more or less efficiently than as estimated here.
- Because the modeling approach assumes closed-loop recycling for most materials, it does not fully reflect the prevalence and diversity of open-loop recycling. Most of the materials in the analysis are recycled into a variety of manufactured products, not just into the original material. Resource limitations prevent an exhaustive analysis of all of the recycling possibilities for each of the materials analyzed.
- For the purpose of simplicity, EPA assumed that increased recycling does not change overall demand for products. In other words, it was assumed that each incremental short ton of recycled inputs would displace virgin inputs in the manufacturing sector. In reality, there may be a relationship between recycling and demand for products with recycled content, since these products become cheaper as the supply of recycled materials increases.

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5 COMPOSTING

This guidance document describes the development of composting emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from composting of yard trimmings and food waste, as well as mixed organics and polylactide (PLA) biopolymer resin.[17]

5.1 A Summary of the GHG Implications of Composting

During composting, microbial decomposition aerobically transforms organic substrates into a stable, humus-like material (Brown and Subler 2007). Although small-scale composting, such as backyard composting, occurs across the United States, WARM models composting only in central composting facilities with windrow piles because data for small-scale composting or other large-scale operations are insufficient.[18] WARM includes composting as a materials management option for yard trimmings, food waste, PLA, and mixed organics.

As modeled in WARM, composting results in some carbon storage (associated with application of compost to agricultural soils), carbon dioxide (CO_2) emissions from transportation and mechanical turning of the compost piles, in addition to fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[19] To estimate the carbon storage from compost application, EPA selected point estimates from the range of emission factors covering various compost application rates and time periods. EPA chose the point estimates based on a typical compost application rate of 20 short tons of compost per acre, averaged over four soil-crop scenarios.[20] EPA selected the carbon storage values for the year 2010 to maintain consistency with the forest carbon storage estimates discussed in the Forest Carbon Storage chapter.[21] Overall, EPA estimates that centralized composting of mixed organics results in net carbon storage of 0.14 $MTCO_2e$ per wet short ton of organic inputs composted and applied to agricultural soil.

5.2 Calculating the GHG Impacts of Composting

The stages of a composting operation with the potential to affect GHG flux include the following processes:

- Collecting and transporting the organic materials to the central composting site.
- Mechanical turning of the compost pile.
- Non-CO_2 GHG emissions during composting (primarily CH_4 and N_2O).
- Storage of carbon after compost application to soils.

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[17] Composting is not included as a material management pathway for paper because of insufficient information on the GHG implications of composting paper products.

[18] Windrows are a widely used method for composting yard trimmings and municipal solid waste, and they are considered to be the most cost-effective composting technology (EPA, 1994; Coker, 2006).

[19] These fugitive emission sources were added in June 2014 to WARM Version 13.

[20] EPA ran the composting simulation on two sites included in CENTURY: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. EPA simulated two harvest regimes on each site, one where corn is harvested for silage and 95 percent of the above-ground biomass is removed and the other one where corn is harvested for grain and the stover is left behind to decompose on the field.

[21] For consistency with the paper recycling/source reduction analysis of forest carbon storage, EPA analyzed the GHG implications of composting at the year 2010. EPA chose 2010 in the paper recycling/source reduction and forest carbon analyses because it represented a delay of 5 to 15 years from the onset of the simulated period of incremental recycling.

Composting also results in biogenic CO_2 emissions associated with decomposition, both during the composting process and after the compost is added to the soil. Because this CO_2 is biogenic in origin, however, it is not counted as a GHG in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks* and is not included in this accounting of emissions and sinks.[22]

Exhibit 5-1: Components of the Composting Net Emission Factor for Food Waste, Yard Trimmings, and Mixed Organics

	Composting of Post-Consumer Material			
Material Type	**Transportation to Composting**	**Fugitive Emissions**	**Soil Carbon Storage**	**Net Emissions (Post-Consumer)**
PLA	0.04	0.07	-0.24	-0.13
Food Waste	0.04	0.05	−0.24	-0.15
Food Waste (meat only)	0.04	0.05	-0.24	-0.15
Food Waste (non-meat)	0.04	0.05	-0.24	-0.15
Beef	0.04	0.05	-0.24	-0.15
Poultry	0.04	0.05	-0.24	-0.15
Grains	0.04	0.05	-0.24	-0.15
Bread	0.04	0.05	-0.24	-0.15
Fruits and Vegetables	0.04	0.05	-0.24	-0.15
Dairy Products	0.04	0.05	-0.24	-0.15
Yard Trimmings[a]	0.04	0.07	−0.24	−0.12
Grass	0.04	0.07	−0.24	−0.12
Leaves	0.04	0.07	−0.24	−0.12
Branches	0.04	0.07	−0.24	−0.12
Mixed Organics	0.04	0.07	−0.24	−0.14

[a] Yard trimmings represent a 50-percent, 25-percent, and 25-percent weighted average of grass, leaves and branches, respectively, based on U.S. waste generation data from EPA (2014).

Exhibit 5-1 shows the three components of the net emission factor for food waste, yard trimmings, PLA, and mixed organics. Because of resource and model resolution constraints, the two approaches EPA used in WARM to calculate carbon storage from compost application model only finished compost and do not distinguish between compost feedstocks; therefore, the emission factors for each organic's input are the same. The following sections provide further detail on the sources and methods used to develop these emission factors. Section 5.2.1 describes how WARM accounts for GHG emissions during transportation of composting materials and the physical turning of the compost. Section 5.2.2 describes the estimates of fugitive emissions of CH_4 and N_2O for composting within WARM. Section 5.2.3 details the methodology for calculating the carbon storage resulting from compost application in soils, and Sections 5.2.4 and 5.2.5 describe in greater detail the components of carbon storage.

5.2.1 CO_2 from Transportation of Materials and Turning of Compost

WARM includes emissions associated with transporting and processing the compost in aerated windrow piles. Transportation energy emissions occur when fossil fuels are combusted to collect and transport yard trimmings and food waste to a composting facility, and then to operate the composting

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[22] For more information on biogenic carbon emissions, see the text box, "CO_2 Emissions from Biogenic Sources" in the WARM Background and Overview chapter.

equipment that turns the compost.[23] To calculate these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 5-2.

Exhibit 5-2: Emissions Associated with Transporting and Turning Compost

Material Type	Diesel Fuel Required to Collect and Transport One Short 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 ($MTCO_2e$)
Organics	0.36	0.22	0.58	0.04

[a] Based on estimates in Table I-17 in FAL, 1994, p.132.

5.2.2 Fugitive Emissions of CH_4 and N_2O During Composting

5.2.2.1 Background on Fugitive Emissions from Composting

During the composting process, microbial activity decomposes waste into a variety of compounds, some of which are emitted from the compost pile as gases. The amount and type of end products formed during these reactions depends on many factors, including the original nutrient balance and composition of the waste, the temperature and moisture conditions of the compost, and the amount of oxygen present in the pile. These processes result in the generation of small amounts of CH_4 and N_2O gases, which contribute to the net GHG emissions associated with the composting pathway.

The scientific literature suggests that there is a wide range of emissions for fugitive gases generated during composting. Local factors can strongly influence the existence and extent of CH_4 and N_2O emissions from composting piles. These local factors include:

- *Aeration*
- *Density of compost*
- *Frequency of turning*
- *Feedstock composition*
- *Climate (temperature and precipitation)*
- *Size of compost piles*

After reviewing a large number of studies, EPA found that Amlinger et al. (2008) provided the most applicable results for WARM and forms the basis of EPA's estimates of fugitive emissions for composted waste in WARM. The study characterizes CH_4 and N_2O emissions for both biowaste and green waste in well-managed compost windrows across several weeks. Biowaste is composed of separated organic household waste, including food waste. Green waste, or garden waste, is composed primarily of plant waste such as grass and yard trimmings. In WARM, food waste is classified as a bio-waste for the purposes of estimating fugitive emissions, whereas yard trimmings is classified as a green waste. Mixed organics and PLA are considered a representative blend of compostable waste, and use a weighted average of the biowaste and green waste emission factors for the relative shares of each waste type composted within the United States.

The three best data points available from Amlinger et al. (2008) are the 21 week value for green waste and the 12 week values for biowaste. Although composting times vary between facilities, most commercial composting facilities process compost in 6 to 12 weeks (CWMI 1998), with purely green

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[23] EPA did not count transportation emissions from delivery of finished compost from the composting facility to its final destination.

waste requiring a longer composting time of 14 to 18 weeks (Zanker Road Resource Management, Undated).

5.2.2.2 *Methane Generated from Composting*

There is a consensus within the scientific literature that CH_4 is emitted in measurable quantities even in well-managed compost piles. Amlinger et al. (2008) conducted an exhaustive review of literature on emissions from composting and supplemented it with their own findings. They found CH_4 emissions occurring across feedstock types even when the piles were managed, although emissions were variable even within the same treatment. In their own experiments, Amlinger et al. (2008) found that CH_4 emissions for green waste feedstock were 0.0139 $MTCO_2e$ per wet ton of fresh matter (FM). The Amlinger study found that CH_4 emissions from biowaste were lower at 0.0066 and 0.0055 $MTCO_2e$ per wet ton of FM, at 9 weeks and 12 weeks, respectively. For biowaste, EPA selected the 12 week value for WARM because the CO_2 equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 5-3: Fugitive CH_4 Emissions from Composting Biowaste and Green Waste

Compost Feedstock	CH_4 Emissions ($MTCO_2e$/ton)
Biowaste	0.0055
Green waste	0.0139

5.2.2.3 *Nitrous Oxide Generated from Composting*

Knowledge of the mechanism of N_2O emissions from composting is significantly less developed than that of either CO_2 or CH_4 emissions. N_2O is formed during both incomplete ammonium oxidation and incomplete denitrification processes, but there is debate over which process is most important in composting (Lou and Nair 2009). While CH_4 is usually detected near the bottom of piles where oxygen is absent, N_2O often forms closer to the surface. For green waste, Amlinger recorded a value of 0.0609 $MTCO_2e$/ton of FM, whereas for biowaste the authors recorded results of 0.0092 and 0.0396 $MTCO_2e$/ton of FM, at 9 weeks and 12 weeks respectively. For biowaste, EPA selected the 12 week value for WARM because the CO_2 equivalent result increases with time of composting and the results stabilized in later weeks of composting.

Exhibit 5-4: Fugitive N_2O Emissions from Composting Biowaste and Green Waste

Compost Feedstock	N_2O Emissions ($MTCO_2e$/ton)
Biowaste	0.0396
Green waste	0.0609

5.2.2.4 *Summary of Fugitive Emissions Generated from Composting*

Combining CH_4 and N_2O emissions, the net fugitive emissions from composting comprise 0.0451 and 0.0748 $MTCO_2e$/ton for biowaste and green waste, respectively. For mixed organics, WARM uses a weighted emission factor that considers the relative amounts of biowaste and green waste composted in the United States.[24] As the composting waste stream is predominantly yard waste, the weighted emission estimate is much closer to the value for green waste, at 0.0724 $MTCO_2e$/ton. For an overview of fugitive emissions by material type, see Exhibit 5-5.

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[24] According to the 2012 EPA MSW Facts and Figures report, 8% of the waste composted in the United States in 2011 was comprised of food waste, whereas the remaining 92% consisted of yard waste (EPA 2014).

Exhibit 5-5: Total Fugitive Emissions from Composting, by Material Type

Material Type	Fugitive Emissions ($MTCO_2e$/ton)
PLA	0.0724
Food Waste	0.0451
Yard Trimmings	0.0748
Grass	0.0748
Leaves	0.0748
Branches	0.0748
Mixed Organics	0.0724

5.2.3 Carbon Storage Resulting from Compost Application to Soils

5.2.3.1 Background on Carbon Storage in Soils

The stock of carbon in soils is the result of a balance between inputs (usually plant matter) and outputs (primarily CO_2 flux during decomposition of organic matter). The entire portion of carbon held in the soil and undergoing decomposition is collectively referred to as “soil organic matter” (SOM) or “soil organic carbon” (SOC). SOC is a mixture of different organic compounds that decompose at vastly differing rates. Soils contain thousands of different SOC compounds that microbial degradation or abiotic condensation reactions transform into new structures. The more complex of these molecular soil structures tend to have a low decomposition rate and often are identified as humus (Davidson and Janssens, 2006). Strong evidence exists that SOC decomposition decreases with increasing depth (Meersmans et al., 2009). The top layers of soil generally contain organic matter (such as plant residues) that decomposes quickly, meaning that carbon in this portion of the soil is likely to be relatively young. The carbon dynamics in deeper soil layers and the driving factors behind vertical distribution of SOC are poorly understood.

During composting, microbes degrade the original waste materials into organic compounds through a variety of pathways. During this decomposition, approximately 80 percent of the initial organic matter is emitted as CO_2 (Beck-Friis et al., 2000). The remainder of the organic compounds eventually stabilize and become resistant to further rapid microbial decomposition (i.e., recalcitrant) (Francou et al., 2008). Mature compost is characterized as containing a high percentage of these stable, humic substances. When the compost is mature, nearly all of the water-soluble compounds (such as dissolved organic carbon) will have leached out (Bernal et al., 1998).

While EPA is currently researching the mechanisms and magnitude of carbon storage, WARM assumes that carbon from compost remains stored in the soil through two main mechanisms: direct storage of carbon in depleted soils and carbon stored in non-reactive humus compounds. WARM calculates the carbon storage impact of each carbon storage path separately and then adds them together to estimate the carbon storage factor associated with each short ton of organics composted.

5.2.3.2 Soil Carbon Storage Calculation

To calculate soil carbon storage, EPA simulated soil organic matter pools using the Century model, which is described in Section 5.2.4. EPA ran more than 30 scenarios with varied compost application rates and frequency, site characteristics, fertilization rates, and crop residue management. Based on this analysis, EPA concluded that while a single compost application does initially increase soil carbon, the carbon storage rate declines with time after the application. Using a timeframe of 10 years to calculate carbon storage, only a fraction of the initial carbon added remained in the soil at the end of that time period. EPA included this fraction of added carbon per short ton of compost that remained present in the soil after 10 years in the WARM composting emission factor, as shown in Exhibit 5-1.[25]

5.2.3.3 Alternative Carbon Storage Hypotheses

When EPA first incorporated into WARM composting as a materials management option, the agency conducted research but could not identify sufficient primary data that could be used to develop quantitative estimates of the soil carbon storage benefits of compost. EPA developed modeling approaches to investigate the possible effects of compost application on soil carbon storage. In addition to the humus formation and depleted soils mechanisms mentioned earlier, EPA considered the following two possible mechanisms for the effect of compost on soil carbon:

- Nitrogen in compost may stimulate higher productivity, thus generating more crop residues. This fertilization effect would increase soil carbon because of the larger volume of crop residues, which serves as organic matter input.
- The application of compost produces a multiplier effect by qualitatively changing the dynamics of the carbon cycling system and increasing the retention of carbon from non-compost sources. Some studies of other compost feedstocks (e.g., farmyard manure, legumes) have indicated that the addition of organic matter to soil plots can increase the potential for storage of soil organic carbon. The carbon increase apparently comes not only from the organic matter directly, but also from retention of a higher proportion of carbon from residues of crops grown on the soil. This multiplier effect could enable compost to increase carbon storage by more than its own direct contribution to carbon mass accumulation.

EPA concluded from the Century simulations that a shortage of nitrogen can modestly increase crop productivity with compost application, which results in higher inputs of crop residues into the soil and an increased carbon storage rate. As noted in Section 5.2.4.4, however, our analysis assumes that farmers will supply sufficient synthetic fertilizer to crops to maintain commercial yields, in addition to any compost added, so that the soil carbon effect of nitrogen fertilization resulting from compost is relatively small. Although several of the experts contacted cited persuasive qualitative evidence of the existence of a multiplier effect, EPA was unable to develop an approach to quantify this process. More information on these two hypotheses and why they were not included in the final carbon storage emission factor appears in Section 5.2.4.4.

5.2.4 Century Model Framework and Simulations

5.2.4.1 Evaluating Possible Soil Carbon Models

As mentioned earlier, EPA's composting analysis included an extensive literature review and interviews with experts to consider whether the application of compost leads to long-term storage of carbon in soils. After determining that neither the literature review nor discussions with experts would yield a basis for a quantitative estimate of soil carbon storage, EPA evaluated the feasibility of a simulation modeling approach. EPA initially identified two simulation models with the potential to be

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[25] Note that if the time frame is extended to longer periods (and many of the recent discussions of agricultural and forestry offsets in the context of carbon credits would indicate that 10 years is well below the consensus time horizon), the fraction of added carbon per ton of compost that remains present in the soil would be smaller. Although the selection of an appropriate time frame is not the subject of this documentation, EPA may later revisit the choice of time frame.

applied to the issue of soil carbon storage from compost application: (1) Century and (2) the Rothamsted C (ROTHC-26.3)[26] model. Both are peer-reviewed models that have structure and application that have been described in scores of publications. The models share several features:

- Ability to run multiyear simulations.
- Capability to construct multiple scenarios covering various climate and soil conditions and loading rates.
- Ability to handle interaction of several soil processes, environmental factors, and management scenarios such as carbon: nitrogen (C:N) ratios, aggregate formation, soil texture (e.g., clay content), and cropping regime.

Given the extensive application of Century in the United States, its availability on the Internet, and its ability to address many of the processes important to compost application, EPA decided to use Century rather than ROTHC-26.3.

5.2.4.2 Century Simulations

For this analysis, EPA developed a basic agricultural scenario in Century where land was converted from prairie to farmland (growing corn) in 1921 and remained growing corn through 2030.[27]

Several sets of detailed site characteristics from past modeling applications are available to users in Century. EPA chose two settings: an eastern Colorado site with clay loam soil and a southwestern Iowa site with silty clay loam soil. Both settings represent fairly typical Midwestern corn belt situations where agricultural activities have depleted soil organic carbon levels. EPA then ran more than 30 scenarios to examine the effect of the following variables on soil carbon storage:

- Compost application rate and frequency.
- Site characteristics (rainfall, soil type, irrigation regime).
- Fertilization rate.
- Crop residue management.

EPA adjusted compost application rates using the organic matter (compost) files for each compost application rate included in the analysis. EPA then compared the effect of applying compost annually for 10 years (1996–2005) at seven different application rates: 1.3, 3.2, 6.5, 10, 15, 20, and 40 wet short tons compost per acre (corresponding to 60–1,850 grams of carbon per square meter).[28]

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[26] This model was developed based on long-term observations of soil carbon at Rothamsted, an estate in the United Kingdom where organic amendments have been added to soils since the 19th century.

[27] EPA is conducting research into compost markets, and initial findings indicate that compost is not often used in large-scale agricultural applications, but it is often applied in high-end markets, such as landscaping. Century and other widely vetted soil carbon models, however, do not readily model the effects of composting on soil carbon for non-agricultural scenarios. Because of this lack of data, EPA chose to simulate composting using the large-scale agricultural scenarios available in Century. EPA is researching methods to improve these assumptions.

[28] The model requires inputs in terms of the carbon application rate in grams per square meter. The relationship between the carbon application rate and compost application rate depends on three factors: the moisture content of compost, the organic matter content (as a fraction of dry weight), and the carbon content (as a fraction of organic matter). Inputs are based on values provided by Dr. Harold Keener of Ohio State University, who estimates that compost has a moisture content of 50 percent, an organic matter fraction (as dry weight) of 88 percent, and a carbon content of 48 percent (as a fraction of organic matter). Thus, on a wet weight basis, 21 percent of compost is carbon.

Description of the Century Soil Model

Century is a FORTRAN model of plant-soil ecosystems that simulates long-term dynamics of carbon, nitrogen, phosphorus, and sulfur. It tracks the movement of carbon through soil pools—active, slow, and passive—and can show changes in carbon levels as a result of the addition of compost.

In addition to soil organic matter pools, carbon can be found in surface (microbial) pools and in above- and below-ground litter pools. The above-ground and below-ground litter pools are divided into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. Carbon additions to the system flow through the various pools and can exit the system (e.g., as CO_2, dissolved carbon, or through crop removals).

The above-ground and below-ground litter pools are split into metabolic and structural pools based on the ratio of lignin to nitrogen in the litter. The structural pools contain all of the lignin and have much slower decay rates than the metabolic pools. The active pool of soil organic matter includes living biomass, some of the fine particulate detritus, most of the non-humic material, and some of the more easily decomposed fulvic acids. The active pool is estimated to have a mean residence time (MRT) of a few months to 10 years (Metherell et al., 1993; Brady and Weil, 1999). The slow pool includes resistant plant material (i.e., high lignin content) derived from the structural pool and other slowly decomposable and chemically resistant components. It has an MRT of 15–100 years. The passive pool of soil organic matter includes very stable materials remaining in the soil for hundreds to thousands of years.

Century does not simulate increased formation of humic substances associated with organic matter additions, nor does it allow for organic matter additions with high humus content to increase the magnitude of the passive pool directly. (Because Century does not account for these processes, EPA developed a separate analysis, described in Section 5.2.4.)

Century contains a submodel to simulate soil organic matter pools. Additional submodels address nitrogen, phosphorus, sulfur, the water budget, leaching, soil temperature, and plant production, as well as individual submodels for various ecosystems (e.g., grassland, cropland). The nitrogen submodel addresses inputs of fertilizer and other sources of nitrogen, mineralization of organic nitrogen, and uptake of nitrogen by plants.

EPA also investigated the effect of compost application frequency on the soil carbon storage rate and total carbon levels. EPA ran the model to simulate compost applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre every year for 10 years (1996–2005) and applications of 1.3 wet short tons compost/acre and 3.2 wet short tons compost/acre applied every 5 years (in 1996, 2001, and 2006). The simulated compost was specified as having 33 percent lignin,[29] 17:1 C:N ratio,[30] 60:1 carbon-to-phosphorus ratio, and 75:1 carbon-to-sulfur ratio.[31] EPA also ran a scenario with no compost application for each combination of site-fertilization-crop residue management. This

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[29] EPA estimated the percentage of lignin based on the lignin fractions for grass, leaves, and branches specified by compost experts (particularly Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University, and lignin fractions reported in M.A. Barlaz [1997]). FAL provided an estimate of the fraction of grass, leaves, and branches in yard trimmings in a personal communication with ICF Consulting, November 14, 1995. Subsequently, FAL obtained and provided data showing that the composition of yard trimmings varies widely in different states. The percentage composition used here (50 percent grass, 25 percent leaves, and 25 percent branches on a wet weight basis) is within the reported range.

[30] The C:N ratio was taken from Brady and Weil (1999).

[31] C:P and C:S ratios were based on the literature and conversations with composting experts, including Dr. Gregory Evanylo at Virginia Polytechnic Institute and State University.

scenario allowed EPA to control for compost application that is, to calculate the change in carbon storage attributable only to the addition of compost.

Finally, EPA simulated two harvest regimes, one where the corn is harvested for silage (where 95 percent of the above-ground biomass is removed) and the other where corn is harvested for grain (where the stover is left behind to decompose on the field). These simulations enabled EPA to isolate the effect of the carbon added directly to the system in the form of compost, as opposed to total carbon inputs, which include crop residues.

5.2.4.3 Analysis of Compost Application Impacts on Depleted Soils

The output data cover the period from 1900 through 2030. In general, EPA focused on the difference in carbon storage between a baseline scenario where no compost was applied and a with-compost scenario. EPA calculated the difference between the two scenarios to isolate the effect of compost application. EPA converted output data in grams of carbon per square meter to $MTCO_2e$ by multiplying by area in square meters and multiplying by the molecular weight ratio of CO_2 to carbon.

To express results in units comparable to those for other sources and sinks, EPA divided the increase in carbon storage by the short tons of organics required to produce the compost.[32] That is, the factors are expressed as a carbon storage rate in units of $MTCO_2e$ per wet short ton of organic inputs (not $MTCO_2e$ per short ton of compost).

As Exhibit 5-6 illustrates, EPA's Century analysis found that the carbon storage rate declines with time after initial application. The rate is similar across application rates and frequencies, and across the site conditions that were simulated. Exhibit 5-6 shows results for the Colorado and Iowa sites, for the 10-, 20-, and 40-ton per acre application rates. As indicated on the graph, the soil carbon storage rate varies from about 0.08 MTCE (0.30 $MTCO_2e$) per wet ton yard trimmings immediately after compost application in 1997 to about 0.02 MTCE (0.07 $MTCO_2e$) per ton in 2030, 24 years after the last application in 2006.

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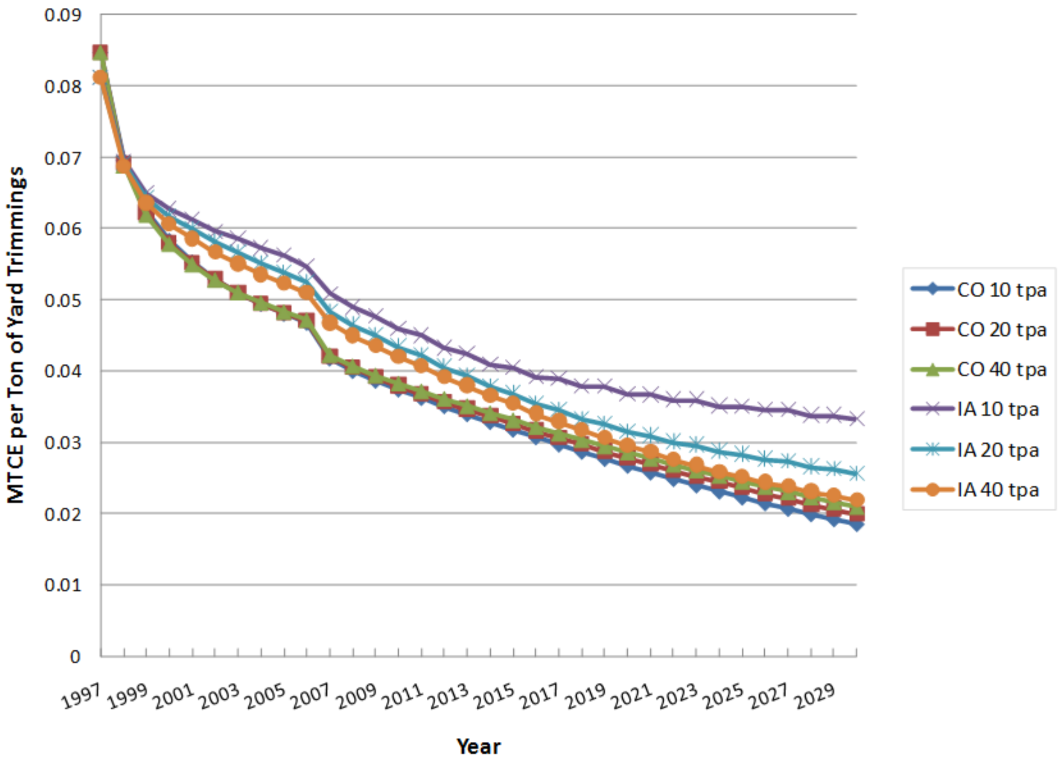
[32] EPA assumes 2.1 tons of yard trimmings are required to generate 1 ton of composted yard trimmings; thus, to convert the results in WARM (in $MTCO_2e$ per wet ton yard trimmings) to $MTCO_2e$ per wet ton of compost, multiply by 2.1. To convert to $MTCO_2e$ per dry ton compost, multiply values in WARM by 4.2 (assuming 50 percent moisture content).

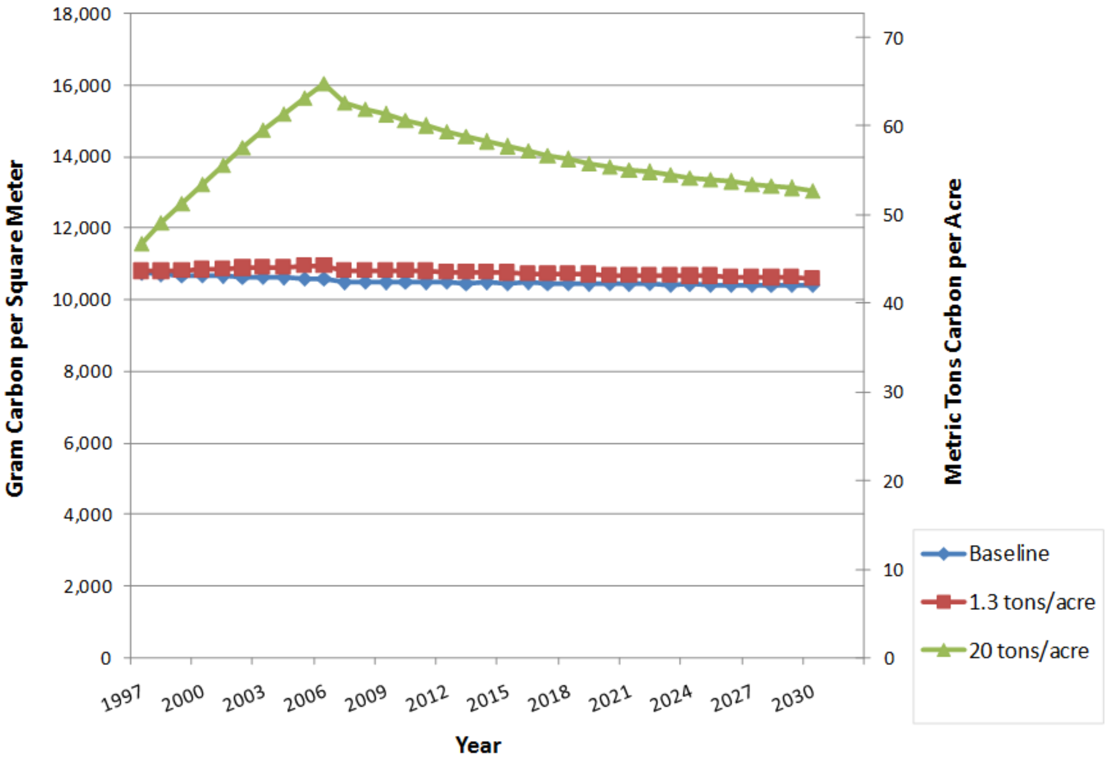
Exhibit 5-6: Soil Carbon Storage—Colorado and Iowa Sites; 10, 20, and 40 Tons-per-Acre Application Rates



The similarity across the various site conditions and application rates reflects the fact that the dominant process controlling carbon retention is the decomposition of organic materials in the various pools. As simulated by Century, this process is governed by first-order kinetics, i.e., the rate is independent of organic matter concentration or the rate of organic matter additions.

When viewed from the perspective of total carbon, rather than as a storage rate per ton of inputs to the composting process, both soil organic carbon concentrations and total carbon stored per acre increase with increasing application rates (see Exhibit 5-7). Soil organic carbon concentrations increase throughout the period of compost application, peak in 2006 (the last year of application), and decline thereafter as a result of decomposition of the imported carbon. Exhibit 5-7 shows total carbon storage (including baseline carbon) in soils on the order of 40 to 65 metric tons per acre. (The range would be higher with higher compost application rates or longer term applications.)

Exhibit 5-7: Total Soil C; Iowa Site, Corn Harvested for Grain



5.2.4.4 Century Simulation of Nitrogen Fertilization Effect

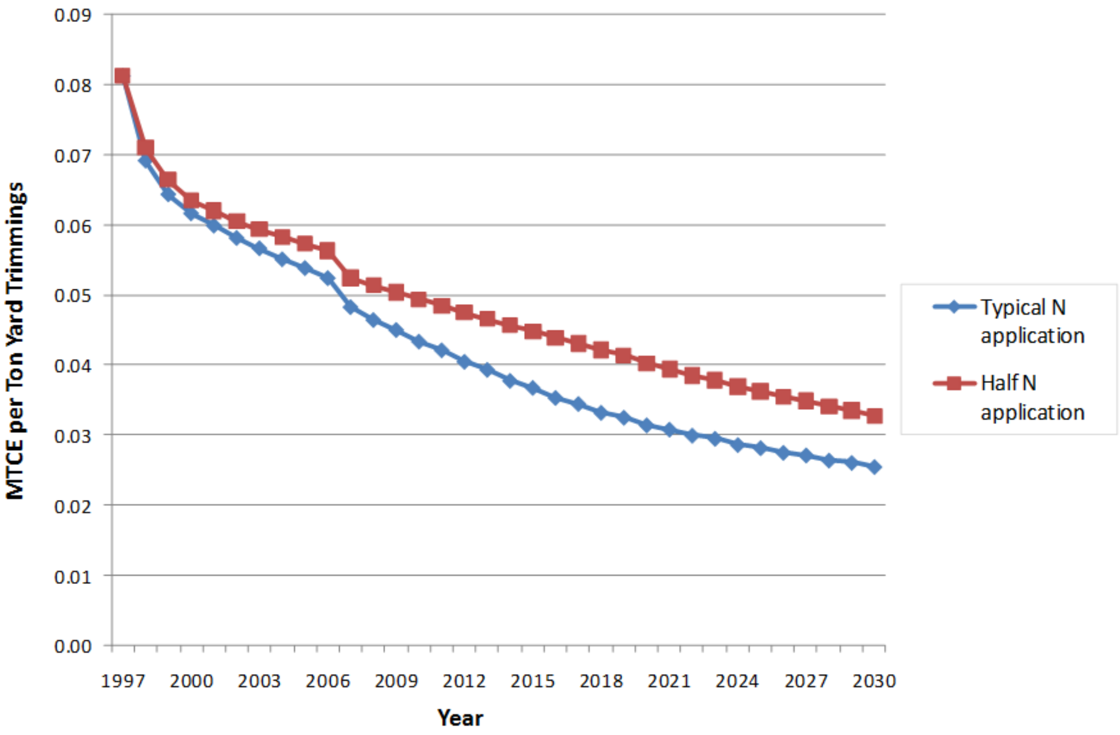
While the decomposition of organic materials is the primary process driving soil carbon retention, EPA's Century analysis also revealed several secondary effects of compost application, including the effects of compost application on nitrogen availability and moisture retention. EPA performed additional Century simulations to quantify the nitrogen fertilization effect, or the hypothesis that mineralization of nitrogen in compost could stimulate crop growth, leading to production of more organic residues and increased soil organic carbon levels. The strength of this effect varies, depending on the availability of other sources of nitrogen (N). To investigate this hypothesis, EPA analyzed different rates of synthetic fertilizer addition ranging from zero up to a typical rate to attain average crop yield (Colorado site: 90 lbs. N/acre; Iowa site: 124 lbs. N/per acre). EPA also evaluated fertilizer application at half of these typical rates.

Exhibit 5-8 shows the carbon storage rate for the Iowa site and the effect of nitrogen fertilization. The two curves in the exhibit represent the difference in carbon storage between a with-compost scenario (20 tons per acre) and a baseline, where compost is not applied. The nitrogen application rates differ in the following ways:

- The curve labeled "Typical N application" represents application of 124 lbs. per acre for both the compost and baseline scenarios. Because the nitrogen added through the compost has little effect when nitrogen is already in abundant supply, this curve portrays a situation where the carbon storage is attributable solely to the organic matter additions in the compost.

- The curve labeled "Half N application" represents application of 62 lbs. per acre. In this scenario, mineralization of nitrogen added by the compost has an incremental effect on crop productivity compared to the baseline. The difference between the baseline and compost application runs reflects both organic matter added by the compost and additional biomass produced in response to the nitrogen contributed by the compost.

Exhibit 5-8: Incremental Carbon Storage as a Function of Nitrogen Application Rate at the Iowa Site



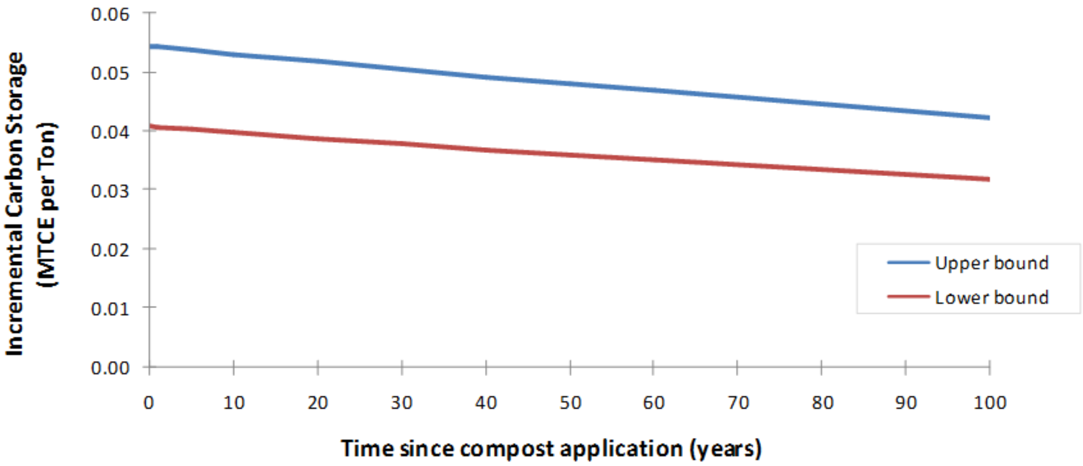
The difference in incremental carbon storage rates between the two fertilization scenarios is less than 0.01 MTCE (0.03 $MTCO_2e$) per ton, indicating that the nitrogen fertilization effect is relatively small. Note that this finding is based on the assumption that farmers applying compost also will apply sufficient synthetic fertilizer to maintain economic crop yields. The effect would be larger if this assumption is not well-founded or in situations where compost is applied as a soil amendment for road construction, landfill cover, or similar situations.

5.2.5 Humus Formation Carbon Storage

Significant evidence exists that compost contains stable compounds, such as humus, and that the carbon stored in that humus should be considered passive when added to the soil because it breaks down much more slowly than crop residues. As mentioned earlier, the Century model does not allow carbon inputs to flow directly into the passive pools; therefore, EPA used a bounding analysis to estimate the upper and lower limits of this humus formation mechanism of carbon storage. This bounding analysis rested on two primary variables: (1) the fraction of carbon in compost that is considered very stable and (2) the rate at which passive carbon is degraded to CO_2. Based on the expert judgment of Dr. Michael Cole from the University of Illinois, EPA found that between 4 to 20 percent of the carbon in compost degrades very quickly, and the remainder can be considered either slow or passive. Dr. Cole found 400 years to be the average of the reported sequestration times of carbon in the soil. The upper and lower bounds of the rate of carbon storage in soils resulting from the humus effect are shown in Exhibit 5-9. EPA took an average value of the upper and lower bounds after 10 years to estimate the carbon storage per short ton of compost that was stored in the passive carbon pool after year 10.

In WARM's final calculation, EPA weighed the carbon values from the two carbon storage mechanisms according to the estimated percentage of compost that is passive (assumed to be 52 percent), and then used the total to estimate the sequestration value associated with composting, as shown in Exhibit 5-11.

Exhibit 5-9: Carbon Storage Resulting from Humus Effect, Bounding Estimate

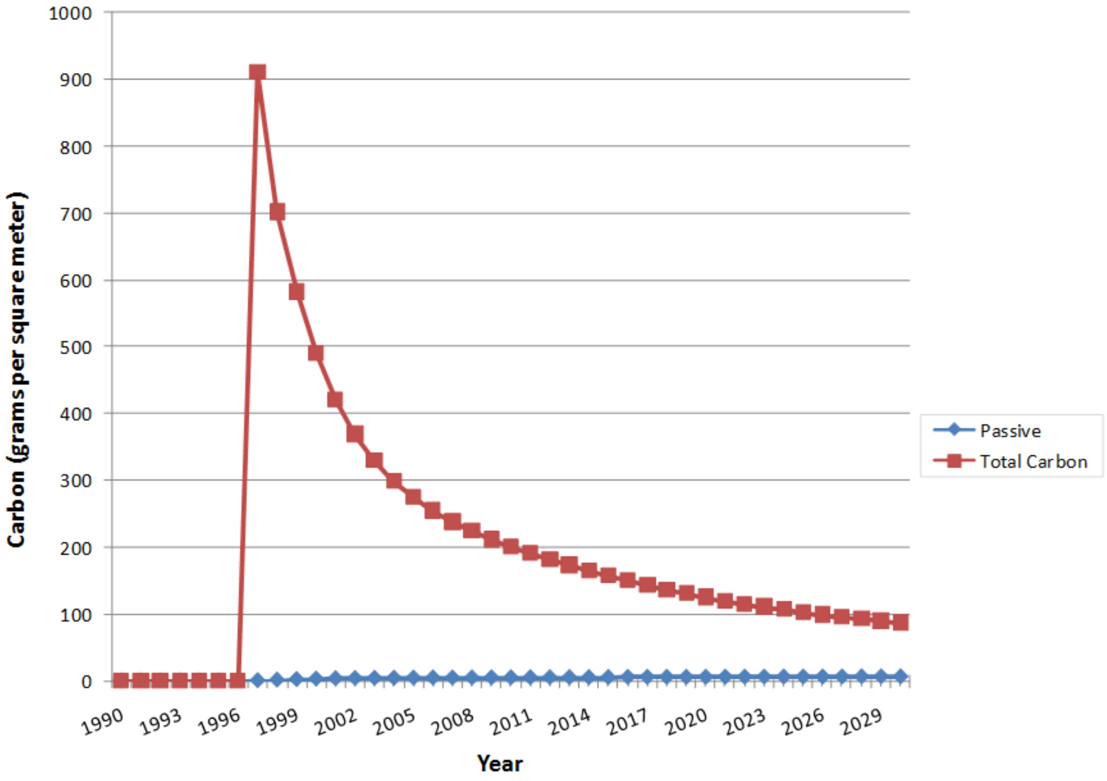


5.2.5.1 *Eliminating the Possibility of Double-Counting*

EPA adopted the approach of adding the humus formation effect to the direct carbon storage effect to capture the range of carbon storage benefits associated with compost application; however, this dual approach creates the possibility of double counting because the Century simulation may include both the direct carbon storage and humus formation effects. In an effort to eliminate double counting, EPA evaluated the way that Century partitions compost carbon after it is applied to the soil.

To do so, EPA ran a Century model simulation of compost addition during a single year and compared the results to a corresponding reference case without compost. EPA calculated the difference in carbon in each of the Century pools for the two simulations and found that the change in the passive pool represented less than 0.01 percent of the change in total carbon; therefore, Century is not adding recalcitrant carbon directly to the passive pool. Next, EPA graphed the change in the passive pool over time to ensure that the recalcitrant compost carbon was not being cycled from the faster pools into the passive pool several years after the compost is applied. As Exhibit 5-10 shows, Century does not introduce significant increments over the base case of recalcitrant carbon into the passive pool at any time.

Exhibit 5-10: Difference in Carbon Storage Between Compost Addition and Base Case Yearly Application with 20 Tons Compost



Based on the analysis, it appears that Century is appropriately simulating carbon cycling and storage for all but the passive carbon introduced by compost application. Because passive carbon represents approximately 52 percent of carbon in compost (the midpoint of 45 percent and 60 percent), EPA scaled the Century results by 48 percent to reflect the proportion of carbon that can be classified as fast or slow (i.e., not passive).

5.2.5.2 WARM Composting Results

Exhibit 5-11 shows the two carbon storage mechanisms included in WARM's analysis of the GHGs associated with composting. The resulting net storage value relies on three main input values: the direct carbon storage, the carbon stored resulting from humus formation, and the percentage of carbon in compost assumed to be passive, or resistant to degradation.

Exhibit 5-11: The Soil Carbon Restoration Effect, the Increased Humus Formation Effect, and the Transportation Emissions for the Typical Compost Application Rate of 20 Short Tons per Acre

	Soil Carbon Restoration					
Scenario	**Unweighted**	**Proportion of C that Is Not Passive (%)**	**Weighted Estimate**	**Increased Humus Formation**	**Transportation Emissions**	**Net Carbon Flux**
Annual application of 20 short tons of compost per acre	-0.04	0.48	-0.07	-0.17	0.04	-0.20

5.3 Limitations

Because of data and resource constraints, this chapter does not explore the full range of conditions under which compost is managed and applied and how these conditions would affect the results of this analysis. Instead, this study attempts to provide an analysis of GHG emissions and sinks associated with centralized composting of organics under a limited set of scenarios. The lack of primary research on carbon storage associated with composting limited EPA's analysis. The limited availability of data forced EPA to rely on two modeling approaches, each with its own set of limitations. In addition, the analysis was limited by the scope of WARM, which is intended to present life-cycle GHG emissions of waste management practices for selected material types, including food discards and yard trimmings.

5.3.1 Limitations of Modeling Approaches

Because of data and resource constraints, EPA was unable to use Century to evaluate the variation in carbon storage impacts for a wide range of compost feedstocks (e.g., yard trimmings mixed with food discards, food discards alone). As noted earlier, resource constraints limited the number of soil types, climates, and compost applications simulated. The Century results also incorporate the limitations of the model itself, which have been well documented elsewhere. Perhaps most important, the model's predictions of soil organic matter levels are driven by four variables: annual precipitation, temperature, soil texture, and plant lignin content. Beyond these, the model is limited by its sensitivity to several factors for which data are difficult or impossible to obtain (e.g., presettlement grazing intensity, nitrogen input during soil development) (Parton et al., 1987). The model's monthly simulation intervals limit its ability to fully address potential interactions between nitrogen supply, plant growth, soil moisture, and decomposition rates, which may be sensitive to conditions that vary on a shorter time scale (Paustian et al., 1992). In addition, the model is not designed to capture the hypothesis that, because of the compost application, soil ecosystem dynamics change and more carbon is stored than is added to the soil (i.e., the multiplier effect).

Century simulates carbon movement through organic matter pools. Although the model is designed to evaluate additions of organic matter in general, EPA does not believe that it has been applied in the past to evaluate the application of organics compost. Century is parameterized to partition carbon to the various pools based on ratios of lignin to nitrogen and lignin to total carbon, not on the amount of organic material that has been converted to humus already. EPA addressed this limitation by developing an add-on analysis to evaluate humus formation in the passive pool, scaling the Century results, and summing the soil carbon storage values. There is some potential for double counting, to the extent that Century is routing some carbon to various pools that is also accounted for in the incremental humus analysis. EPA believes that this effect is likely to be minor.

The bounding analysis used to analyze increased humus formation is limited by the lack of data specifically dealing with composts composed of yard trimmings or food discards. This analysis is also limited by the lack of data on carbon in compost that is passive. The approach of taking the average value from the two scenarios is simplistic, but it appears to be the best available option.

5.3.2 Limitations Related to the Scope of the Emission Factors

As indicated earlier, this chapter describes EPA's estimates of the GHG-related impacts of composting organics. EPA developed these estimates within the framework of the larger WARM development effort; therefore, the presentation of results, estimation of emissions and sinks, and description of ancillary benefits is not comprehensive. The remainder of this section describes specific limitations of the compost analysis.

As noted in the other documentation chapters, the GHG impacts of composting reported in this chapter are calculated using a methodology that facilitates comparison between composting and other possible disposal options for yard trimmings (i.e., landfilling and combustion). To present absolute GHG emission factors for composted yard trimmings that could be used to compare composting to a baseline of leaving yard trimmings on the ground where they fall, EPA would need to analyze the home soil. In particular, the carbon storage benefits of composting would need to be compared to the impact of removal of yard trimmings on the home soil.

As mentioned in Section 5.2, the lack of data and resources constrained EPA's analysis and, therefore, the analysis considers a small sampling of feedstocks and a specific application scenario (i.e., degraded agricultural soil). EPA analyzed two types of compost feedstocks—yard trimmings and food discards—although sewage sludge, animal manure, and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils, despite widespread use of compost in land reclamation, silviculture, horticulture, and landscaping.

This analysis did not consider the full range of soil conservation and management practices that could be used in combination with compost and the impacts of those practices on carbon storage. Some research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no tillage, residue management, crop rotation, wintering, and summer fallow elimination. Research also suggests that allowing crop residues to remain on the soil rather than turning them over helps to protect and sustain the soil while simultaneously enriching it. Alternatively, conventional tillage techniques accelerate soil erosion, increase soil aeration, and hence lead to greater GHG emissions (Lal et al., 1998). Compost use also has been shown to increase soil water retention; moister soil gives a number of ancillary benefits, including reduced irrigation costs and reduced energy used for pumping water. Compost can also play an important role in the adaptation strategies that will be necessary as climate zones shift and some areas become more arid.

As is the case in other chapters, the methodology EPA used to estimate GHG emissions from composting did not allow for variations in transportation distances. EPA recognizes that the density of landfills versus composting sites in any given area would have an effect on the extent of transportation emissions derived from composting. For example, in states that have a higher density of composting sites, the hauling distance to such a site would be smaller and thus require less fuel than transportation to a landfill. Alternatively, transporting compost from urban areas, where compost feedstocks may be collected, to farmlands, where compost is typically applied, could require more fuel because of the large distance separating the sites.

In addition to the carbon storage benefits of adding compost to agricultural soils, composting can lead to improved soil quality, improved productivity, and cost savings. For example, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation.

5.3.3 Ongoing Research to Improve Composting Estimates

EPA is researching several aspects of the composting analysis to improve existing assumptions based on updated research that is emerging. EPA's literature review focused on the following key topics: potential end uses and markets for compost, the shares of compost currently used in different applications in the United States, humus formation, the carbon storage timeframe, the multiplier effect, and other environmental benefits of composting.

Research on the potential end uses and markets for compost suggested that the horticultural/landscaping markets appear to be the most popular markets for compost in the United States. While data quantifying the size of these markets are limited, this finding suggests that the assumptions underlying the current WARM modeling may need to be re-examined. Further research into this subject may be warranted to determine exactly how compost is used in these urban or higher-end markets.

During EPA's research on carbon storage mechanisms, the agency uncovered new field research that may provide a basis for using primary data to quantify the carbon storage emission factor. If EPA decides to calculate a new carbon sequestration value based on field data, both the Century and bounding analyses will be superseded by this approach. EPA has also conducted extensive research into potential GHG emissions from composting. Preliminary research indicates that small amounts of both CH_4 and N_2O emissions are released during composting, even in well-managed piles.

Addressing the possible GHG emission reductions and other environmental benefits achievable by applying compost instead of chemical fertilizers, fungicides, and pesticides was beyond the scope of this documentation. Manufacturing those agricultural products requires energy. To the extent that compost may replace or reduce the need for these substances, composting may result in reduced energy-related GHG emissions. Although EPA understands that generally compost is applied for its soil amendment properties rather than for pest control, compost has been effective in reducing the need for harmful or toxic pesticides and fungicides.[33] Analyses of these benefits, however, are highly sensitive to assumptions about composting and fertilizer application rates, and information on the typical applications of these two soil additions is lacking.

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[33] For example, the use of compost may reduce or eliminate the need for soil fumigation with methyl bromide (an ozone-depleting substance) to kill plant pests and pathogens.

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6 COMBUSTION

This document presents an overview of combustion as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Included are estimates of the net greenhouse gas (GHG) emissions from combustion of most of the materials considered in WARM and several categories of mixed waste.

6.1 A Summary of the GHG Implications of Combustion

Combustion of municipal solid waste (MSW) results in emissions of CO_2 and N_2O. Note that CO_2 from combustion of biomass (such as paper products and yard trimmings) is not counted because it is biogenic (as explained in the Introduction & Overview chapter). WARM estimates emissions from combustion of MSW in waste-to-energy (WTE) facilities. WARM does not consider any recovery of materials from the MSW stream that may occur before MSW is delivered to the combustor.

In the United States, about 80 WTE facilities process more than 30 million tons of MSW annually (ERC, 2014). WTE facilities can be divided into three categories: (1) mass burn, (2) modular and (3) refuse-derived fuel (RDF). A mass burn facility generates electricity and/or steam from the combustion of mixed MSW. Most of the facilities (76 percent) employ mass burn technology. Modular WTE plants are generally smaller than mass burn plants, and are prefabricated off-site so that they can be assembled quickly where they are needed. Because of their similarity to mass burn facilities, modular facilities are treated as part of the mass burn category for the purposes of this analysis.

An RDF facility combusts MSW that has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (such as shredding and material recovery) that result in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher heating value than that used by mass burn or modular WTE. MSW processing into RDF involves both manual and mechanical separation to remove materials such as glass and metals that have little or no fuel value. In the United States, approximately 14 facilities combust RDF (ERC, 2010).

This study analyzed the net GHG emissions from combustion of all individual and mixed waste streams in WARM at mass burn and RDF facilities, with the exception of asphalt concrete, drywall and fiberglass insulation. These three materials were excluded because EPA determined that they are not typically combusted at end of life. Note that **WARM incorporates only the emission factors for mass burn facilities**, due to (1) the relatively small number of RDF facilities in the United States and (2) the fact that the RDF emission factors are based on data from only one RDF facility.

Net emissions consist of (1) emissions from the transportation of waste to a combustion facility, (2) emissions of non-biogenic CO_2, and (3) emissions of N_2O minus (4) avoided GHG emissions from the electric utility sector and (5) avoided GHG emissions due to the recovery and recycling of ferrous metals at the combustor. There is some evidence that as combustor ash ages, it absorbs CO_2 from the atmosphere. However, EPA did not count absorbed CO_2 because the quantity is estimated to be less than 0.02 $MTCO_2e$ per ton of MSW combusted.[34] The results of this analysis for the materials contained in WARM and the explanations for each of these results are discussed in section 6.3.

6.2 Calculating the GHG Impacts of Combustion

This study's general approach was to estimate (1) the gross emissions of CO_2 and N_2O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) the CO_2 emissions avoided because of displaced electric utility

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[34] Based on data provided by Dr. Jürgen Vehlow of the Institut für Technische Chemie in Karlsruhe, Germany, EPA estimated that the ash from one ton of MSW would absorb roughly 0.004 MTCE of CO_2.

generation and decreased energy requirements for production processes using recycled inputs. A comprehensive evaluation would also consider the fate of carbon remaining in combustor ash. Depending on its chemical form, carbon may be aerobically degraded to CO_2, anaerobically degraded to CH_4, or remain in a relatively inert form and be stored. Unless the ash carbon is converted to CH_4 (which EPA considers unlikely), the effect on the net GHG emissions will be very small. To obtain an estimate of the *net* GHG emissions from MSW combustion, the GHG emissions avoided were subtracted from the direct GHG emissions. EPA estimated the net GHG emissions from waste combustion per ton of mixed MSW and per ton of each selected material in MSW. The remainder of this section describes how EPA developed these estimates.

6.2.1 Emissions of CO_2 from WTE Facilities

The carbon in MSW has two distinct origins: some of it is derived from sustainably harvested biomass (i.e., carbon in plant matter that was converted from CO_2 in the atmosphere through photosynthesis), and the remainder is from non-biomass sources, e.g., plastic and synthetic rubber derived from petroleum.

As explained in the Background and Overview chapter, WARM considers only CO_2 that derives from fossil sources and does not consider biogenic CO_2 emissions. Therefore, only CO_2 emissions from the combustion of non-biomass components of MSW—plastic, textiles and rubber—were counted. These components make up a relatively small share of total MSW, so only a small portion of the total CO_2 emissions from combustion are considered in WARM.

To estimate the non-biogenic carbon content of the plastics, textiles, rubber and leather contained in one ton of mixed MSW, EPA first establishes assumptions for the non-biogenic share of carbon in these materials. For plastics in products in MSW, EPA assumes that all carbon is non-biogenic carbon, because biogenic plastics likely make up a small but unknown portion of products. For rubber and leather products in MSW, EPA assumes that the non-biogenic share of carbon contained in clothing and footwear is 25 percent; this assumption is based on expert judgment. The non-biogenic share of carbon in containers, packaging, and other durables is 100 percent; and the non-biogenic share of carbon in other nondurables is 75 percent (EPA, 2010). For textile products in MSW, EPA assumes that the non-biogenic share of carbon is 55 percent (DeZan, 2000). EPA then calculates the non-biogenic carbon content of each of these material groups. For plastics in products in MSW, EPA uses the molecular formula of each resin type to assume that PET is 63 percent carbon; PVC is 38 percent carbon; polystyrene is 92 percent carbon; HDPE, LDPE, and polypropylene are 86 percent carbon; and a weighted average of all other resins is 66 percent carbon (by weight). Based on the amount of each plastic discarded in 2010 (EPA, 2014c), EPA calculates a weighted carbon content of 78 percent for plastics in mixed MSW. For rubber and leather products, EPA uses the weighted average carbon content of rubbers consumed in 2002 to estimate a carbon content of 85 percent (by weight) for rubber and leather products in mixed MSW. For textiles, EPA uses the average carbon content of the four main synthetic fiber types to estimate a carbon content of 70 percent (by weight) for textiles in mixed MSW. Next, using data from BioCycle's *The State of Garbage in America* (Van Haaren et al., 2010), EPA assumes that 7 percent of discards are combusted in the United States. Data from BioCycle is used instead of EPA's *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* report (EPA, 2014c), because it is based off of direct reporting, and provides a more accurate representation of the amount of materials discarded at WTE facilities. Additionally, these data are also used in order to maintain consistency with the data source used in EPA's annual *Inventory of U.S. Greenhouse Gas Emissions and Sinks* report. Based on these assumptions, EPA estimates that there are 0.10 tons of non-biogenic carbon in the plastic, textiles, rubber and leather contained in one ton of mixed MSW (EPA, 2014c; Van Haaren et al., 2010).

The 10 percent non-biomass carbon content of mixed MSW was then converted to units of $MTCO_2e$ per short ton of mixed MSW combusted. The resulting value for mixed MSW is shown in Exhibit 6-1. Note that if EPA had used a best-case assumption for textiles (i.e., assuming that they have no petrochemical-based fibers), the resulting value for mixed MSW would have been slightly lower. The values for CO_2 emissions are shown in column (b) of Exhibit 6-1.

Exhibit 6-1: Gross GHG Emissions from MSW Combustion ($MTCO_2e$/Short Ton of Material Combusted)

(a) Product/Material	(b) Combustion CO_2 Emissions From Non-Biomass per Short Ton Combusted	(c) Combustion N_2O Emissions per Short Ton Combusted	(d) Transportation CO_2 Emissions per Short Ton Combusted	(e) Gross GHG Emissions per Short Ton Combusted (e = b + c + d)
Aluminum Cans	–	–	0.03	0.03
Aluminum Ingot	–	–	0.03	0.03
Steel Cans	–	–	0.03	0.03
Copper Wire	–	–	0.03	0.03
Glass	–	–	0.03	0.03
HDPE	2.79	–	0.03	2.82
LDPE	2.79	–	0.03	2.82
PET	2.04	–	0.03	2.06
LLDPE	2.79	–	0.03	2.82
PP	2.79	–	0.03	2.82
PS	3.01	–	0.03	3.04
PVC	1.25	–	0.03	1.28
PLA	–	–	0.03	0.03
Corrugated Containers	–	0.04	0.03	0.06
Magazines/Third-Class Mail	–	0.04	0.03	0.06
Newspaper	–	0.04	0.03	0.06
Office Paper	–	0.04	0.03	0.06
Phone Books[a]	–	0.04	0.03	0.06
Textbooks[a]	–	0.04	0.03	0.06
Dimensional Lumber	–	0.04	0.03	0.06
Medium-Density Fiberboard	–	0.04	0.03	0.06
Food Waste	–	0.04	0.03	0.06
Food Waste (meat only)	–	0.04	0.03	0.06
Food Waste (non-meat)	–	0.04	0.03	0.06
Beef	–	0.04	0.03	0.06
Poultry	–	0.04	0.03	0.06
Grains	–	0.04	0.03	0.06
Bread	–	0.04	0.03	0.06
Fruits and Vegetables	–	0.04	0.03	0.06
Dairy Products	–	0.04	0.03	0.06
Yard Trimmings	–	0.04	0.03	0.06
Grass	–	0.04	0.03	0.06
Leaves	–	0.04	0.03	0.06
Branches	–	0.04	0.03	0.06
Mixed Paper (general)	–	0.04	0.03	0.06
Mixed Paper (primarily residential)	–	0.04	0.03	0.06
Mixed Paper (primarily from offices)	–	0.04	0.03	0.06
Mixed Metals	–	–	0.03	0.03
Mixed Plastics	2.33	–	0.03	2.36
Mixed Recyclables	0.07	0.03	0.03	0.13
Mixed Organics	–	0.04	0.03	0.06
Mixed MSW	0.36	0.04	0.03	0.43

(a) Product/Material	(b) Combustion CO_2 Emissions From Non-Biomass per Short Ton Combusted	(c) Combustion N_2O Emissions per Short Ton Combusted	(d) Transportation CO_2 Emissions per Short Ton Combusted	(e) Gross GHG Emissions per Short Ton Combusted (e = b + c + d)
Carpet	1.67	–	0.03	1.69
Personal Computers	0.38	–	0.03	0.41
Clay Bricks	NA	NA	NA	NA
Concrete	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA
Tires	2.20	–	0.03	2.22
Asphalt Concrete	NA	NA	NA	NA
Asphalt Shingles	0.65	0.04	0.03	0.72
Drywall	NA	NA	NA	NA
Fiberglass Insulation	NA	NA	NA	NA
Vinyl Flooring	0.28	–	0.03	0.31
Wood Flooring	–	0.04	0.05	0.08

– = Zero emissions.

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

[a] The values for phone books and textbooks are proxies, based on newspaper and office paper, respectively.

6.2.2 Emissions of N_2O from WTE Facilities

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a global warming potential (GWP) 298 times that of CO_2 (EPA, 2014b; IPCC, 2007; IPCC, 2006). The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. This study averaged the midpoints of each range and converted the units to $MTCO_2e$ of N_2O per ton of MSW. The resulting estimate is 0.04 $MTCO_2e$ of N_2O emissions per ton of mixed MSW combusted. Because the IPCC did not report N_2O values for combustion of individual components of MSW, EPA used the 0.04 value not only for mixed MSW, but also as a proxy for all components of MSW, except for aluminum cans, steel cans, glass, HDPE, LDPE and PET. This exception was made because at the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans, glass, and plastics do not contain nitrogen, EPA concluded that running these materials through an MSW combustor would not result in N_2O emissions.

6.2.3 Emissions of CO_2 from Transportation of Waste and Ash

The combustion emission factors also include CO_2 emissions from the transportation of waste and the subsequent transportation of the residual waste ash to the landfill. For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA uses an estimate for transporting mixed MSW developed by FAL (1994). Transportation of any individual material in MSW is assumed to use the same amount of energy as transportation of mixed MSW.

6.2.4 Estimating Utility CO_2 Emissions Avoided

Most WTE plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumes that the energy recovered with MSW combustion would be in the form of electricity, with the exception of two materials that are not assumed to be combusted at WTE plants. For tires, the avoided utility CO_2 emissions per ton of tires combusted is based on the weighted average of three tire combustion pathways: combustion at cement kilns, power plants, and pulp and paper mills. For asphalt shingles, the avoided utility CO_2 emissions per ton of shingles combusted is equal to the amount of avoided refinery gas combusted at cement kilns where asphalt shingles are combusted. The avoided utility CO_2 emissions analysis is shown in Exhibit 6-2. EPA uses three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of mixed MSW and of each separate waste material considered, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 6-2: Avoided Utility GHG Emissions from Combustion at WTE Facilities

(a) Material Combusted	(b) Energy Content (Million Btu Per Ton)	(c) Mass Burn Combustion System Efficiency (%)	(d) RDF Combustion System Efficiency (%)	(e) Emission Factor for Utility-Generated Electricity[a] ($MTCO_2e$/ Million Btu of Electricity Delivered)	(f) Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities[a] ($MTCO_2e$) (f = b × c × e)	(g) Avoided Utility CO_2 per Ton Combusted at RDF Facilities ($MTCO_2e$) (g = b × d × e)
Aluminum Cans	-0.67[b]	17.8%	16.3%	0.22	-0.03	-0.02
Aluminum Ingot	-0.7	17.8%	16.3%	0.22	-0.03	-0.02
Steel Cans	-0.42[b]	17.8%	16.3%	0.22	-0.02	-0.01
Copper Wire	-0.55[c]	17.8%	16.3%	0.22	-0.02	-0.02
Glass	-0.47[b]	17.8%	16.3%	0.22	-0.02	-0.02
HDPE	40.0[d]	17.8%	16.3%	0.22	1.55	1.42
LDPE	39.8[d]	17.8%	16.3%	0.22	1.55	1.41
PET	21.2	17.8%	16.3%	0.22	0.82	0.75
LLDPE	39.9	17.8%	16.3%	0.22	1.55	1.42
PP	39.9	17.8%	16.3%	0.22	1.55	1.42
PS	36.0	17.8%	16.3%	0.22	1.40	1.28
PVC	15.8	17.8%	16.3%	0.22	0.61	0.56
PLA	16.7	17.8%	16.3%	0.22	0.65	0.59
Corrugated Containers	14.1[d]	17.8%	16.3%	0.22	0.55	0.50
Magazines/Third-Class Mail	10.5[d]	17.8%	16.3%	0.22	0.41	0.37
Newspaper	15.9[d]	17.8%	16.3%	0.22	0.62	0.56
Office Paper	13.6[d]	17.8%	16.3%	0.22	0.53	0.48
Phone Books	15.9[d]	17.8%	16.3%	0.22	0.62	0.56
Textbooks	13.6[d]	17.8%	16.3%	0.22	0.53	0.48
Dimensional Lumber	16.6[f]	17.8%	16.3%	0.22	0.65	0.59
Medium-Density Fiberboard	16.6[f]	17.8%	16.3%	0.22	0.65	0.59
Food Waste	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Food Waste (meat only)	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Food Waste (non-meat)	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Beef	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Poultry	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Grains	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Bread	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Fruits and Vegetables	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Dairy Products	4.7[d]	17.8%	16.3%	0.22	0.18	0.17
Yard Trimmings	5.6[g]	17.8%	16.3%	0.22	0.22	0.20

(a) Material Combusted	(b) Energy Content (Million Btu Per Ton)	(c) Mass Burn Combustion System Efficiency (%)	(d) RDF Combustion System Efficiency (%)	(e) Emission Factor for Utility-Generated Electricity[a] (MTCO$_2$e/ Million Btu of Electricity Delivered)	(f) Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities[a] (MTCO$_2$e) (f = b × c × e)	(g) Avoided Utility CO$_2$ per Ton Combusted at RDF Facilities (MTCO$_2$e) (g = b × d × e)
Grass	5.6[g]	17.8%	16.3%	0.22	0.22	0.20
Leaves	5.6[g]	17.8%	16.3%	0.22	0.22	0.20
Branches	5.6[g]	17.8%	16.3%	0.22	0.22	0.20
Mixed Paper (general)	NA	17.8%	16.3%	0.22	0.55	NA
Mixed Paper (primarily residential)	NA	17.8%	16.3%	0.22	0.55	NA
Mixed Paper (primarily from offices)	NA	17.8%	16.3%	0.22	0.51	NA
Mixed Metals	NA	17.8%	16.3%	0.22	-0.02	NA
Mixed Plastics	NA	17.8%	16.3%	0.22	1.11	NA
Mixed Recyclables	NA	17.8%	16.3%	0.22	0.51	NA
Mixed Organics	NA	17.8%	16.3%	0.22	0.20	NA
Mixed MSW	10.0[h]	17.8%	16.3%	0.22	0.39	0.35
Carpet	15.2[i]	17.8%	16.3%	0.22	0.59	0.54
Personal Computers	3.1[j]	17.8%	16.3%	0.22	0.12	0.11
Clay Bricks	NA	NA	NA	NA	NA	NA
Concrete	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA
Tires	27.8[k]	NA	NA	NA	1.57	1.57
Asphalt Concrete	NA	NA	NA	NA	NA	NA
Asphalt Shingles	8.8	NA[l]	NA[l]	NA[l]	1.05[m]	1.05[m]
Drywall	NA	NA	NA	NA	NA	NA
Fiberglass Insulation	NA	NA	NA	NA	NA	NA
Vinyl Flooring	15.8	17.8%	16.3%	0.22	0.61	0.56
Wood Flooring	18.0[n]	21.5%[o]	16.3%	0.22	0.85	0.64

NA = Not applicable.

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

[a] The values in this column are based on national average emissions from utility-generated electricity. The Excel version of WARM also allows users to choose region-specific utility-generated factors, which are contained in Exhibit 6-4.

[b] EPA developed these estimates based on data on the specific heat of aluminum, steel and glass and calculated the energy required to raise the temperature of aluminum, steel and glass from ambient temperature to the temperature found in a combustor (about 750° Celsius), based on Incropera and DeWitt (1990).

[c] Average of aluminum and steel.

[d] Source: EPA (1995). "Magazines" used as proxy for magazines/third-class mail; "mixed paper" used as a proxy for the value for office paper and textbooks; "newspapers" used as a proxy for phone books.

[e] Source: Gaines and Stodolsky (1993).

[f] EPA used the higher end of the MMBtu factor for basswood from the USDA-FS. Basswood is a relatively soft wood, so its high-end MMBtu content should be similar to an average factor for all wood types (Fons et al., 1962).

[g] Proctor and Redfern, Ltd. and ORTECH International (1993).

[h] Source: IWSA and American Ref-Fuel (personal communication, October 28, 1997). Mixed MSW represents the entire waste stream as disposed of.

[i] Source: Realff, M. (2010).

[j] Source: FAL (2002b).

[k] Tires used as tire-derived fuel substitute for coal in cement kilns and electric utilities; used as a substitute for natural gas in pulp and paper facilities. Therefore, columns (d) through (h) are a weighted average of multiple tire combustion pathways, and are not calculated in the same manner as the other materials and products in the table.

[l] The avoided utility GHG emissions are assumed to equal avoided cement kiln refinery gas combustion, so this factor is not used.

[m] Assumes avoided cement kiln refinery gas combustion.

[n] Bergman and Bowe (2008), Table 3, p. 454. Note that this is in good agreement with values already in WARM for lumber and medium-density fiberboard.

[o] Based on average heat rate of U.S. dedicated biomass electricity plants.

6.2.4.1 Energy Content

The energy content of each of the combustible materials in WARM is contained in column (b) of Exhibit 6-2. For the energy content of mixed MSW, EPA used a value of 10.0 million Btu (MMBtu) per short ton of mixed MSW combusted, which is a value commonly used in the WTE industry (IWSA and American Ref-Fuel, 1997). This estimate is within the range of values (9.0 to 13.0 MMBtu per ton) reported by FAL (1994) and is slightly higher than the 9.6 MMBtu per ton value reported in EPA's *MSW Fact Book* (EPA, 1995). For the energy content of RDF, a value of 11.4 MMBtu per ton of RDF combusted was used (Harrington 1997). This estimate is within the range of values (9.6 to 12.8 MMBtu per ton) reported by the DOE's National Renewable Energy Laboratory (NREL, 1992). For the energy content of specific materials in MSW, EPA consulted three sources: (1) EPA's *MSW Fact Book* (1995), a compilation of data from primary sources, (2) a report by Environment Canada (Procter and Redfern, Ltd. and ORTECH International, 1993), and (3) a report by Argonne National Laboratories (Gaines and Stodolsky, 1993). EPA assumes that the energy contents reported in the first two of these sources were for materials with moisture contents typically found for the materials in MSW (the sources imply this but do not explicitly state it). The Argonne study reports energy content on a dry weight basis.

6.2.4.2 Combustion System Efficiency

To estimate the combustion system efficiency of mass burn plants, EPA uses a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, M. 1997).

To estimate the combustion system efficiency of RDF plants, EPA evaluated three sources: (1) data supplied by an RDF processing facility located in Newport, MN (Harrington, 1997); (2) the Integrated Waste Services Association report, *The 2000 Waste-to-Energy Directory: Year 2000* (IWSA, 2000); and (3) the National Renewable Energy Laboratory (NREL, 1992). EPA uses the Newport Processing Facility's reported net value of 572 kWh generated per ton of RDF for two reasons. First, this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provides a complete set of data for evaluating the overall system efficiency of an RDF plant. The net energy value reported accounts for the estimated energy required to process MSW into RDF and the estimated energy consumed by the RDF combustion facility. The dataset includes estimates on the composition and amount of MSW delivered to the processing facility, as well as estimates for the heat value of RDF, the amount of energy required to process MSW into RDF, and the amount of energy used to operate the RDF facility.

Next, EPA considers losses in transmission and distribution of electricity specific to WTE combustion facilities. The U.S. average transmission and distribution ("line") loss rate is about 9 percent, although for some facilities or cities, this rate may be lower. According to IWSA and American Ref-Fuel (1997), this rate could be as low as 4 percent. IWSA supports a 5-percent line loss rate, and for purposes of this analysis, we assume this value. Using the 5-percent loss rate, EPA estimates that 523 kWh are delivered per ton of waste combusted at mass burn facilities, and 544 kWh are delivered per ton of waste input at RDF facilities.

EPA then uses the value for the delivered kWh per ton of waste combusted to derive the implicit combustion system efficiency (i.e., the percentage of energy in the waste that is ultimately delivered in the form of electricity). To determine this efficiency, we estimate the MMBtu of MSW needed to deliver 1 kWh of electricity. EPA divides the MMBtu per ton of waste by the delivered kWh per ton of waste to obtain the MMBtu of waste per delivered kWh. The result is 0.0191 MMBtu per kWh for mass burn and 0.0210 MMBtu per kWh for RDF. The physical constant for the energy in 1 kWh (0.0034 MMBtu) is then divided by the MMBtu of MSW and RDF needed to deliver 1 kWh, to estimate the total system efficiency at 17.8 percent for mass burn and 16.3 percent for RDF (see Exhibit 6-2, columns (d) and (e)). Note that the total system efficiency is the efficiency of translating the energy content of the fuel into the energy content of delivered electricity. The estimated system efficiencies of 17.8 and 16.3 percent reflect losses in (1) converting energy in the fuel into steam, (2) converting energy in steam into electricity, and (3) delivering electricity.

6.2.4.3 Electric Utility Carbon Emissions Avoided

To estimate the avoided utility GHG emissions from waste combustion, EPA uses “non-baseload” emission factors from EPA’s Emissions and Generation Resource Integrated Database (eGRID). EPA made the decision to use non-baseload factors rather than a national average of only fossil-fuel plants[35] because the non-baseload emission rates provide a more accurate estimate of the marginal emissions rate. The non-baseload rates scale emissions from generating units based on their capacity factor. Plants that run at more than 80 percent capacity are considered “baseload” generation and not included in the “non-baseload” emission factor; a share of generation from plants that run between 80 percent and 20 percent capacity is included in the emission factor based on a “linear relationship,” and all plants with capacity factors below 20 percent are included (E.H. Pechan & Associates, 2006).

In order to capture the regional differences in the emissions rate due to the variation in sources of electricity generation, WARM first uses state-level eGRID non-baseload emission factors and aggregates them into weighted average regional emission factors based on fossil-fuel-only state electricity generation. The geographic regions are based on U.S. Census Bureau-designated areas. Exhibit 6-3 contains a map, prepared by the U.S. Census Bureau, of the nine regions. Exhibit 6-4 shows the national average eGRID emission factor and the factors for each of the nine geographic regions. In addition to the calculated regional non-baseload emission factors, EPA also utilizes eGRID’s national non-baseload emission factor to represent the national average non-baseload avoided utility emission factor. The resulting non-baseload regional and national average estimates for utility carbon emissions avoided for each material at mass burn facilities are shown in Exhibit 6-5. Columns (g) and (h), respectively, of Exhibit 6-2 show the national average estimates for mass burn and RDF facilities.

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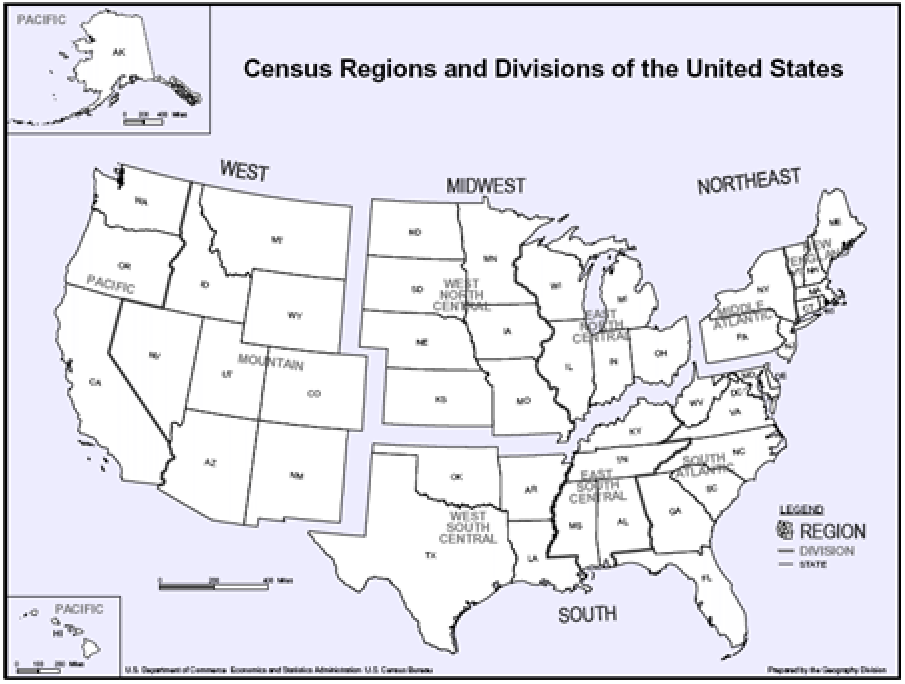
[35] While coal accounts for 48 percent of U.S. primary energy consumption—and 70 percent of fossil-fuel consumption—in the electricity sector, these plants may serve as baseload power with marginal changes in electricity supply met by natural gas plants in some areas (EIA, 2010). Natural gas plants have a much lower emissions rate than the coal-dominated national average of fossil-fuel plants.

Exhibit 6-3: Electric Utility Regions Used in WARM



Source: U.S. Census Bureau (2009).

Exhibit 6-4: Avoided Utility Emission Factors by Region

Region	Emission Factors for Utility-Generated Electricity[a] (MTCO$_2$e/Million Btu of Electricity Delivered)
National Average	0.218
Pacific	0.145
Mountain	0.227
West-North Central	0.296
West-South Central	0.178
East-North Central	0.280
East-South Central	0.250
New England	0.162
Middle Atlantic	0.214
South Atlantic	0.230

[a] Includes transmission and distributions losses, which are assumed to be 7% (EIA, 2012).

Exhibit 6-5: Avoided Utility GHG Emissions at Mass Burn Facilities by Region (MTCO$_2$e/Short Ton of Material Combusted)

Material Combusted	National Average	Pacific	Mount-ain	West-North Central	West-South Central	East-North Central	East-South Central	New England	Middle Atlantic	South Atlantic
Aluminum Cans	-0.03	-0.02	-0.03	-0.04	-0.02	-0.03	-0.03	-0.02	-0.03	-0.03
Aluminum Ingot	-0.03	-0.02	-0.03	-0.04	-0.02	-0.03	-0.03	-0.02	-0.03	-0.03
Steel Cans	-0.02	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02
Copper Wire	-0.02	-0.01	-0.02	-0.03	-0.02	-0.03	-0.02	-0.02	-0.02	-0.02
Glass	-0.02	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02	-0.01	-0.02	-0.02
HDPE	1.55	1.03	1.62	2.11	1.27	2.00	1.78	1.15	1.53	1.64
LDPE	1.55	1.03	1.61	2.10	1.26	1.99	1.77	1.14	1.52	1.63
PET	0.82	0.55	0.86	1.12	0.67	1.06	0.95	0.61	0.81	0.87
LLDPE	1.55	1.03	1.62	2.11	1.27	1.99	1.78	1.15	1.52	1.63
PP	1.55	1.03	1.62	2.11	1.27	1.99	1.78	1.15	1.52	1.63
PS	1.40	0.93	1.46	1.90	1.14	1.80	1.61	1.04	1.37	1.47

Material Combusted	National Average	Pacific	Mount-ain	West-North Central	West-South Central	East-North Central	East-South Central	New England	Middle Atlantic	South Atlantic
PVC	0.61	0.41	0.64	0.83	0.50	0.79	0.70	0.45	0.60	0.65
PLA	0.65	0.43	0.68	0.88	0.53	0.84	0.75	0.48	0.64	0.69
Corrugated Containers	0.55	0.36	0.57	0.74	0.45	0.70	0.63	0.41	0.54	0.58
Magazines/Third-Class Mail	0.41	0.27	0.43	0.56	0.33	0.53	0.47	0.30	0.40	0.43
Newspaper	0.62	0.41	0.64	0.84	0.50	0.79	0.71	0.46	0.61	0.65
Office Paper	0.53	0.35	0.55	0.72	0.43	0.68	0.61	0.39	0.52	0.56
Phone Books	0.62	0.41	0.64	0.84	0.50	0.79	0.71	0.46	0.61	0.65
Textbooks	0.53	0.35	0.55	0.72	0.43	0.68	0.61	0.39	0.52	0.56
Dimensional Lumber	0.65	0.43	0.67	0.88	0.53	0.83	0.74	0.48	0.63	0.68
Medium-Density Fiberboard	0.65	0.43	0.67	0.88	0.53	0.83	0.74	0.48	0.63	0.68
Food Waste	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Food Waste (meat only)	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Food Waste (non-meat)	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Beef	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Poultry	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Grains	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Bread	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Fruits and Vegetables	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Dairy Products	0.18	0.12	0.19	0.25	0.15	0.24	0.21	0.14	0.18	0.19
Yard Trimmings	0.22	0.14	0.23	0.30	0.18	0.28	0.25	0.16	0.21	0.23
Mixed MSW	0.39	0.26	0.41	0.53	0.32	0.50	0.45	0.29	0.38	0.41
Carpet	0.59	0.39	0.62	0.80	0.48	0.76	0.68	0.44	0.58	0.62
Personal Computers	0.12	0.08	0.12	0.16	0.10	0.15	0.14	0.09	0.12	0.13
Tires[a]	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.57
Asphalt Shingles[b]	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Vinyl Flooring	0.61	0.41	0.64	0.83	0.50	0.79	0.70	0.45	0.60	0.65
Wood Flooring	0.85	0.56	0.88	1.15	0.69	1.09	0.97	0.63	0.83	0.89

Note that the “National Average” column is also represented in column (g) of Exhibit 6-2.

[a] Assumes weighted average avoided utility GHG emissions for multiple tire combustion pathways.

[b] Assumes avoided cement kiln refinery gas combustion.

6.2.5 Avoided CO_2 Emissions Due to Steel Recycling

WARM estimates the avoided CO_2 emissions from increased steel recycling made possible by steel recovery from WTE plants for steel cans, mixed MSW, personal computers and tires. Most MSW combusted with energy recovery in the United States is combusted at WTE plants that recover ferrous metals (e.g., iron and steel).[36] Note that EPA does not credit increased recycling of nonferrous materials due to a lack of data on the proportions of those materials being recovered. Therefore, the result tends to overestimate net GHG emissions from combustion.

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[36] EPA did not consider any recovery of materials from the MSW stream that might occur before MSW is 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.

For mixed MSW, EPA estimates the amount of steel recovered per ton of mixed MSW combusted, based on (1) the amount of MSW combusted in the United States, and (2) the amount of steel recovered, post-combustion. Ferrous metals are recovered at approximately 98 percent of WTE facilities in the United States (Bahor, 2010) and at five RDF processing facilities that do not generate power on-site. These facilities recovered a total of nearly 706,000 short tons per year of ferrous metals in 2004 (IWSA, 2004). By dividing 706,000 short tons (total U.S. steel recovery at combustors) by total U.S. combustion of MSW, which is 28.5 million tons (Van Haaren al., 2010), EPA estimates that 0.02 short tons of steel are recovered per short ton of mixed MSW combusted (as a national average).

For steel cans, EPA first estimates the national average proportion of steel cans entering WTE plants that would be recovered. As noted above, approximately 98 percent of MSW destined for combustion goes to facilities with a ferrous recovery system. At these plants, approximately 90 percent of steel is recovered (Bahor, 2010). EPA multiplies these percentages to estimate the weight of steel cans recovered per ton of MSW combusted—about 0.88 tons recovered per ton combusted.

Finally, to estimate the avoided CO_2 emissions due to increased recycling of steel, EPA multiplies (1) the weight of steel recovered by (2) the avoided CO_2 emissions per ton of steel recovered. The estimated avoided CO_2 emissions results are in column (d) of Exhibit 6-6. For more information on the GHG benefits of recycling, see the Recycling and Metals chapters.

Exhibit 6-6: Avoided GHG Emissions Due to Increased Steel Recovery from MSW at WTE Facilities

(a) Material Combusted	(b) Short Tons of Steel Recovered per Short Ton of Waste Combusted (Short Tons)	(c) Avoided CO_2 Emissions per Short Ton of Steel Recovered ($MTCO_2e$/Short Ton)	(d) Avoided CO_2 Emissions per Short Ton of Waste Combusted ($MTCO_2e$/Short Ton)[a]
Aluminum Cans	–	–	–
Aluminum Ingot	–	–	–
Steel Cans	0.88	1.81	-1.60
Copper Wire	–	–	–
Glass	–	–	–
HDPE	–	–	–
LDPE	–	–	–
PET	–	–	–
LLDPE	–	–	–
PP	–	–	–
PS	–	–	–
PVC	–	–	–
PLA	–	–	–
Corrugated Containers	–	–	–
Magazines/Third-Class Mail	–	–	–
Newspaper	–	–	–
Office Paper	–	–	–
Phone Books	–	–	–
Textbooks	–	–	–
Dimensional Lumber	–	–	–
Medium-Density Fiberboard	–	–	–
Food Waste	–	–	–
Food Waste (meat only)	–	–	–
Food Waste (non-meat)	–	–	–
Beef	–	–	–
Poultry	–	–	–
Grains	–	–	–
Bread	–	–	–
Fruits and Vegetables	–	–	–

(a) Material Combusted	(b) Short Tons of Steel Recovered per Short Ton of Waste Combusted (Short Tons)	(c) Avoided CO_2 Emissions per Short Ton of Steel Recovered ($MTCO_2e$/Short Ton)	(d) Avoided CO_2 Emissions per Short Ton of Waste Combusted ($MTCO_2e$/Short Ton)[a]
Dairy Products	–	–	–
Yard Trimmings	–	–	–
Mixed Paper (general)	–	–	–
Mixed Paper (primarily residential)	–	–	–
Mixed Paper (primarily from offices)	–	–	–
Mixed Metals	–	–	–
Mixed Plastics	–	–	–
Mixed Recyclables	–	–	–
Mixed Organics	–	–	–
Mixed MSW	0.03	1.81	-0.05
Carpet	–	–	–
Personal Computers	0.25	1.81	-0.46
Clay Bricks	–	–	–
Concrete	–	–	–
Fly Ash	–	–	–
Tires	0.06	1.80	-0.10
Asphalt Concrete	–	–	–
Asphalt Shingles	–	–	–
Drywall	–	–	–
Fiberglass Insulation	–	–	–
Vinyl Flooring	–	–	–
Wood Flooring	–	–	–

– = Zero emissions.

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] The value in column (d) is a national average and is weighted to reflect 90 percent recovery at the 98 percent of facilities that recover ferrous metals.

[b] Assumes that only 68 percent of facilities that use TDF recover ferrous metals.

6.3 Results

The national average results of this analysis are shown in Exhibit 6-7. The results from the last column of Exhibit 6-1, the last two columns of Exhibit 6-2, and the last column of Exhibit 6-6 are shown in columns (b) through (e) in Exhibit 6-7. The net GHG emissions from combustion of each material at mass burn and RDF facilities are shown in columns (f) and (g), respectively. These net values represent the gross GHG emissions (column (b)), minus the avoided GHG emissions (columns (c), (d) and (e)). As stated earlier, these estimates of net GHG emissions are expressed for combustion in absolute terms, and are not values relative to another waste management option, although they must be used comparatively, as all WARM emission factors must be. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

Exhibit 6-7: Net National Average GHG Emissions from Combustion at WTE Facilities

(a)	(b)	(c)	(d)	(e)	(f = b – c – e)	(g = b – d – e)
Material Combusted	Gross GHG Emissions per Ton Combusted ($MTCO_2e$/ Short Ton)	Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities ($MTCO_2e$ / Short Ton)[a]	Avoided Utility GHG Emissions per Ton Combusted at RDF Facilities ($MTCO_2e$ / Short Ton)	Avoided CO_2 Emissions per Ton Combusted Due to Steel Recovery ($MTCO_2e$ / Short Ton)	Net GHG Emissions from Combustion at Mass Burn Facilities ($MTCO_2e$ / Short Ton)	Net GHG Emissions from Combustion at RDF Facilities ($MTCO_2e$ / Short Ton)
Aluminum Cans	0.03	-0.03	-0.02	–	0.05	0.05
Aluminum Ingot	0.03	-0.03	-0.02	–	0.05	0.05
Steel Cans	0.03	-0.02	-0.01	1.60	-1.55	-1.56
Copper Wire	0.03	-0.02	-0.02	–	0.05	0.05
Glass	0.03	-0.02	-0.02	–	0.05	0.04
HDPE	2.82	1.55	1.42	–	1.27	1.40
LDPE	2.82	1.55	1.41	–	1.27	1.41
PET	2.06	0.82	0.75	–	1.24	1.31
LLDPE	2.82	1.55	1.42	–	1.27	1.41
PP	2.82	1.55	1.42	–	1.27	1.41
PS	3.04	1.40	1.28	–	1.64	1.76
PVC	1.28	0.61	0.56	–	0.67	0.72
PLA	0.03	0.65	0.59	–	-0.62	-0.57
Corrugated Containers	0.06	0.55	0.50	–	-0.48	-0.44
Magazines/Third-Class Mail	0.06	0.41	0.37	–	-0.35	-0.31
Newspaper	0.06	0.62	0.56	–	-0.55	-0.50
Office Paper	0.06	0.53	0.48	–	-0.47	-0.42
Phone Books	0.06	0.62	0.56	–	-0.55	-0.50
Textbooks	0.06	0.53	0.48	–	-0.47	-0.42
Dimensional Lumber	0.06	0.65	0.59	–	-0.58	-0.53
Medium-Density Fiberboard	0.06	0.65	0.59	–	-0.58	-0.53
Food Waste	0.06	0.18	0.17	–	-0.12	-0.10
Food Waste (meat only)	0.06	0.18	0.17	–	-0.12	-0.10
Food Waste (non-meat)	0.06	0.18	0.17	–	-0.12	-0.10
Beef	0.06	0.18	0.17	–	-0.12	-0.10
Poultry	0.06	0.18	0.17	–	-0.12	-0.10
Grains	0.06	0.18	0.17	–	-0.12	-0.10
Bread	0.06	0.18	0.17	–	-0.12	-0.10
Fruits and Vegetables	0.06	0.18	0.17	–	-0.12	-0.10
Dairy Products	0.06	0.18	0.17	–	-0.12	-0.10
Yard Trimmings	0.06	0.22	0.20	–	-0.15	-0.13
Grass	0.06	0.22	0.20	–	-0.15	-0.13
Leaves	0.06	0.22	0.20	–	-0.15	-0.13
Branches	0.06	0.22	0.20	–	-0.15	-0.13
Mixed Paper (general)[b]	0.06	0.55	NA	–	-0.49	-0.44
Mixed Paper (primarily residential)[b]	0.06	0.55	NA	–	-0.48	-0.44

(a) Material Combusted	(b) Gross GHG Emissions per Ton Combusted ($MTCO_2e$/ Short Ton)	(c) Avoided Utility GHG Emissions per Ton Combusted at Mass Burn Facilities ($MTCO_2e$ / Short Ton)[a]	(d) Avoided Utility GHG Emissions per Ton Combusted at RDF Facilities ($MTCO_2e$ / Short Ton)	(e) Avoided CO_2 Emissions per Ton Combusted Due to Steel Recovery ($MTCO_2e$ / Short Ton)	(f = b – c – e) Net GHG Emissions from Combustion at Mass Burn Facilities ($MTCO_2e$ / Short Ton)	(g = b – d – e) Net GHG Emissions from Combustion at RDF Facilities ($MTCO_2e$ / Short Ton)
Mixed Paper (primarily from offices)[b]	0.06	0.51	NA	–	-0.44	-0.40
Mixed Metals	0.03	-0.02	NA	1.04	-0.99	-1.06
Mixed Plastics	2.36	1.11	NA	–	1.25	1.36
Mixed Recyclables	0.13	0.51	NA	0.04	-0.42	-0.38
Mixed Organics	0.06	0.20	NA	–	-0.14	-0.12
Mixed MSW	0.43	0.39	0.35	0.05	-0.01	0.02
Carpet	1.69	0.59	0.54	–	1.10	1.15
Personal Computers	0.41	0.12	0.11	0.46	-0.17	-0.16
Clay Bricks	NA	NA	NA	NA	NA	NA
Concrete	NA	NA	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA	NA	NA
Tires[c]	2.22	1.57	1.57	0.13	0.52	0.52
Asphalt Concrete	NA	NA	NA	NA	NA	NA
Asphalt Shingles	0.72	1.05[m]	1.05[m]	–	-0.34	-0.34
Drywall	NA	NA	NA	NA	NA	NA
Fiberglass Insulation	NA	NA	NA	NA	NA	NA
Vinyl Flooring	0.31	0.61	0.56	–	-0.30	-0.25
Wood Flooring	0.08	0.85	0.64	–	-0.76	-0.55

Note that totals may not sum due to independent rounding, and more digits may be displayed than are significant.

[a] The values in this column represent the national average avoided utility GHG emissions. WARM also allows users to use region-specific avoided utility emissions, which are contained in Exhibit 6-5.

[b] The summary values for mixed paper are based on the proportions of the four paper types (corrugated containers, magazines/third-class mail, newspaper and office paper) that constitute the different “mixed paper” definitions.

[c] Tires used as TDF substitute for coal in cement kilns and utility boilers and as a substitute for natural gas, coal and biomass in pulp and paper facilities.

In the Excel version of WARM, the user can select the state where the waste is being disposed of to determine the combustion emissions based on regional avoided utility emission factors. This functionality is not available in the online version of WARM, which only allows for national average emissions calculations.

Net GHG emissions are estimated to be negative for all biogenic sources of carbon (paper and wood products, organics) because CO_2 emissions from these sources are not counted, as discussed earlier.

As shown in Exhibit 6-7, combustion of plastics results in substantial net GHG emissions. This result is primarily because of the high content of non-biomass carbon in plastics. Also, when combustion of plastics results in electricity generation, the utility carbon emissions avoided (due to displaced utility fossil fuel combustion) are much lower than the carbon emissions from the combustion of plastics. This result is largely due to the lower system efficiency of WTE plants compared with electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions for steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants. Combustion of mixed MSW results in slightly negative GHG emissions because of the high proportion of biogenic carbon and steel.

6.4 Limitations

The certainty of the analysis presented in this chapter is limited by the reliability of the various data elements used. The most significant limitations are as follows:

- Combustion system efficiency of WTE plants may be improving. If efficiency improves, more utility CO_2 will be displaced per ton of waste combusted (assuming no change in utility emissions per kWh), and the net GHG emissions from combustion of MSW will decrease.
- Data for the RDF analysis were provided by the Minnesota Office of Environmental Assistance and were obtained from a single RDF processing facility and a separate RDF combustion facility. Research indicates that each RDF processing and combustion facility is different. For example, some RDF combustion facilities may generate steam for sale off-site, which can affect overall system efficiency. In addition, the amount of energy required to process MSW into RDF and the amount of energy used to operate RDF combustion facilities can be difficult to quantify and can vary among facilities on daily, seasonal and annual bases. This is one of the reasons that RDF factors are not included in WARM.
- The reported ranges for N_2O emissions were broad. In some cases, the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. Thus, the average value used for mixed MSW and for all MSW components should be interpreted as approximate values.
- For mixed MSW, the study assumes that all carbon in textiles is from synthetic fibers derived from petrochemicals (whereas, in fact, some textiles are made from cotton, wool and other natural fibers). Because EPA assumed that all carbon in textiles is non-biogenic, all of the CO_2 emissions from combustion of textiles as GHG emissions were counted. This assumption will slightly overstate the net GHG emissions from combustion of mixed MSW, but the magnitude of the error is small because textiles represent only a small fraction of the MSW stream. Similarly, the MSW category of “rubber and leather” contains some biogenic carbon from leather and natural rubber. By not considering this small amount of biogenic carbon, the analysis slightly overstates the GHG emissions from MSW combustion.
- Because the makeup of a given community’s mixed MSW may vary from the national average, the energy content also may vary from the national average energy content used in this analysis. For example, MSW from communities with a higher- or lower-than-average recycling rate may have a different energy content, and MSW with more than the average proportion of dry leaves and branches will have a higher energy content.
- 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 for aluminum cans (i.e., close 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.

- This analysis uses the “non-baseload” emission factors for electricity as the proxy for fuel displaced at the margin when WTE plants displace utility electricity. These non-baseload emission factors vary depending on the state where the waste is assumed to be combusted. If some other fuel or mix of fuels is displaced at the margin (e.g., a more coal-heavy fuel mix), the avoided utility CO_2 would be different.

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7 LANDFILLING

This chapter presents an overview of landfilling as a waste management strategy in relation to the development of material-specific emission factors for EPA's Waste Reduction Model (WARM). Estimates of the net greenhouse gas (GHG) emissions from landfilling most of the materials considered in WARM and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables and mixed municipal solid waste (MSW)) are included in the chapter.

7.1 A Summary of the GHG Implications of Landfilling

When food waste, yard trimmings, paper and wood are landfilled, anaerobic bacteria degrade the materials, producing methane (CH_4) and carbon dioxide (CO_2). CH_4 is counted as an anthropogenic GHG because, even if it is derived from sustainably harvested biogenic sources, degradation would not result in CH_4 emissions if not for deposition in landfills. The CO_2 is not counted as a GHG because is it considered part of the natural carbon cycle of growth and decomposition; for more information, see the text box on biogenic carbon in the Introduction & Background chapter. The other materials in WARM either do not contain carbon or do not biodegrade measurably in anaerobic conditions, and therefore do not generate any CH_4.

In addition to carbon emissions, some of the carbon in these materials (i.e., food waste, yard trimmings, paper and wood) is stored in the landfill because these materials are not completely decomposed by anaerobic bacteria. Because this carbon storage would not normally occur under natural conditions (virtually all of the biodegradable material would degrade to CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic sink. However, carbon in plastics and rubber that remains in the landfill is not counted as stored carbon because it is of fossil origin. Fossil carbon (e.g., petroleum, coal) is already considered "stored" in its natural state; converting it to plastic or rubber and putting it in a landfill only moves the carbon from one storage site to another.

EPA developed separate estimates of emissions from (1) landfills without gas recovery systems, (2) those that flare CH_4, (3) those that combust CH_4 for energy recovery, and (4) the national average mix of these three categories. The national average emission estimate accounts for the extent to which CH_4 will not be managed at some landfills, flared at some landfills, and combusted onsite for energy recovery at others.[37] The assumed mix of the three landfill categories that make up the national average for all material types are presented in Exhibit 7-1. These estimates are based on the amount of CH_4 recovered by U.S. landfills, as cited in the *Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2012* (EPA 2014b). WARM assumes that construction and demolition landfills do not flare or collect CH_4.

Exhibit 7-1: Percentage of CH_4 Generated from Each Type of Landfill

Material/Product	Percentage of CH_4 from Landfills without LFG Recovery	Percentage of CH_4 from Landfills with LFG Recovery and Flaring	CH_4 from Landfills with LFG Recovery and Electricity Generation (%)
Construction and Demolition Materials	100%	–	–
All Other Materials	18%	38%	44%

– = Zero Emissions.

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[37] Although gas from some landfills is piped to an offsite power plant and combusted there, for the purposes of WARM, the simplifying assumption was that all gas for energy recovery was combusted onsite. This assumption was made due to the lack of information about the frequency of offsite power generation, piping distances and losses from pipelines.

7.2 Calculating the GHG Impacts of Landfilling

The landfilling emission factors are made up of the following components:

1. CH_4 emissions from anaerobic decomposition of biogenic carbon compounds;
2. Transportation CO_2 emissions from landfilling equipment;
3. Biogenic carbon stored in the landfill; and
4. CO_2 emissions avoided through landfill gas-to-energy projects.

As mentioned above, WARM does not calculate CH_4 emissions, stored carbon or CO_2 avoided for materials containing only fossil carbon (e.g., plastics, rubber). These materials have net landfilling emissions that are very low because they include only the transportation-related emissions from landfilling equipment. Some materials (e.g., newspaper and dimensional lumber) result in net storage (i.e., carbon storage exceeds CH_4 plus transportation energy emissions) at all landfills, regardless of whether gas recovery is present, while others (e.g., food waste) result in net emissions regardless of landfill gas collection and recovery practices. Whether the remaining materials result in net storage or net emissions depends on the landfill gas recovery scenario.

7.2.1 Carbon Stocks and Flows in Landfills

Exhibit 7-2 shows the carbon flows within a landfill system. Carbon entering the landfill can have one of several fates: exit as CH_4, exit as CO_2, exit as volatile organic compounds (VOCs), exit dissolved in leachate, or remain stored in the landfill.[38]

After entering landfills, a portion of the biodegradable material decomposes and eventually is transformed into landfill gas and/or leachate. Aerobic bacteria initially decompose the waste until the available oxygen is consumed. This stage usually lasts less than a week and is followed by the anaerobic acid state, in which carboxylic acids accumulate, the pH decreases, and some cellulose and hemicellulose decomposition occurs. Finally, during the methanogenic state, bacteria further decompose the biodegradable material into CH_4 and CO_2.

The rate of decomposition in landfills is affected by a number of factors, including: (1) waste composition; (2) factors influencing microbial growth (moisture, available nutrients, pH, temperature); and (3) whether the operation of the landfill retards or enhances waste decomposition. Most studies have shown that the amount of moisture in the waste, which can vary widely within a single landfill, is a critical factor in the rate of decomposition (Barlaz et al., 1990).

Among the research conducted on the various components of the landfill carbon system, by far the most to date has focused on the transformation of landfill carbon into CH_4. This interest has been spurred by a number of factors, including EPA's 1996 rule requiring large landfills to control landfill gas emissions (40 Code of Federal Regulations Part 60, Subparts Cc and WWW), the importance of CH_4 emissions in GHG inventories, and the market for CH_4 as an energy source. CH_4 production occurs in the methanogenic stage of decomposition, as methanogenic bacteria break down the fermentation products from earlier decomposition processes. Since CH_4 emissions result from waste decomposition, the quantity and duration of the emissions is dependent on the same factors that influence waste degradability (e.g., waste composition, moisture). The CH_4 portion of each material type's emission factor is discussed further in section 7.2.2.

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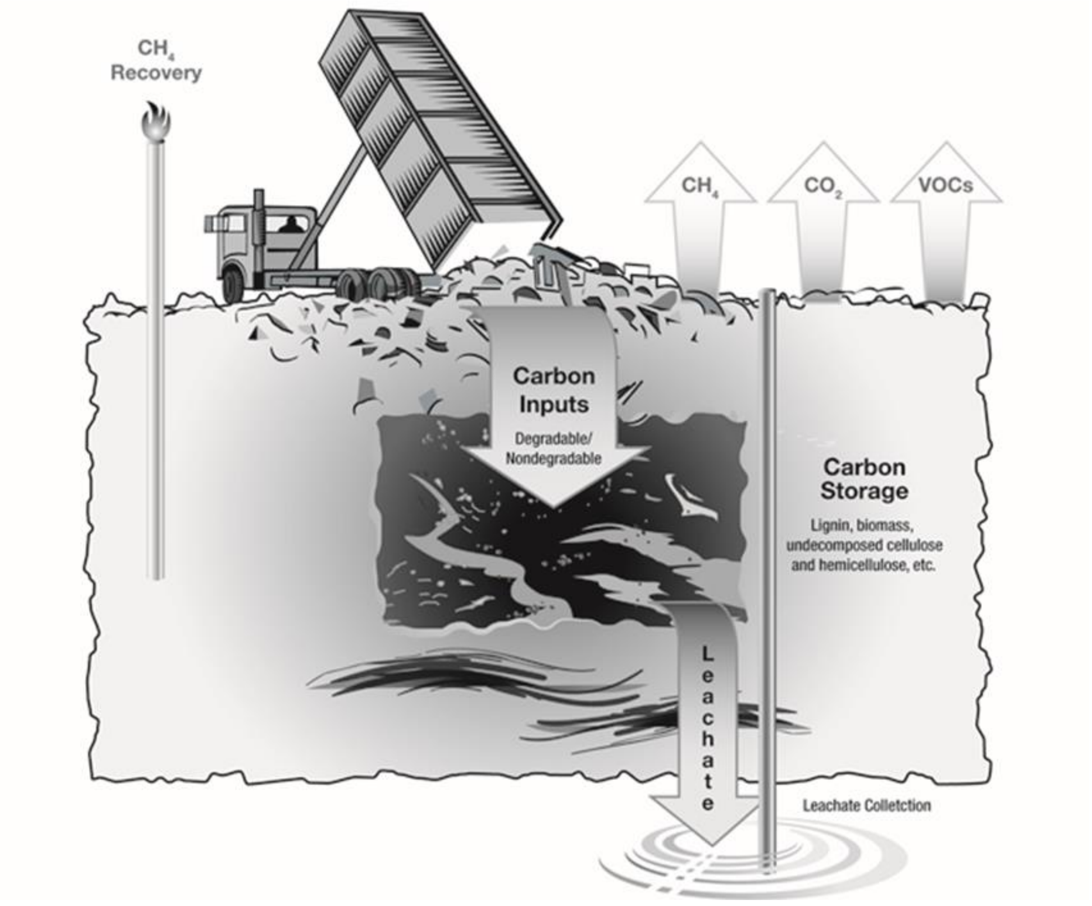
[38] The exhibit and much of the ensuing discussion are taken directly from Freed et al. (2004).

Carbon dioxide is produced in the initial aerobic stage and in the anaerobic acid stage of decomposition. However, relatively little research has been conducted to quantify CO_2 emissions during these stages. Emissions during the aerobic stage are generally assumed to be a small proportion of total organic carbon inputs, and a screening-level analysis indicates that less than 1 percent of carbon is likely to be emitted through this pathway (Freed et al., 2004). Once the methanogenic stage of decomposition begins, landfill gas *as generated* is composed of approximately 50 percent CH_4 and 50 percent CO_2 (Bingemer and Crutzen, 1987). However, landfill gas *as collected* generally has a higher CH_4 concentration than CO_2 concentration (sometimes as much as a 60 percent: 40 percent ratio), because some of the CO_2 is dissolved in the leachate as part of the carbonate system ($CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- \leftrightarrow CO_3^{2-}$).

Exhibit 7-2: Landfill Carbon Mass Balance



Source: Freed et al. (2004).

To date, very little research has been conducted on the role of VOC emissions in the landfill carbon mass balance. Given the thousands of compounds entering the landfill environment, tracking the biochemistry by which these compounds ultimately are converted to VOC is a complex undertaking. Existing research indicates that ethane, limonene, *n*-decane, *p*-dichlorobenzene and toluene may be among the most abundant landfill VOCs (Eklund et al., 1998). Hartog (2003) reported non-CH_4 volatile organic compound concentrations in landfill gas at a bioreactor site in Iowa, averaging 1,700 parts per million (ppm) carbon by volume in 2001 and 925 ppm carbon by volume in 2002. If the VOC concentrations in landfill gas are generally of the order of magnitude of 1,000 ppm, VOCs would have a small role in the overall carbon balance, as concentrations of CH_4 and CO_2 will both be hundreds of times larger.

Leachate is produced as water percolates through landfills. Factors affecting leachate formation include the quantity of water entering the landfill, waste composition, and the degree of decomposition. Because it may contain materials capable of contaminating groundwater, leachate (and the carbon it contains) is typically collected and treated before being released to the environment, where it eventually degrades into CO_2. However, leachate is increasingly being recycled into the landfill as a means of inexpensive disposal and to promote decomposition, increasing the mass of biodegradable materials collected by the system and consequently enhancing aqueous degradation (Chan et al., 2002; Warith et al., 1999). Although a significant body of literature exists on landfill leachate formation, little research is available on the carbon implications of this process. Based on a screening analysis, Freed et al. (2004) found that loss as leachate may occur for less than 1 percent of total carbon inputs to landfills.

In mass balance terms, carbon storage can be characterized as the carbon that remains after accounting for the carbon exiting the system as landfill gas or dissolved in leachate. On a dry weight basis, municipal refuse contains 30–50 percent cellulose, 7–12 percent hemicellulose and 15–28 percent lignin (Hilger and Barlaz, 2001). Although the degradation of cellulose and hemicellulose in landfills is well documented, lignin does not degrade to a significant extent under anaerobic conditions (Colberg, 1988). Landfills in effect store some of carbon from the cellulose and hemicellulose and all of the carbon from the lignin that is buried initially. The amount of storage will vary with environmental conditions in the landfill; pH and moisture content have been identified as the two most important variables controlling decomposition (Barlaz et al, 1990). These variables and their effects on each material type's emission factor are discussed further below.

7.2.2 Estimating Emissions from Landfills

As discussed in section 7.2.1, when biodegradable materials such as wood products, food wastes and yard trimmings are placed into a landfill, a fraction of the carbon within these materials degrades into CH_4 emissions. The quantity and timing of CH_4 emissions released from the landfill depends upon three factors: (1) how much of the original material decays into CH_4, (2) how readily the material decays under different landfill moisture conditions, and (3) landfill gas collection practices. This section describes how these three factors are addressed in WARM.

7.2.2.1 Methane Generation and Landfill Carbon Storage

The first step is to determine the amount of carbon contained in degradable materials that is emitted from the landfill as CH_4, and the amount that remains in long-term storage within the landfill. Although a large body of research exists on CH_4 generation from mixed solid wastes, only a few investigators—most notably Dr. Morton Barlaz and colleagues at North Carolina State University—have measured the behavior of specific waste wood, paper, food waste and yard trimming components. The results of their experiments yield data on the inputs—specifically the initial carbon contents, CH_4 generation and carbon stored—that are required for calculating material-specific emission factors for WARM.

Barlaz (1998) developed a series of laboratory experiments designed to measure biodegradation of these materials in a simulated landfill environment, in conditions designed to promote decomposition (i.e., by providing ample moisture and nutrients). Each waste component (e.g., grass, branches, leaves, paper) was dried; analyzed for cellulose, hemicellulose and lignin content; weighed; placed in two-liter plastic containers (i.e., reactors); and allowed to decompose anaerobically under moist conditions (Eleazer et al., 1997). At the end of the experiment, the contents of the reactors were dried, weighed and analyzed for cellulose, hemicellulose, lignin and (in the case of food waste only) protein content. The carbon in these residual components is assumed to represent carbon that would remain undegraded over the long term in landfills: that is, it would be stored.

Based on these components, Dr. Barlaz estimated the initial biogenic carbon content of each waste material as a percent of dry matter. For some materials, the carbon content estimates have been updated to reflect more recent studies or to better reflect changes in material composition in recent years. Exhibit 7-3 shows the initial carbon contents of the wastes analyzed by Barlaz (1998) and Wang et al. (2011).

Exhibit 7-3: Initial Biogenic Carbon Content of Materials Tested in Barlaz (1998) and Wang et al. (2011)

Material	Initial Biogenic Carbon Content, % of Dry Matter	Source
Corrugated Containers	47%	Barlaz (1998)
Newspaper	49%	Barlaz (1998)
Office Paper	32%	Barlaz (1998)[a]
Coated Paper	34%	Barlaz (1998)
Food Waste	51%	Barlaz (1998)
Grass	45%	Barlaz (1998)
Leaves	46%	Barlaz (1998)
Branches	49%	Barlaz (1998)
Mixed MSW	42%	Barlaz (1998)
Gypsum Board	5%	Barlaz (1998)
Dimensional Lumber	49%	Wang et al. (2011)
Medium-density Fiberboard	44%	Wang et al. (2011)
Wood Flooring[b]	46%	Wang et al. (2011)

[a] Based on 2014 discussions with Dr. Morton Barlaz, the carbon content of office paper has been updated to account for an average calcium carbonate ($CaCO_3$) content of 20 percent in office paper in recent years.

[b] Based on an average of carbon content values for red oak and plywood in Wang et al. (2011).

The principal stocks and flows in the landfill carbon balance are:

- Initial carbon content (Initial C);
- Carbon output as CH_4 (CH_4^C);
- Carbon output as CO_2 (CO_2^C); and
- Residual carbon (i.e., landfill carbon storage, LF^C).

The initial carbon content, along with the other results from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments are used to estimate each material type's emission factor in WARM. The Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments did not capture CO_2 emissions in the carbon balance; however, in a simple system where the only carbon fates are CH_4, CO_2 and carbon storage, the carbon balance can be described as

$$CH_4^C + CO_2^C + LF^C = \text{Initial C}$$

If the only decomposition is anaerobic, then $CH_4^C = CO_2^C$.[39] Thus, the carbon balance can be expressed as

$$= \text{Initial C}2\times CH_4^C+LF^C=\text{Initial C}$$

Exhibit 7-4 shows the measured experimental values, in terms of the percentage of initial carbon for each of the materials analyzed, the implied landfill gas yield, and the sum of outputs as a percentage of initial carbon (Barlaz, 1998; Wang et al., 2013; Wang et al., 2011; Levis et al., 2013). As the sum of the outputs shows, the balance between carbon outputs and carbon inputs generally was not perfect. This imbalance is attributable to measurement uncertainty in the analytic techniques.

Exhibit 7-4: Experimental Values for CH_4 Yield and Carbon Storage[a]

(a) Material	(b) Measured CH_4 Yield as a % of Initial Carbon	(c) Implied Yield of Landfill Gas (CH_4+CO_2) as a Proportion of Initial Carbon (c = 2 × b)	(d) Measured Proportion of Initial Carbon Stored	(e) Output as % of Initial Carbon (e = c + d)
Corrugated Containers	17%	35%	55%	90%
Newspaper	8%	16%	85%	100%
Office Paper	29%	58%	12%	70%
Coated Paper	13%	26%	79%	100%
Food Waste	32%	63%	16%	79%
Grass	17%	34%	53%	88%
Leaves	5%	10%	85%	95%
Branches	7%	14%	77%	91%
Mixed MSW	16%	32%	19%	50%
Gypsum Board	0%	0%	55%	55%
Dimensional Lumber	1%	3%	88%	91%
Medium-density Fiberboard	1%	1%	84%	85%
Wood Flooring	2%	5%	99%	100%

[a] The CH_4, CO_2, and carbon stored from these experiments represents only the biogenic carbon in each material type.

To calculate the WARM emission factors, adjustments were made to the measured values so that exactly 100 percent of the initial carbon would be accounted for. After consultation with Dr. Barlaz, the following approach was adopted to account for exactly 100 percent of the initial carbon:

- For most materials where the total carbon output is less than the total carbon input (e.g., corrugated containers, office paper, food waste, grass, leaves), the "missing" carbon was assumed to be emitted as equal quantities of CH_4^C and CO_2^C. In these cases (corrugated containers, office paper, food waste, grass, leaves), the CH_4^C was increased with respect to the measured values as follows:

$$\frac{\text{Initial C-LF}^C}{2}=CH_4^C$$

This calculation assumes that $CO_2^C = CH_4^C$. In essence, the adjustment approach was to increase landfill gas production, as suggested by Dr. Barlaz.

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[39] The emissions ratio of CH_4 to CO_2 is 1:1 for carbohydrates (e.g., cellulose, hemicellulose). For proteins, the ratio is 1.65 CH_4 per 1.55 CO_2; for protein, it is $C_{3.2}H_5ON_{0.86}$ (Barlaz et al., 1989). Given the predominance of carbohydrates, for all practical purposes, the overall ratio is 1:1.

- For coated paper, newspaper, and wood flooring, where carbon outputs were greater than initial carbon, the measurements of initial carbon content and CH_4 mass were assumed to be accurate. Here, the adjustment approach was to decrease carbon storage. Thus, landfill carbon storage was calculated as the residual of initial carbon content minus ($2 \times CH_4^C$).

  The resulting adjusted CH_4 yields and carbon storage are presented in Exhibit 7-5.

- For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH_4 yield as a percentage of initial carbon was considered to be the most realistic estimate for methane yield, based on consultation with Dr. Barlaz. Therefore, no adjustment was made for these materials.

  - For gypsum board, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by Dr. Barlaz. As such, methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0% in WARM.

Exhibit 7-5: Adjusted CH_4 Yield and Carbon Storage by Material Type

Material	Adjusted Yield of CH_4 as Proportion of Initial Carbon	Adjusted Carbon Storage as Proportion of Initial Carbon
Corrugated Containers[a]	22%	55%
Newspaper[b]	8%	84%
Office Paper[a]	44%	12%
Coated Paper[b]	13%	74%
Food Waste[a]	42%	16%
Grass[a]	23%	53%
Leaves[a]	8%	85%
Branches[c]	7%	77%
Mixed MSW[c]	16%	19%
Gypsum Board[d]	0%	55%
Dimensional Lumber[c]	1%	88%
Medium-density Fiberboard[c]	1%	84%
Wood Flooring[b]	2%	95%

[a] CH_4 yield is adjusted to account for measurement uncertainty in the analytic techniques to measure these quantities. For corrugated containers, office paper, food waste, grass, leaves, the yield of CH_4 was increased such that the proportion of initial carbon emitted as landfill gas (i.e., $2 \times CH_4$) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

[b] For coated paper, newspaper, and wood flooring, the proportion of initial carbon that is stored in the landfill is decreased such that the proportion of initial carbon emitted as landfill gas (i.e., $2 \times CH_4$) plus the proportion that remains stored in the landfill is equal to 100% of the initial carbon.

[c] For branches, dimensional lumber, medium-density fiberboard, and mixed MSW, the measured CH_4 yield as a percentage of initial carbon and measured proportion of initial carbon stored shown in columns b and d, respectively of Exhibit 7-4 was considered to be the most realistic estimate for methane yield. Therefore, these values were not adjusted.

[d] For gypsum board, the sulfate in wallboard is estimated to reduce methane generation; thus, the methane yield from gypsum board is likely to be negligible and is therefore adjusted to 0%.

Dr. Barlaz's experiment did not test all of the biodegradable material types in WARM. EPA identified proxies for the remaining material types for which there were no experimental data. Magazines and third-class mail placed in a landfill were assumed to contain a mix of coated paper and office paper and were therefore assumed to behave like an average of those two materials. Similarly, phone books and textbooks were assumed to behave in the same way as newspaper and office paper, respectively. Results from two studies by Wang et al. were used for dimensional lumber, medium-density fiberboard, and wood flooring (Wang et al., 2013; Wang et al., 2011). For wood flooring, the ratio of dry-to-wet weight was adjusted to more accurately represent the moisture content of wood lumber (Staley and Barlaz, 2009). Drywall was assumed to have characteristics similar to gypsum board. Exhibit 7-6 shows the landfill CH_4 emission factors and the final carbon storage factors for all applicable material types.

Exhibit 7-6: CH_4 Yield for Solid Waste Components

Material/Product	Initial Biogenic Carbon Content	Adjusted Yield of CH_4 as Proportion Of Initial Carbon	Final (Adjusted) CH_4 Generation, $MTCO_2e$/Dry Metric Ton[a]	Final (Adjusted) CH_4 Generation ($MTCO_2e$ /Wet Short Ton)[b]
Corrugated Containers	47%	22%	3.48	2.62
Magazines/Third-Class Mail	33%	28%	3.11	2.59
Newspaper	49%	8%	1.33	1.05
Office Paper	32%	44%	4.71	3.89
Phone Books	49%	8%	1.33	1.05
Textbooks	32%	44%	4.71	3.89
Dimensional Lumber	49%	1%	0.24	0.17
Medium-Density Fiberboard	44%	1%	0.08	0.06
Food Waste	51%	42%	7.13	1.75
Yard Trimmings				
Grass	45%	23%	3.48	0.57
Leaves	46%	8%	1.17	0.65
Branches	49%	7%	1.12	0.85
Mixed MSW	42%	16%	2.23	1.62
Drywall	5%	0%	0	0
Wood Flooring	46%	2%	0.35	0.24

[a] Final adjusted CH_4 generation per dry metric ton is the product of the initial carbon content and the final percent carbon emitted as CH_4 multiplied by the molecular ratio of carbon to CH_4 (12/16).

[b] CH_4 generation is converted from per dry metric ton to per wet short ton by multiplying the CH_4 generation on a dry metric ton basis by (1 – the material's moisture content) and by converting from metric tons to short tons of material.

7.2.2.2 Component-Specific Decay Rates

The second factor in estimating material-specific landfill emissions is the rate at which a material decays under anaerobic conditions in the landfill. The decay rate is an important factor that influences the landfill collection efficiency described further in the next section. Although the final adjusted CH_4 yield shown in Exhibit 7-6 will eventually occur no matter what the decay rate, the rate at which the material decays influences how much of the CH_4 yield will eventually be captured for landfills with collection systems.

Recent studies by De la Cruz and Barlaz (2010) found that different materials degrade at different rates relative to bulk MSW rates of decay. For example, one short ton of a relatively inert wood material—such as lumber—will degrade slowly and produce a smaller amount of methane than food waste, which readily decays over a much shorter timeframe. Materials will also degrade faster under wetter landfill conditions. Consequently, the rate at which CH_4 emissions are generated from decaying material in a landfill depends upon: (1) the type of material placed in the landfill, and (2) the moisture conditions of the landfill.

De la Cruz and Barlaz (2010) measured component-specific decay rates in laboratory experiments that were then scaled to field-level, component-specific decay rates based on mixed MSW field-scale decay rates published in EPA (1998) guidance.

To scale the laboratory-scale, component-specific decay rate measurements to field-scale values, De la Cruz and Barlaz (2010) assumed that the weighted average decay rate for a waste mixture of the same composition as MSW would be equal to the bulk MSW decay rate. They also related a lab-scale decay rate for mixed MSW to the field-scale decay rate using a scaling factor. Using these two relationships, the authors were able to estimate field-scale decay rates for different materials based on the laboratory data. The following equations were used to estimate the component-specific decay rates:

Equation 1

$$f \times \sum_{i=1}^{n} k_{lab,i} \times (wt.fraction)_i = decay\ rate$$

Equation 2

$$k_{field,i} = f \times k_{lab,i}$$

where,

f = a correction factor to force the left side of the equation to equal the overall MSW decay rate

$k_{lab,i}$ = the component-specific decay rate calculated from lab experiments

$k_{field,i}$ = the component-specific decay rate determined for the field

i = the i^{th} waste component

Based on the results from De la Cruz and Barlaz (2010), the Excel version of WARM allows users to select different component-specific decay rates based on different assumed moisture contents of the landfill to estimate the rate at which CH_4 is emitted for each material type (or “component”). The five MSW decay rates used are:

1. k = 0.02/year (“Dry”), corresponding to landfills receiving fewer than 20 inches of annual precipitation: based values reported in EPA (2010)
2. k = 0.04/year (“Moderate”), corresponding to landfills receiving between 20 and 40 inches of annual precipitation: based values reported in EPA (2010)
3. k = 0.06/year (“Wet”), corresponding to landfills receiving greater than 40 inches of annual precipitation: based values reported in EPA (2010)
4. k = 0.12/year (“Bioreactor”), corresponding to landfills operating as bioreactors where water is added until the moisture content reaches 40 percent moisture on a wet-weight basis: based on expert judgment using values reported in Barlaz et al. (2010) and Tolaymat et al. (2010)
5. k = 0.052/year (“National Average”), corresponding to a weighted average based on the share of waste received at each landfill type: based on expert judgment using values reported in EPA (2010)

The final waste component-specific decay rates as a function of landfill moisture conditions are provided in Exhibit 7-7.

Exhibit 7-7: Component-Specific Decay Rates (yr^{-1}) by Landfill Moisture Scenario

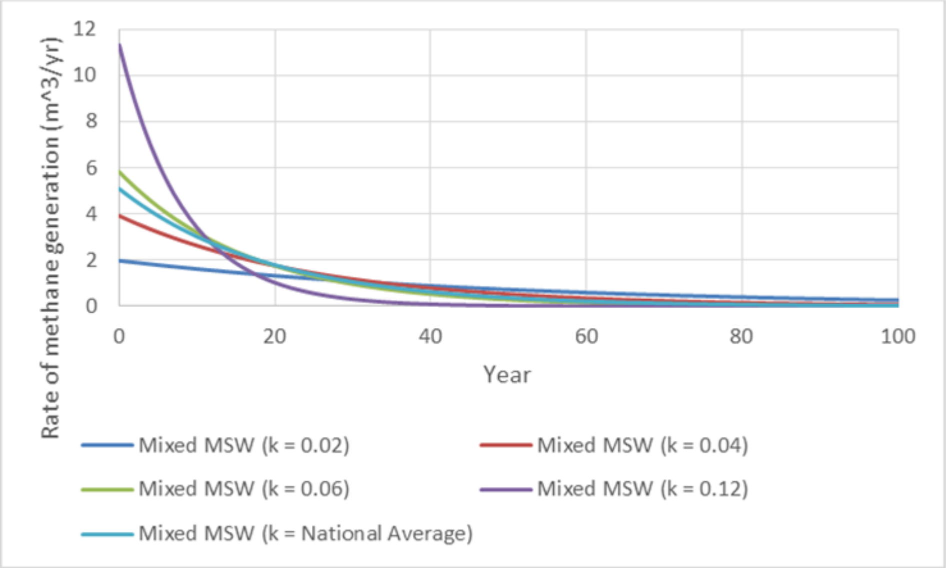
Material	Landfill Moisture Conditions				
	Dry	Moderate	Wet	Bioreactor	National Average
Corrugated Containers	0.01	0.02	0.03	0.06	0.03
Magazines/Third-Class Mail	0.06	0.12	0.18	0.37	0.16
Newspaper	0.02	0.03	0.05	0.10	0.04
Office Paper	0.01	0.03	0.04	0.09	0.04
Phone Books	0.02	0.03	0.05	0.10	0.04
Textbooks	0.01	0.03	0.04	0.09	0.04
Dimensional Lumber	0.04	0.08	0.12	0.25	0.11
Medium-Density Fiberboard	0.03	0.06	0.10	0.19	0.08
Food Waste	0.07	0.14	0.22	0.43	0.19
Yard Trimmings	0.10	0.20	0.29	0.59	0.26
Grass	0.15	0.30	0.45	0.89	0.39
Leaves	0.09	0.17	0.26	0.51	0.22
Branches	0.01	0.02	0.02	0.05	0.02
Mixed MSW	0.02	0.04	0.06	0.12	0.05
Drywall[a]	–	–	–	–	–
Wood Flooring[a]	–	–	–	–	–

– = Zero Emissions.

[a] Decay rates were not estimated since WARM assumes that the construction and demolition landfills where these materials are disposed of do not collect landfill gas.

The profile of methane emissions as materials decay in landfills over time is commonly approximated using a first-order decay methodology summarized in De la Cruz and Barlaz (2010). The CH_4 generation potential of landfilled waste decreases gradually throughout time and can be estimated using first order decomposition mathematics. The profile of methane emissions from landfills over time for mixed MSW is shown in Exhibit 7-8 as a graphic representation of the methane emissions approximated using a first-order decay equation. As Exhibit 7-8 shows, materials will degrade faster under wetter conditions in landfills (i.e., landfills whose conditions imply higher decay rates for materials).

Exhibit 7-8. Rate of Methane Generation for Mixed MSW as a Function of Decay Rate



Although in each landfill moisture scenario, the total final CH_4 yield for solid waste components (Exhibit 7-6) will eventually be emitted over time, the rate at which methane is emitted greatly depends on the decay rate. Finally, since different materials have very different methane emission profiles in landfills, the effectiveness and timing of the installation of landfill gas collection systems can greatly influence methane emissions, as discussed in the next section.

7.2.2.3 Landfill Gas Collection

WARM estimates the amount of methane that is collected by landfill gas collection equipment. In practice, the landfill gas collection system efficiency does not remain constant over the duration of gas production. Rather, the gas collection system at any particular landfill is typically expanded over time. Usually, only a small percentage (or none) of the gas produced soon after waste burial is collected, while almost all of the gas produced is collected once a final cover is installed. To provide a better estimate of gas collection system efficiency, EPA uses a Monte Carlo analysis to estimate the fraction of produced gas that is vented directly, flared and utilized for energy recovery while considering annual waste disposal and landfill operating life (Levis and Barlaz 2014).[40]

The gas collection efficiencies that WARM uses are evaluated from the perspective of a short ton of a specific material placed in the landfill at year zero. The efficiencies are calculated based on one of five moisture conditions (dry, moderate, wet, bioreactor, and national average conditions, described in section 7.2.2.2) and one of four landfill gas collection practices over a 100-year time period, which is approximately the amount of time required for 95 percent of the potential landfill gas to be produced under the “Dry” (k = 0.02/yr) landfill scenario. The final average efficiency is equal to the total CH_4 collected over 100 years divided by the total CH_4 produced over 100 years.

The combination of four different landfill gas collection scenarios and five different landfill moisture conditions means there are 20 possible landfill gas collection efficiencies possible for each material in WARM. The landfill collection efficiency scenarios are described below and the assumptions for each are shown in Exhibit 7-9:

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[40] This improved analysis of landfill gas collection was incorporated in June 2014 into WARM Version 13.

1. Typical collection – phased-in collection with an improved cover; judged to represent the average U.S. landfill, although every landfill is unique and a typical landfill is an approximation of reality.
2. Worst-case collection – the minimum collection requirements under EPA's New Source Performance Standards.
3. Aggressive collection – landfills where the operator is aggressive in gas collection relative to a typical landfill; bioreactor landfills are assumed to collect gas aggressively.
4. California regulatory scenario[41] – equivalent to landfill management practices based on California regulatory requirements.

Exhibit 7-9: WARM Gas Collection Scenario Assumptions and Efficiencies Compared to EPA AP-42 (1998) with Landfill Gas Recovery for Energy

			Landfill Gas Collection Efficiency (%) for Mixed MSW[a]				
			MSW Decay Rate (yr^{-1})				
Scenario	**Gas Collection Scenario Description**	**Gas Collection Scenario**	**0.02**	**0.04**	**0.06**	**0.12**	**National Average**
AP-42	EPA default gas collection assumption (EPA 1998 AP-42) (not modeled in WARM)	All years: 75%	75.0	75.0	75.0	75.0	75.0
1	"Typical collection", judged to represent the average U.S. landfill	Years 0–1: 0% Years 2-4: 50% Years 5–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90%	68.2	65.0	64.1	60.6	64.8
2	"Worst-case collection" under EPA New Source Performance Standards (NSPS)	Years 0-4: 0% Years 5-9: 50% Years 10–14: 75% Years 15 to 1 year before final cover: 82.5% Final cover: 90%	66.2	61.3	59.2	50.6	60.3
3	"Aggressive gas collection," typical bioreactor operation	Year 0: 0% Years 0.5-2: 50% Years 3–14: 75% Years 15 to 1 year before final cover: 82.5% Final Cover: 90%	68.6	65.8	66.3	63.9	66.4
4	"California regulatory scenario", landfill management based on California regulatory requirements	Year 0: 0% Year 1: 50% Years 2-7: 80% Years 8 to 1 year before final cover: 85% Final cover: 90%	83.6	79.5	77.4	72.9	78.8

[a] The values in this table are for landfills that recover gas for energy. In reality, a small share of gas recovered is eventually flared. The values provided in this table include both the gas recovered for energy and the small portion recovered for flaring.

The landfill gas collection efficiencies by material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions are provided in Exhibit 7-10. In addition to

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[41] This additional landfill gas collection scenario was incorporated in June 2014 into WARM Version 13 to allow WARM users to estimate and view landfill management results based on California regulatory requirements.

the gas collected, EPA also takes into account the percentage of gas that is flared, oxidized and emitted for landfills that recover gas for energy, as described in Levis and Barlaz (2014). Some of the uncollected methane is oxidized to CO_2 as it passes through the landfill cover; Levis and Barlaz (2014) adapted EPA recommendations for methane oxidation (71 FR 230, 2013) to develop the following oxidation rates at various stages of landfill gas collection:

- Without gas collection or final cover: 10 percent
- With gas collection before final cover: 20 percent
- After final cover installation: 35 percent

In the EPA recommendations, the fraction of uncollected methane that is oxidized varies with the methane flux (mass per area per time) and ranges from 10 percent to 35 percent (71 FR 230, 2013). Measurement or estimation of the methane flux is possible on a site-specific basis but requires assumptions on landfill geometry and waste density to estimate flux for a generic landfill as is represented by WARM. As such, the methane oxidation values published by EPA were used as guidance for the values listed above. Landfills with a final cover and a gas collection system in place will have a relatively low flux through the cover, which justifies the upper end of the range (35 percent) given by EPA. Similarly, landfills without a gas collection system in place will have a relatively high flux, suggesting that an oxidation rate of 10 percent is most appropriate. Landfills with a gas collection system in place but prior to final cover placement were assigned an oxidation rate of 20 percent. Based on preliminary calculations for a variety of landfill geometries and waste densities, Levis and Barlaz (2014) determined that the methane flux would justify an oxidation rate of 25 percent most but not all of the time. As such, an oxidation rate of 20 percent was adopted in WARM for landfills with gas collection before final cover (Levis and Barlaz, 2014).

For landfill gas that is not collected for energy use, EPA takes into account the percentage of landfill CH_4 that is flared (when recovery for flaring is assumed), oxidized near the surface of the landfill, and emitted. Based on analysis by Levis and Barlaz, EPA estimated the percentage of the landfill CH_4 generated that are either flared, chemically oxidized or converted by bacteria to CO_2, and emitted for each material type for each of the four landfill collection efficiency scenarios and each of the five moisture conditions (Levis and Barlaz, 2014).

Exhibit 7-10: Waste Component-Specific Collection Efficiencies by Landfill Moisture Condition with Landfill Gas Recovery for Energy

Material/ Product	Typical Landfill Scenario					Worst-Case Landfill Scenario					Aggressive Collection Landfill Scenario					California Regulations Collection Scenario				
	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.
Corrugated Containers	61%	55%	54%	55%	56%	60%	54%	53%	50%	54%	61%	56%	56%	58%	57%	66%	59%	60%	62%	61%
Magazines/ Third-Class Mail	59%	55%	52%	45%	54%	55%	46%	40%	26%	43%	61%	58%	57%	51%	57%	67%	63%	61%	54%	62%
Newspaper	62%	59%	59%	57%	59%	61%	56%	55%	49%	56%	62%	59%	61%	60%	61%	67%	64%	65%	65%	65%
Office Paper	62%	58%	58%	57%	59%	61%	56%	55%	50%	56%	62%	59%	60%	60%	60%	67%	63%	64%	65%	64%
Phone Books	62%	59%	59%	57%	59%	61%	56%	55%	49%	56%	62%	59%	61%	60%	61%	67%	64%	65%	65%	65%
Textbooks	62%	58%	58%	57%	59%	61%	56%	55%	50%	56%	62%	59%	60%	60%	60%	67%	63%	64%	65%	64%
Dimensional Lumber	62%	59%	57%	50%	58%	59%	52%	48%	35%	50%	63%	61%	60%	55%	60%	68%	66%	65%	60%	65%
Medium-Density Fiberboard	62%	60%	59%	53%	59%	60%	55%	51%	40%	53%	63%	62%	62%	58%	62%	68%	66%	67%	62%	67%
Food Waste	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Food Waste (meat only)	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Food Waste (non-meat)	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Beef	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Poultry	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Grains	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Bread	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Fruits and Vegetables	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Dairy Products	58%	53%	50%	42%	52%	53%	43%	36%	22%	40%	59%	56%	55%	49%	55%	65%	61%	59%	51%	60%
Yard Trimmings	54%	47%	44%	39%	47%	47%	37%	31%	21%	35%	55%	51%	49%	44%	50%	61%	55%	52%	45%	54%
Grass	49%	43%	39%	33%	41%	39%	27%	20%	9%	25%	51%	47%	45%	39%	46%	57%	51%	48%	38%	50%
Leaves	56%	51%	47%	40%	49%	50%	40%	33%	19%	37%	58%	54%	52%	46%	53%	64%	59%	57%	48%	58%
Branches	61%	53%	51%	52%	54%	60%	52%	51%	49%	53%	61%	54%	53%	54%	55%	65%	57%	57%	58%	59%

Material/ Product	Typical Landfill Scenario					Worst-Case Landfill Scenario					Aggressive Collection Landfill Scenario					California Regulations Collection Scenario				
	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.	Dry	Moderate	Wet	Bio-reactor	National Avg.
Mixed MSW	62%	60%	60%	57%	60%	61%	56%	55%	47%	56%	63%	61%	62%	60%	62%	67%	65%	67%	65%	66%
Gypsum[a]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wood Flooring[a]	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

– = Zero Emissions.

[a] WARM assumes that construction and demolition landfills do not collect landfill gas.

7.2.3 Emissions from Transportation to Landfills and Landfill Operation

In addition to CH_4 emissions from waste decomposition in landfills, WARM includes transportation CO_2 emissions from collecting MSW and running landfill operational equipment in each material type's landfill emission factor. The amount of diesel fuel required to collect a short ton of waste and operate the necessary equipment to manage the landfill was taken from FAL (1994). Exhibit 7-11 provides the transportation emission factor calculation.

Exhibit 7-11: Transportation CO_2 Emissions Assumptions and Calculation

Equipment	Diesel Fuel (gallons/ 10^3 lbs of MSW landfilled)	Total Energy (Btu/10^3 lb of MSW landfilled)	Total Energy (Btu/Short Ton of MSW landfilled)	MTCE (per million Btus)	Total ($MTCO_2e$/Short Ton)
Collection Vehicles	0.90	148,300	296,600	–	–
Landfill Equipment	0.70	115,400	230,800	–	–
Total	**1.60**	**263,700**	**527,400**	**0.02**	**0.04**

– = Zero Emissions.

7.2.4 Estimating Landfill Carbon Storage

The other anthropogenic fate of carbon in landfills is storage. As described in section 7.2.1, a portion of the carbon in biodegradable materials (i.e., food waste, yard trimmings, paper and wood) that is not completely decomposed by anaerobic bacteria remains stored in the landfill. This carbon storage would not normally occur under natural conditions, so it is counted as an anthropogenic sink (IPCC, 2006; Bogner et al., 2007).

The discussion in section 7.2.2 on initial carbon contents and CH_4 generation includes the measured carbon stored from the Barlaz (1998), Wang et al. (2013), Wang et al. (2011), and Levis et al. (2013) experiments. For the most part, the amount of stored carbon measured as the output during these experiments is considered the final ratio of carbon stored to total initial dry weight of each material type. For newspaper, wood flooring, and coated paper—which is used to estimate landfill characteristics for magazines and third-class mail—the amount of carbon stored is reduced because carbon outputs were *greater than* initial carbon.

To estimate the final carbon storage factor, the proportion of initial carbon stored found in Exhibit 7-5 is multiplied by the initial carbon contents in Exhibit 7-3 to obtain the ratio of carbon storage to dry weight for each material type found in Exhibit 7-12. These estimates are then converted from dry weight to wet weight and from grams to metric tons of CO_2 per wet short ton of material. The last column of Exhibit 7-12 provides the final carbon storage factors for the biodegradable solid waste components modeled in WARM.

Exhibit 7-12: Carbon Storage for Solid Waste Components

Material/Product	Ratio of Carbon Storage to Dry Weight (gram C/dry gram)	Ratio of Dry Weight to Wet Weight	Ratio of Carbon Storage to Wet Weight (gram C/wet gram)	Amount of Carbon Stored ($MTCO_2e$ per Wet Short Ton)
Corrugated Containers	0.26	0.83	0.22	0.72
Magazines/Third-Class Mail	0.15	0.92	0.13	0.45
Newspaper	0.41	0.87	0.36	1.19
Office Paper	0.04	0.91	0.04	0.12
Phone Books	0.41	0.87	0.36	1.12
Textbooks	0.04	0.91	0.04	0.12
Dimensional Lumber	0.44	0.75	0.33	1.09
Medium-Density Fiberboard	0.37	0.75	0.28	0.92
Food Waste	0.08	0.27	0.02	0.07
Yard Trimmings	0.31	0.46	0.16	0.54
Grass	0.24	0.18	0.04	0.14
Leaves	0.39	0.62	0.24	0.79
Branches	0.38	0.84	0.32	1.06
Mixed MSW	0.08	0.80	0.06	0.21
Drywall	0.03	0.94	0.02	0.08
Wood Flooring	0.44	0.75	0.33	1.09

7.2.5 Electric Utility GHG Emissions Avoided

The CH_4 component of landfill gas that is collected from landfills can be combusted to produce heat and electricity, and recovery of heat and electricity from landfill gas offsets the combustion of other fossil fuel inputs. WARM models the recovery of landfill gas for electricity generation and assumes that this electricity offsets non-baseload electricity generation in the power sector.

WARM applies non-baseload electricity emission rates to calculate the emissions offset from landfill gas energy recovery because the model assumes that incremental increases in landfill energy recovery will affect non-baseload power plants (i.e., power plants that are “demand-following” and adjust to marginal changes in the supply and demand of electricity). EPA calculates non-baseload emission rates as the average emissions rate from power plants that combust fuel and have capacity factors less than 0.8 (EPA, 2014a).

EPA estimates the avoided GHG emissions per $MTCO_2e$ of CH_4 combusted using several physical constants and data from EPA’s Landfill Methane Outreach Program and eGRID (EPA, 2013; EPA, 2014a). The mix of fuels used to produce electricity varies regionally in the United States; consequently, EPA applies a different CO_2-intensity for electricity generation depending upon where the electricity is offset. The Excel version of WARM includes CO_2-intensity emission factors for non-baseload electricity generated in nine different U.S. regions as well as a U.S.-average CO_2-intensity (EPA, 2014a). The formula used to calculate the quantity of electricity generation emissions avoided per $MTCO_2e$ of CH_4 combusted is as follows:

$$\frac{BTU_{CH4}}{H_{LFGTE}} \times a \times E_{Grid} = R$$

Where:

Btu_{CH4} = Energy content of CH_4 per $MTCO_2e$ CH_4 combusted; assumed to be 1,012 Btu per cubic foot of CH_4 (EPA, 2013), converted into Btu per $MTCO_2e$ CH_4 assuming 20 grams per cubic foot of CH_4 at standard temperature and pressure and a global warming potential of CH_4 of 21

H_{LFGTE} = Heat rate of landfill gas to energy conversion; assumed to be 11,700 Btu per kWh generated (EPA, 2013)

a = Net capacity factor of electricity generation; assumed to be 85 percent (EPA, 2013)

E_{grid} = Non-baseload CO_2-equivalent GHG emissions intensity of electricity produced at the regional or national electricity grid; values assumed for each region and U.S. average are shown in Exhibit 7-14

R = Ratio of GHG emissions avoided from electricity generation per $MTCO_2e$ of CH_4 combusted for landfill gas to energy recovery

Exhibit 7-13 shows variables in the GHG emissions offset for the national average fuel mix. The final ratio is the product of columns (a) through (h). Exhibit 7-14 shows the amount of carbon avoided per kilowatt-hour of generated electricity and the final ratio of $MTCO_2e$ avoided of utility carbon per $MTCO_2e$ of CH_4 combusted (column (g) and resulting column (i)).

Exhibit 7-13: Calculation to Estimate Utility GHGs Avoided through Combustion of Landfill CH_4 for Electricity Based on National Average Electricity Grid Mix

(a) Metric Tons CH_4/$MTCO_2e$ CH_4 Combusted	(b) Grams CH_4/Metric Ton CH_4	(c) Cubic Ft. CH_4/ Gram CH_4	(d) Btu/Cubic Ft. CH_4	(e) kWh Electricity Generated/ Btu	(f) Electricity Generation Efficiency	(g) Kg Utility CO_2 Avoided/ kWh Generated Electricity	(h) Metric Tons Avoided Utility CO_2/Kg Utility CO_2	(i) Ratio of $MTCO_2e$ Avoided Utility CO_2 per $MTCO_2e$ CH_4 Combusted
0.04	1,000,000	0.05	1,012	0.00009	0.85	0.74	0.001	0.11

Exhibit 7-14: Ratio of $MTCO_2e$ Avoided Utility Carbon per $MTCO_2e$ CH_4 Combusted by Region

Region	Kg Utility CO_2 Avoided/kWh Generated Electricity	Ratio of $MTCO_2e$ Avoided Utility C per $MTCO_2e$ CH_4
Pacific	0.49	0.07
Mountain	0.78	0.11
West-North Central	1.01	0.15
West-South Central	0.61	0.09
East-North Central	0.96	0.14
East-South Central	0.85	0.13
New England	0.55	0.08
Mid Atlantic	0.73	0.11
South Atlantic	0.78	0.12
National Average	0.74	0.11

If regional avoided utility emission factors are not employed, WARM calculates U.S.-average avoided utility emission factors based on the percent of CH_4 generated at landfills in the nation with landfill gas recovery and electricity production found in Exhibit 7-1, and assuming U.S.-average, non-baseload electricity GHG emission intensity. Exhibit 7-15 shows this calculation for each material type for the national average fuel mix.

Exhibit 7-15: Overall Avoided Utility CO$_2$ Emissions per Short Ton of Waste Material (National Average Grid Mix)

(a)	(b)	Methane from Landfills With LFG Recovery and Electricity Generation					(h)
Material	CH$_4$ Generation (MTCO$_2$e/ Wet Short Ton) (Exhibit 7-6)	(c) Percentage of CH$_4$ Recovered (Exhibit 7-10)	(d) Utility GHG Emissions Avoided per MTCO$_2$e CH$_4$ Combusted (MTCO$_2$e) (Exhibit 7-14)	(e) Percentage of CH$_4$ Recovered for Electricity Generation Not Utilized Due to LFG System "Down Time"	(f) Utility GHG Emissions Avoided (MTCO$_2$e/Wet Short Ton) ($f = b \times (1-c) \times d \times (1-e)$)	(g) Percentage of CH$_4$ From Landfills With LFG Recovery and Electricity Generation (Exhibit 7-1)	Net Avoided CO$_2$ Emissions from Energy Recovery (MTCO$_2$e/ Wet Short Ton) ($h = f \times g$)
Corrugated Containers	2.62	56%	-0.11	3%	-0.16	44%	-0.07
Magazines/ Third-Class Mail	2.59	54%	-0.11	3%	-0.15	44%	-0.06
Newspaper	1.05	59%	-0.11	3%	-0.07	44%	-0.03
Office Paper	3.89	59%	-0.11	3%	-0.24	44%	-0.11
Phone Books	1.05	59%	-0.11	3%	-0.07	44%	-0.03
Textbooks	3.89	59%	-0.11	3%	-0.24	44%	-0.11
Dimensional Lumber	0.17	58%	-0.11	3%	-0.01	44%	-0.004
Medium-Density Fiberboard	0.06	59%	-0.11	3%	-0.004	44%	-0.002
Food Waste	1.75	52%	-0.11	3%	-0.10	44%	-0.04
Yard Trimmings	0.66	47%	-0.11	3%	-0.03	44%	-0.01
Grass	0.57	41%	-0.11	3%	-0.02	44%	-0.01
Leaves	0.65	49%	-0.11	3%	-0.03	44%	-0.01
Branches	0.85	54%	-0.11	3%	-0.05	44%	-0.02
Mixed MSW	1.62	60%	-0.11	3%	-0.10	44%	-0.04
Drywall[a]	0.00	–	–	–	–	–	–
Wood Flooring[a]	0.24	–	–	–	–	–	–

– = Zero Emissions.

[a] WARM assumes that construction and demolition landfills do not collect landfill gas.

7.2.6 Net GHG Emissions from Landfilling

CH$_4$ emissions, transportation CO$_2$ emissions, carbon storage and avoided utility GHG emissions are then summed to estimate the net GHG emissions from landfilling each material type. Exhibit 7-16 shows the net emission factors for landfilling each material based on typical landfill gas collection practices, average landfill moisture conditions (i.e., for landfills receiving between 20 and 40 inches of precipitation annually), and U.S.-average non-baseload electricity grid mix.

Exhibit 7-16: Net GHG Emissions from Landfilling (MTCO₂e/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)
Aluminum Cans	–	0.04	–	–	–	0.04
Aluminum Ingot	–	0.04	–	–	–	0.04
Steel Cans	–	0.04	–	–	–	0.04
Copper Wire	–	0.04	–	–	–	0.04
Glass	–	0.04	–	–	–	0.04
HDPE	–	0.04	–	–	–	0.04
LDPE	–	0.04	–	–	–	0.04
PET	–	0.04	–	–	–	0.04
LLDPE	–	0.04	–	–	–	0.04
PP	–	0.04	–	–	–	0.04
PS	–	0.04	–	–	–	0.04
PVC	–	0.04	–	–	–	0.04
PLA	–	0.04	–	–	-1.66	-1.62
Corrugated Containers	–	0.04	1.19	-0.07	-0.72	0.45
Magazines/Third-Class Mail	–	0.04	1.14	-0.06	-0.45	0.67
Newspaper	–	0.04	0.46	-0.03	-1.19	-0.73
Office Paper	–	0.04	1.71	-0.11	-0.12	1.52
Phonebooks	–	0.04	0.46	-0.03	-1.19	-0.73
Textbooks	–	0.04	1.71	-0.11	-0.12	1.52
Dimensional Lumber	–	0.04	0.07	0.00	-1.09	-0.98
Medium-density Fiberboard	–	0.04	0.02	0.00	-0.92	-0.86
Food Waste	–	0.04	0.79	-0.04	-0.07	0.71
Food Waste (meat only)	–	0.04	0.79	-0.04	-0.07	0.71
Food Waste (non-meat)	–	0.04	0.79	-0.04	-0.07	0.71
Beef	–	0.04	0.79	-0.04	-0.07	0.71
Poultry	–	0.04	0.79	-0.04	-0.07	0.71
Grains	–	0.04	0.79	-0.04	-0.07	0.71
Bread	–	0.04	0.79	-0.04	-0.07	0.71
Fruits and Vegetables	–	0.04	0.79	-0.04	-0.07	0.71
Dairy Products	–	0.04	0.79	-0.04	-0.07	0.71
Yard Trimmings	–	0.04	0.32	-0.01	-0.54	-0.19
Grass	–	0.04	0.29	-0.01	-0.14	0.17
Leaves	–	0.04	0.30	-0.01	-0.79	-0.47
Branches	–	0.04	0.40	-0.02	-1.06	-0.65
Mixed Paper (general)	–	0.04	1.11	-0.07	-0.69	0.40
Mixed Paper (primarily residential)	–	0.04	1.09	-0.06	-0.72	0.35
Mixed Paper (primarily from offices)	–	0.04	1.22	-0.07	-0.49	0.69
Mixed Metals	–	0.04	–	–	–	0.04
Mixed Plastics	–	0.04	–	–	–	0.04
Mixed Recyclables	–	0.04	0.96	-0.05	-0.62	0.32
Mixed Organics	–	0.04	0.57	-0.03	-0.30	0.29
Mixed MSW	–	0.04	0.70	-0.04	-0.21	0.48
Carpet	–	0.04	–	–	–	0.04
Personal Computers	–	0.04	–	–	–	0.04

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)
Clay Bricks	–	0.04	–	–	–	0.04
Concrete	–	0.04	–	–	–	0.04
Fly Ash	–	0.04	–	–	–	0.04
Tires	–	0.04	–	–	–	0.04
Asphalt Concrete	–	0.04	–	–	–	0.04
Asphalt Shingles	–	0.04	–	–	–	0.04
Drywall	–	0.04	–	–	-0.08	-0.04
Fiberglass Insulation	–	0.04	–	–	–	0.04
Vinyl Flooring	–	0.04	–	–	–	0.04
Wood Flooring[a]	–	0.04	0.22	0.00	-1.09	-0.83

– = Zero Emissions.

[a] WARM assumes that construction and demolition landfills do not collect landfill gas

In WARM, emissions from landfills are dependent on the user selection of one of four different landfill scenarios (i.e., "Landfills: National Average," "Landfills Without LFG Recovery," "Landfills With LFG Recovery and Flaring," and "Landfills With LFG Recovery and Electric Generation") as described in section 1. The net landfilling emission factors for landfilling each material based on the default options in WARM (i.e., typical landfill gas collection practices, average landfill moisture conditions and U.S.-average non-baseload electricity grid mix) are shown in Exhibit 7-17.

Exhibit 7-17: Landfilling Net Emission Factors in WARM Using Default Options ($MTCO_2e$/Ton)

Material	Landfills: National Average (Exhibit 7-16)	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Aluminum Cans	0.04	0.04	0.04	0.04
Aluminum Ingot	0.04	0.04	0.04	0.04
Steel Cans	0.04	0.04	0.04	0.04
Copper Wire	0.04	0.04	0.04	0.04
Glass	0.04	0.04	0.04	0.04
HDPE	0.04	0.04	0.04	0.04
LDPE	0.04	0.04	0.04	0.04
PET	0.04	0.04	0.04	0.04
LLDPE	0.04	0.04	0.04	0.04
PP	0.04	0.04	0.04	0.04
PS	0.04	0.04	0.04	0.04
PVC	0.04	0.04	0.04	0.04
PLA	-1.62	-1.62	-1.62	-1.62
Corrugated Containers	0.45	1.68	0.46	-0.08
Magazines/Third-Class Mail	0.67	1.92	0.58	0.23
Newspaper	-0.73	-0.21	-0.73	-0.94
Office Paper	1.52	3.41	1.53	0.73
Phonebooks	-0.73	-0.21	-0.73	-0.94
Textbooks	1.52	3.41	1.53	0.73
Dimensional Lumber	-0.98	-0.90	-0.99	-1.01
Medium-density Fiberboard	-0.86	-0.83	-0.86	-0.87
Food Waste	0.71	1.54	0.64	0.43
Food Waste (meat only)	0.71	1.54	0.64	0.43

Material	Landfills: National Average (Exhibit 7-16)	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Food Waste (non-meat)	0.71	1.54	0.64	0.43
Beef	0.71	1.54	0.64	0.43
Poultry	0.71	1.54	0.64	0.43
Grains	0.71	1.54	0.64	0.43
Bread	0.71	1.54	0.64	0.43
Fruits and Vegetables	0.71	1.54	0.64	0.43
Dairy Products	0.71	1.54	0.64	0.43
Yard Trimmings	-0.19	0.10	-0.21	-0.29
Grass	0.17	0.41	0.14	0.10
Leaves	-0.47	-0.16	-0.49	-0.57
Branches	-0.65	-0.26	-0.64	-0.82
Mixed Paper (general)	0.40	1.59	0.40	-0.10
Mixed Paper (primarily residential)	0.35	1.51	0.35	-0.14
Mixed Paper (primarily from offices)	0.69	2.03	0.66	0.16
Mixed Metals	0.04	0.04	0.04	0.04
Mixed Plastics	0.04	0.04	0.04	0.04
Mixed Recyclables	0.32	1.28	0.45	-0.18
Mixed Organics	0.29	0.84	0.24	0.09
Mixed MSW	0.48	1.29	0.48	0.15
Carpet	0.04	0.04	0.04	0.04
Personal Computers	0.04	0.04	0.04	0.04
Clay Bricks	0.04	0.04	0.04	0.04
Concrete	0.04	0.04	0.04	0.04
Fly Ash	0.04	0.04	0.04	0.04
Tires	0.04	0.04	0.04	0.04
Asphalt Concrete	0.04	0.04	0.04	0.04
Asphalt Shingles	0.04	0.04	0.04	0.04
Drywall	-0.04	-0.04	-0.04	-0.04
Fiberglass Insulation	0.04	0.04	0.04	0.04
Vinyl Flooring	0.04	0.04	0.04	0.04
Wood Flooring	-0.83	-0.83	-0.83	-0.83

7.3 Limitations

The landfilling analysis has several limitations associated with it; these are discussed in the following paragraphs.

- The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate. Because of the high global warming potential of CH_4, small changes in the LFG recovery rate (for the national average landfill) could have a large effect on the net GHG impacts of landfilling each material and the ranking of landfilling relative to other MSW management options.
- The distribution of waste in place is not a perfect proxy for the distribution of ongoing waste generation destined for landfill.
- Ongoing shifts in the use of landfill cover and liner systems are likely to influence the rate of CH_4 generation and collection. As more landfills install effective covers and implement controls to

keep water and other liquids out, conditions will be less favorable for degradation of biodegradable wastes. Over the long term, these improvements may result in a decrease in CH_4 generation and an increase in carbon storage. Moreover, Dr. Barlaz believes that the CH_4 yields from his laboratory experiments are likely to be higher than CH_4 yields in a landfill, because the laboratory experiments were designed to generate the maximum amount of CH_4 possible. If the CH_4 yields from the laboratory experiments were higher than yields in a landfill, the net GHG emissions from landfilling biodegradable materials would be lower than estimated here.

- EPA assumed that once wastes are disposed in a landfill, they are never removed. In other words, it was assumed that landfills are never “mined.” A number of communities have mined their landfills—removing and combusting the waste—in order to create more space for continued disposal of waste in the landfill. To the extent that landfills are mined in the future, it is incorrect to assume that carbon stored in a landfill will remain stored. For example, if landfilled wastes are later combusted, the carbon that was stored in the landfill will be oxidized to CO_2 in the combustor.
- The estimate of avoided utility GHG emissions per unit of CH_4 combusted assumes that all landfill gas-to-energy projects produce electricity. In reality, some projects are “direct gas” projects, in which CH_4 is piped directly to the end user for use as fuel. In these cases, the CH_4 typically replaces natural gas as a fuel source. Because natural gas use is less GHG-intensive than average electricity production, direct gas projects will tend to offset fewer GHG emissions than electricity projects will—a fact not reflected in the analysis.
- For landfilling of yard trimmings (and other organic materials), EPA assumed that all carbon storage in a landfill environment is incremental to the storage that occurs in a non-landfill environment. In other words, it was assumed that in a baseline where yard trimmings are returned to the soil (i.e., in a non-landfill environment), all of the carbon is decomposed relatively rapidly (i.e., within several years) to CO_2, and there is no long-term carbon storage. To the extent that long-term carbon storage occurs in the baseline, the estimates of carbon storage reported here are overstated, and the net postconsumer GHG emissions are understated.
- The key assumptions that have not already been discussed as limitations are the assumptions used in developing “corrected” CH_4 yields for biodegradable materials in MSW. Because of the high GWP of CH_4, a small difference between estimated and actual CH_4 generation values would have a large effect on the GHG impacts of landfilling and the ranking of landfilling relative to other MSW management options.

7.4 References

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8 ENERGY IMPACTS

Other chapters in EPA's Waste Reduction Model (WARM) focus on the effects of materials management decisions on greenhouse gases (GHG). Generally, a large portion of GHG emissions is related to energy use in resource acquisition, manufacturing, transportation, and end-of-life life-cycle stages. Not all GHG emissions are related to energy, however, and the effects of GHG are not directly translatable to energy impacts. One of the benefits of WARM is to help users see results in terms of both GHG (metric tons of carbon dioxide equivalent or carbon equivalent) and energy (millions of Btu). For background, see the Background and Overview chapter.

The energy effects of materials occur in each life-cycle stage—source reduction, recycling and reuse, manufacturing—and knowledge of those effects can reduce the demand for raw materials and energy. Energy savings can also result from some waste disposal practices, including waste-to-energy combustors and landfill gas-to-energy systems.

To better understand the relationship between materials management and energy use, WARM provides energy factors for four management scenarios (source reduction, recycling, combustion, and landfilling). This chapter discusses how these energy factors affect the relationship between energy savings and GHG benefits.

8.1 Methodology for Developing Energy Factors

The WARM methodology described in the other chapters is similar; the methodology in this chapter focuses on all life-cycle components as they appear through the lens of energy consumption or savings, rather than GHG emissions. Components such as forest carbon storage and landfill carbon sequestration are not components in the energy life cycle, and thus we have not included them as energy factors. We base energy factors primarily on the amount of energy required to produce one ton of a given material. The total energy consumed is a result of direct fuel and electricity consumption associated with raw material acquisition and manufacturing, fuel consumption for transportation, and embedded energy. The other WARM chapters on specific materials describe the energy required for processing and transporting virgin and recycled materials. Although the GHG emission factors are a product of the electricity fuel mix and the carbon coefficients of fuels, our methodology in this chapter is based only on energy consumption; therefore, the energy required for the total process to make one ton of a particular material is the sum of energy consumed across all fuel types.

The total energy, or embodied energy, required to manufacture each material comprises two components: (1) process and transportation energy, and (2) embedded energy (i.e., energy content of the raw material). The first component, to process and transport a material, is conceptually straightforward; but the second component, embedded energy, is more complex. Embedded energy is the energy inherently contained in the raw materials used to manufacture a product. For example, the embedded energy of plastics comes from the petroleum needed to make them. Because petroleum has an inherent energy value, the amount of energy that is saved through plastic recycling and source reduction is directly related to the energy that could have been produced if the petroleum had been used as an energy source rather than as a raw material input. Another example is aluminum, which includes an embedded energy component. The aluminum smelting process requires a carbon anode, which is consumed during the electrolytic reduction process; carbon anodes are made from coal, itself an energy source. Additional examples are carpet and personal computers that contain embedded energy in their plastic (carpet, computers) and aluminum (computers only) components. Total energy values also include both nonrenewable and renewable sources. For example, some aspects of the paper life-cycle include renewable fuel sources that have little effect on GHG emissions.

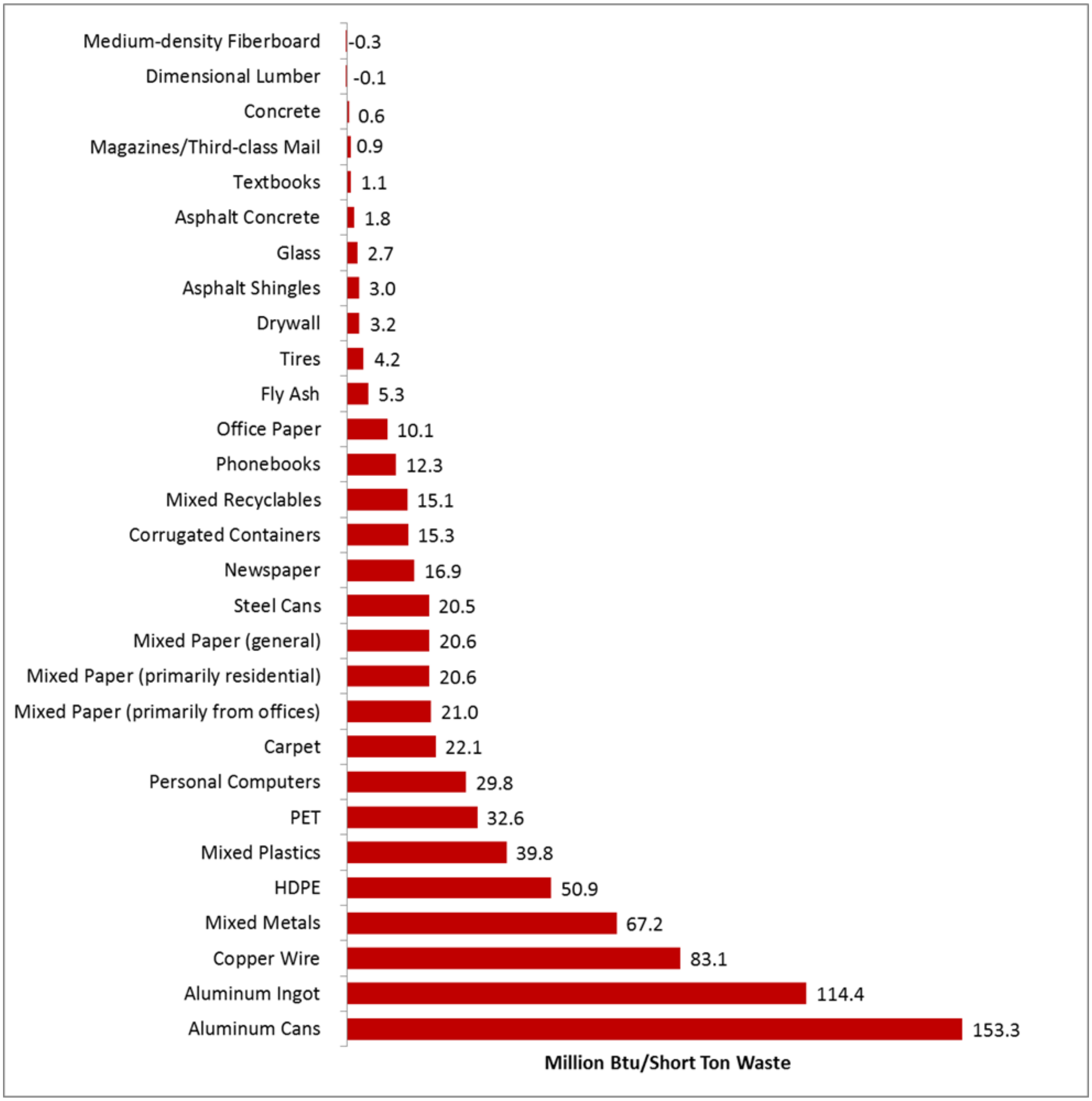
8.2 Energy Implications for Waste Management Options

This chapter discusses the life-cycle energy implications for four management scenarios. As with the GHG emission factors discussed in other chapters, negative values indicate net energy savings.

Waste reduction efforts, such as source reduction and recycling, can result in significant energy savings. Source reduction techniques, such as double-sided copying, reducing the weight of products (light-weighting), and reducing generation of food waste are, in most cases, more effective at reducing energy than recycling because source reduction significantly lowers energy consumption associated with raw material extraction and manufacturing processes.

In relating recycling to landfill disposal, the greatest energy savings per ton come from aluminum cans, as shown in Exhibit 7-1. The savings reflect the nature of aluminum production—manufacturing aluminum cans from virgin inputs is very energy intensive, whereas relatively little energy is required to manufacture cans from recycled aluminum. Significant energy savings also result from recycling carpet because the recycled material can be used to produce secondary goods, and thus avoiding the energy-intensive processes required to manufacture those secondary goods.

Exhibit 8-1: Energy Savings per Short Ton of Recycled Material (Relative to Landfilling).



Note: Positive numbers indicate energy savings from recycling; negative numbers indicate that additional energy is required, compared to landfilling. This figure excludes materials in WARM for which recycling is not a viable end-of-life management option.

Some materials, such as dimensional lumber and medium-density fiberboard, actually consume more energy when they are made from recycled inputs. For those materials, the recovery and processing of recycled material is more energy intensive than making the material from virgin inputs. Although those materials may not provide an energy benefit from recycling from the perspective of GHG emissions, recycling them is still beneficial. For more information on this topic, see Section 8.4.

8.3 Applying Energy Factors

Fuels and energy are limited and expensive resources, and it is increasingly important to examine the effects of waste management practices on energy. Organizations can use the energy factors presented in Exhibit 8-6 through Exhibit 8-11 to quantify energy savings associated with waste management practices. Organizations can use these comparisons to weigh the benefits of switching from landfilling to another waste management option. For example, researchers used the comparisons to evaluate the benefits of voluntary programs aimed at source reduction and recycling, such as EPA's WasteWise and Pay-as-You-Throw programs. Additional information about the methodology of deriving and applying these factors is available in the chapters on individual materials.

To apply the WARM energy factors, two scenarios are necessary: (1) a baseline scenario that represents current management practices (e.g., disposing of one ton of steel cans in a landfill), and (2) an alternative scenario that represents the alternative management practice (e.g., recycling a ton of steel cans).[42] With these scenarios, it is possible to calculate the amount of energy consumed or avoided in the baseline and alternative management practices and then to calculate the difference between the alternative scenario and the baseline scenario. The result represents the energy consumed or avoided that is attributable to the alternative management scenario.

Exhibit 8-2 illustrates the application of these factors. The baseline management scenario in the example uses disposal in a landfill that has national average conditions. The Btu number represents the amount of energy required to transport and process the ton. The alternate scenario is based on recycling the ton of cans. The difference, shown as a negative number, indicates that recycling one ton of steel cans rather than landfilling them reduces the energy consumed by 20.5 million Btu.

Exhibit 8-2: Comparison of Waste Reduction Scenarios

Baseline: landfill 1 ton of steel cans	1 ton x 0.53 million Btu/ton = 0.53 million Btu
Alternate: recycle 1 ton of steel cans	1 ton x −19.97 million Btu/ton = −19.97 million Btu
Energy Impacts: −19.97 million Btu – 0.53 million Btu = - 20.5 million Btu	

Note: Negative numbers indicate avoided emissions or energy savings.

8.4 Relating Energy Savings to GHG Benefits

Because it can be difficult to conceptualize energy savings in Btu and GHG emissions reductions in metric ton carbon dioxide equivalent ($MTCO_2e$), the common way to express the amount, the results can be converted to common equivalents such as barrels of crude oil or gallons of gasoline, as shown in Exhibit 8-3. These interpreted results produce important nuances, particularly when applied to convert $MTCO_2e$ savings to equivalent energy savings. The conversion is complicated for two reasons: (1) GHG reductions reflect both energy and non-energy savings, and (2) the energy savings reflect savings across a range of fossil fuels. Thus, conversions from total GHG reductions to an equivalency for barrels of oil must be done with caution.

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[42] The energy factors are expressed in terms of million Btu of energy per short ton of material managed. In the case of recycling, EPA defines one ton of material managed as one ton *collected* for recycling.

Exhibit 8-3: Common Energy Conversion Factors and Emissions Equivalencies

Common Energy Conversion Factors	Emissions Equivalencies
Fuel: • Million Btu per Barrel of Oil: 5.8 • Gallons per Barrel of Oil: 42 • Million Btu per Gallon of Gasoline: 0.125 ***Cars (average passenger car over one year):*** • Fuel Consumption (gallons of gas): 529 • Fuel Consumption (Million Btu/year): 66 ***Household (average household per year):*** • Million Btu per day: 0.30 Source: EPA, 2014	***Propane Cylinders Used for Home BBQs:*** • CO_2 emissions per cylinder (metric tons): 0.024 ***Railroad Cars Worth of Coal:*** • CO_2 emissions per Railcar (metric tons): 186.5 ***Cars (average passenger car over one year):*** • CO_2 Emissions (metric tons): 4.8 Source: EPA, 2014

Although energy savings are often associated with GHG emissions savings, it is inaccurate to directly convert overall GHG emission benefits into energy savings equivalents. Equivalencies must remain consistent within the energy category or the GHG emission context in which they were created. Exhibit 8-4 illustrates GHG benefits derived from energy savings achieved through recycling relative to landfilling. For example, for asphalt shingles, 100 percent of the GHG savings associated with recycling rather than landfilling are energy-related, whereas for glass, only about half of the GHG savings are energy-related. Because the GHG benefits of glass recycling consist of some energy and some non-energy-related savings, this material type demonstrates the difficulties of converting GHG savings to energy equivalents.[43]

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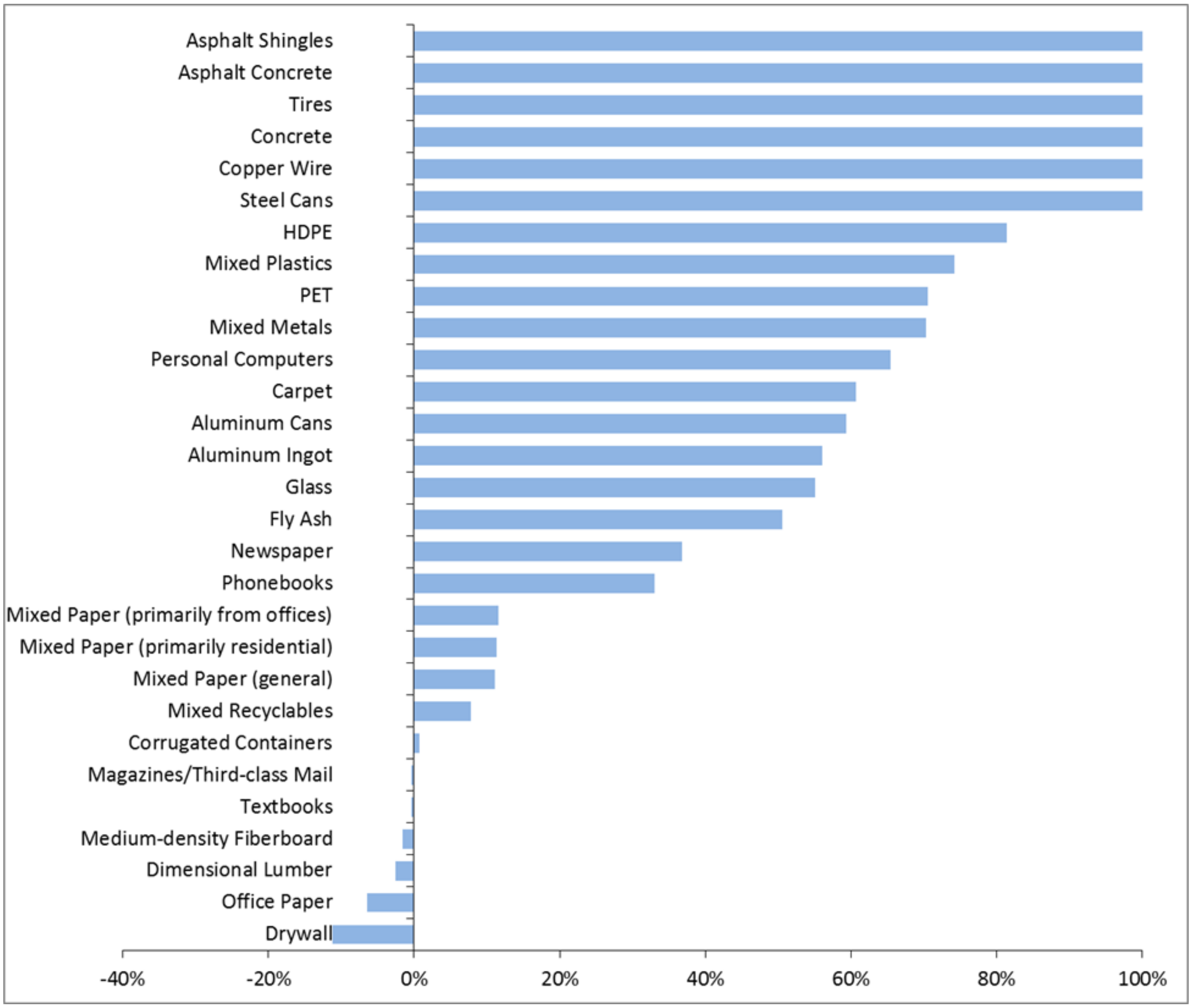
[43] The percentage of emissions savings derived from energy is negative for some paper and wood products because the entire comparative benefit of recycling over landfilling for these materials results from non-energy factors, such as forest carbon storage and landfill carbon sequestration. For more information, see the Forest Carbon Storage and Landfilling chapters.

Exhibit 8-4: Recycling GHG Benefits Attributable to Energy Savings (Relative to Landfilling)



Note: Positive numbers indicate GHG benefits attributable to energy savings from recycling; negative numbers indicate that additional energy GHG emissions result from energy required for recycling, compared to landfilling. This figure excludes materials in WARM for which recycling is not a viable end-of-life management option.

Exhibit 8-5 shows how energy savings and GHG savings can differ for a single scenario. The example is for total derived GHG benefits from recycling glass and the conversion of energy savings is to barrels of oil. Using the common equivalency factors, the GHG emission benefits are equivalent to GHG emissions from the combustion of 74 barrels of oil. In contrast, the energy savings associated with recycling glass are equivalent to the energy content of 46 barrels of oil.

Exhibit 8-5: Comparison of Emissions and Energy Benefits from Recycling

Recycling 100 Short Tons of Glass Compared to Landfilling	
GHG Emission Benefits: 32 $MTCO_2e$	Equivalent to the combustion emissions from **74** barrels of oil.
Energy Savings: 265 Million Btu	Equivalent to the energy contained in **46** barrels of oil.

The difference between the benefits and the conversions has important implications. The term "energy savings" covers a diverse mix of fuels (petroleum, electricity, natural gas, coal). In reality, glass manufacturing depends mainly on energy produced from electricity, coal, and natural gas, not from petroleum. The equivalency, stated as "barrels of oil," is only a simplified and recognizable energy equivalent; little or no petroleum is actually saved. Exhibit 8-6, Exhibit 8-7, Exhibit 8-8 and Exhibit 8-9 show the components of the energy impact factors for source reduction, recycling, combustion, and landfilling, respectively. Exhibit 8-10 shows the net energy impacts of the four materials management options and Exhibit 8-11 compares the energy impacts of source reduction, recycling, and combustion to a baseline of landfilling.

Exhibit 8-6: Energy Impacts for Source Reduction (Million Btu/Ton of Material Source Reduced)

(a)	(b)		(c)		(d)	
	Raw Materials Acquisition and Manufacturing Process Energy		Raw Materials Acquisition and Manufacturing Transport Energy		Net Energy (d = b + c)	
Material/Product	**Displace Current Mix of Virgin and Recycled Inputs**	**Displace Virgin Inputs**	**Displace Current Mix of Virgin and Recycled Inputs**	**Displace Virgin Inputs**	**Displace Current Mix of Virgin and Recycled Inputs**	**Displace Virgin Inputs**
Aluminum Cans	-88.74	-199.30	-0.91	-1.23	-89.66	-200.53
Aluminum Ingot	-126.03	-126.03	-0.89	-0.89	-126.92	-126.92
Steel Cans	-25.11	-31.58	-4.74	-4.93	-29.85	-36.51
Copper Wire	-121.45	-122.52	-0.88	-0.79	-122.32	-123.31
Glass	-5.99	-6.49	-0.88	-0.93	-6.87	-7.43
HDPE	-58.06	-63.88	-3.16	-3.23	-61.22	-67.11
LDPE	-67.77	-67.77	-3.28	-3.28	-71.05	-71.05
PET	-48.85	-49.97	-1.53	-1.49	-50.38	-51.46
LDPE	-67.77	-67.77	-3.28	-3.28	-71.05	-71.05
PP	-63.78	-63.78	-2.85	-2.85	-66.63	-66.63
PS	-72.21	-72.21	-2.81	-2.81	-75.02	-75.02
PVC	-46.52	-46.52	-1.94	-1.94	-48.47	-48.47
PLA	-29.19	-29.19	-0.64	-0.64	-29.83	-29.83
Corrugated Containers	-20.45	-25.13	-1.80	-1.98	-22.25	-27.11
Magazines/Third-class Mail	-32.95	-32.99	-0.25	-0.25	-33.20	-33.24
Newspaper	-35.80	-39.92	-0.64	-0.75	-36.44	-40.67
Office Paper	-36.32	-37.01	-0.25	-0.25	-36.57	-37.27
Phonebooks	-39.61	-39.61	-0.54	-0.54	-40.14	-40.14
Textbooks	-35.01	-35.07	-0.54	-0.54	-35.55	-35.61
Dimensional Lumber	-2.53	-2.53	-1.12	-1.12	-3.65	-3.65
Medium-density Fiberboard	-10.18	-10.18	-1.68	-1.68	-11.85	-11.85
Food Waste	-12.81	-12.81	-1.74	-1.74	-14.56	-14.56
Food Waste (meat only)	-40.86	-40.86	-2.74	-2.74	-43.60	-43.60
Food Waste (non-meat)	-5.71	-5.71	-1.49	-1.49	-7.20	-7.20
Beef	-62.25	-62.25	-1.63	-1.63	-63.88	-63.88
Poultry	-22.80	-22.80	-3.68	-3.68	-26.48	-26.48
Grains	-5.35	-5.35	-0.26	-0.26	-5.62	-5.62
Bread	-6.34	-6.34	-0.17	-0.17	-6.51	-6.51
Fruits and Vegetables	-2.95	-2.95	-2.12	-2.12	-5.07	-5.07
Dairy Products	-13.61	-13.61	-0.65	-0.65	-14.27	-14.27
Yard Trimmings	NA	NA	NA	NA	NA	NA
Grass	NA	NA	NA	NA	NA	NA
Leaves	NA	NA	NA	NA	NA	NA
Branches	NA	NA	NA	NA	NA	NA
Mixed Paper						
Mixed Paper (general)	-28.31	-31.68	-1.09	-1.20	-29.40	-32.89
Mixed Paper (primarily residential)	-27.45	-30.98	-1.16	-1.28	-28.62	-32.26
Mixed Paper (primarily from offices)	-34.20	-35.58	-0.41	-0.44	-34.61	-36.02
Mixed Metals	-47.47	-85.42	-3.40	-3.63	-50.87	-89.05
Mixed Plastics	-52.47	-26.86	-2.17	-2.17	-54.64	-29.03
Mixed Recyclables	NA	NA	NA	NA	NA	NA
Mixed Organics	NA	NA	NA	NA	NA	NA
Mixed MSW	NA	NA	NA	NA	NA	NA
Carpet	-89.70	-89.70	-1.36	-1.36	-91.06	-91.06

(a)	(b) Raw Materials Acquisition and Manufacturing Process Energy		(c) Raw Materials Acquisition and Manufacturing Transport Energy		(d) Net Energy (d = b + c)	
Material/Product	Displace Current Mix of Virgin and Recycled Inputs	Displace Virgin Inputs	Displace Current Mix of Virgin and Recycled Inputs	Displace Virgin Inputs	Displace Current Mix of Virgin and Recycled Inputs	Displace Virgin Inputs
Personal Computers	-951.71	-951.71	-5.03	-5.03	-956.74	-956.74
Clay Bricks	-5.10	-5.10	-0.03	-0.03	-5.13	-5.13
Concrete	NA	-0.05	NA	-0.19	NA	-0.24
Fly Ash	NA	-4.77	NA	-0.10	NA	-4.87
Tires	-71.14	-73.79	-0.52	-0.49	-71.66	-74.28
Asphalt Concrete	-0.95	-0.95	-0.73	-0.73	-1.68	-1.68
Asphalt Shingles	-2.19	-2.19	-0.93	-0.93	-3.11	-3.11
Drywall	-3.08	-3.08	-0.45	-0.45	-3.53	-3.53
Fiberglass Insulation	-3.97	-4.74	-0.73	-0.79	-4.70	-5.53
Vinyl Flooring	-9.58	-9.58	-1.14	-1.14	-10.73	-10.73
Wood Flooring	-13.13	-13.13	-1.36	-1.36	-14.49	-14.49

Note: Negative numbers = Energy savings. NA = Not applicable.

Exhibit 8-7: Energy Impacts for Recycling (Million Btu/Ton of Material Recycled)

Material/Product	Recycled Input Credit Process Energy	Recycled Input Credit Transportation Energy	Net Energy (Post-Consumer)
Aluminum Cans	-152.32	-0.44	-152.76
Aluminum Ingot	-113.53	-0.32	-113.85
Steel Cans	-19.40	-0.56	-19.97
Copper Wire	-81.64	-0.95	-82.59
Glass	-1.91	-0.21	-2.13
HDPE	-49.79	-0.56	-50.36
LDPE	NA	NA	NA
PET	-33.25	1.19	-32.05
LLDPE	NA	NA	NA
PP	NA	NA	NA
PS	NA	NA	NA
PVC	NA	NA	NA
PLA	NA	NA	NA
Corrugated Containers	-14.32	-0.74	-15.05
Magazines/Third-class Mail	-0.69	0.00	-0.69
Newspaper	-16.07	-0.42	-16.49
Office Paper	-10.08	0.00	-10.08
Phonebooks	-11.93	0.00	-11.93
Textbooks	-1.03	0.00	-1.03
Dimensional Lumber	0.52	0.07	0.59
Medium-density Fiberboard	0.65	0.21	0.86
Food Waste	NA	0.58	0.58
Food Waste (meat only)	NA	0.58	0.58
Food Waste (non-meat)	NA	0.58	0.58
Beef	NA	0.58	0.58
Poultry	NA	0.58	0.58
Grains	NA	0.58	0.58
Bread	NA	0.58	0.58
Fruits and Vegetables	NA	0.58	0.58
Dairy Products	NA	0.58	0.58
Yard Trimmings	NA	0.58	0.58
Grass	NA	0.58	0.58
Leaves	NA	0.58	0.58
Branches	NA	0.58	0.58
Mixed Paper (general)	-18.92	-1.45	-20.37
Mixed Paper (primarily residential)	-18.92	-1.45	-20.37
Mixed Paper (primarily from offices)	-19.39	-1.46	-20.85
Mixed Metals	-66.12	-0.52	-66.64
Mixed Plastics	-39.75	0.50	-39.25
Mixed Recyclables	-14.39	-0.46	-14.85
Mixed Organics	NA	0.58	0.58
Mixed MSW	NA	NA	NA
Carpet	-21.84	0.27	-21.57
Personal Computers	-29.52	0.27	-29.24
Clay Bricks	NA	NA	NA
Concrete	-0.01	-0.09	-0.11
Fly Ash	-4.77	0.00	-4.77
Tires	-4.91	1.24	-3.67
Asphalt Concrete	-0.54	-0.69	-1.22
Asphalt Shingles	-2.00	-0.46	-2.46
Drywall	-2.15	-0.50	-2.65
Fiberglass Insulation	NA	NA	NA
Vinyl Flooring	NA	NA	NA

Material/Product	Recycled Input Credit Process Energy	Recycled Input Credit Transportation Energy	Net Energy (Post-Consumer)
Wood Flooring	NA	NA	NA

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 8-8: Energy Impacts for Combustion (Million Btu/Ton of Material Combusted)

Material/Product	Electric Utility Fuel Consumption	Energy Impacts due to Steel Recovery	Transportation to Combustion Facility	Net Energy (Post-Consumer)
Aluminum Cans	0.34	NA	0.30	0.63
Aluminum Ingot	0.34	NA	0.30	0.63
Steel Cans	0.21	-17.61	0.30	-17.10
Copper Wire	0.27	NA	0.30	0.57
Glass	0.24	NA	0.30	0.53
HDPE	-20.00	NA	0.30	-19.71
LDPE	-19.89	NA	0.30	-19.60
PET	-10.61	NA	0.30	-10.31
LLDPE	-19.96	NA	0.30	-19.67
PP	-19.97	NA	0.30	-19.67
PS	-18.02	NA	0.30	-17.72
PVC	-7.88	NA	0.30	-7.59
PLA	-8.38	NA	0.30	-8.08
Corrugated Containers	-7.05	NA	0.30	-6.75
Magazines/Third-class Mail	-5.26	NA	0.30	-4.97
Newspaper	-7.96	NA	0.30	-7.66
Office Paper	-6.81	NA	0.30	-6.51
Phonebooks	-7.96	NA	0.30	-7.66
Textbooks	-6.81	NA	0.30	-6.51
Dimensional Lumber	-8.31	NA	0.30	-8.01
Medium-density Fiberboard	-8.31	NA	0.30	-8.01
Food Waste	-2.37	NA	0.30	-2.08
Food Waste (meat only)	-2.37	NA	0.30	-2.08
Food Waste (non-meat)	-2.37	NA	0.30	-2.08
Beef	-2.37	NA	0.30	-2.08
Poultry	-2.37	NA	0.30	-2.08
Grains	-2.37	NA	0.30	-2.08
Bread	-2.37	NA	0.30	-2.08
Fruits and Vegetables	-2.37	NA	0.30	-2.08
Dairy Products	-2.37	NA	0.30	-2.08
Yard Trimmings	-2.80	NA	0.30	-2.51
Grass	-2.80	NA	0.30	-2.51
Leaves	-2.80	NA	0.30	-2.51
Branches	-2.80	NA	0.30	-2.51
Mixed Paper (general)	-7.08	NA	0.30	-6.78
Mixed Paper (primarily residential)	-7.05	NA	0.30	-6.75
Mixed Paper (primarily from offices)	-6.50	NA	0.30	-6.21
Mixed Metals	0.25	-11.42	0.30	-10.87
Mixed Plastics	-14.30	NA	0.30	-14.01
Mixed Recyclables	-6.51	-0.46	0.30	-6.68
Mixed Organics	-2.58	NA	0.30	-2.28
Mixed MSW	-5.00	NA	0.30	-4.71
Carpet	-7.61	NA	0.30	-7.31
Personal Computers	-1.53	-5.04	0.30	-6.27
Clay Bricks	NA	NA	NA	NA
Concrete	NA	NA	NA	NA
Fly Ash	NA	NA	NA	NA
Tires	-27.78	-1.01	0.30	-28.49
Asphalt Concrete	NA	NA	NA	NA
Asphalt Shingles	-8.80	NA	0.30	-8.50
Drywall	NA	NA	NA	NA

Material/Product	Electric Utility Fuel Consumption	Energy Impacts due to Steel Recovery	Transportation to Combustion Facility	Net Energy (Post-Consumer)
Fiberglass Insulation	NA	NA	NA	NA
Vinyl Flooring	-7.88	NA	0.30	-7.59
Wood Flooring	-10.87	NA	0.30	-10.58

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 8-9: Energy Impacts for Landfilling (Million Btu/Ton of Material Landfilled)

Material/Product	Transportation to Landfill	Electric Utility Fuel Consumption	Net Energy (Post-Consumer)
Aluminum Cans	0.53	NA	0.53
Aluminum Ingot	0.53	NA	0.53
Steel Cans	0.53	NA	0.53
Copper Wire	0.53	NA	0.53
Glass	0.53	NA	0.53
HDPE	0.53	NA	0.53
LDPE	0.53	NA	0.53
PET	0.53	NA	0.53
LLDPE	0.53	NA	0.53
PP	0.53	NA	0.53
PS	0.53	NA	0.53
PVC	0.53	NA	0.53
PLA	0.53	NA	0.53
Corrugated Containers	0.53	-0.31	0.21
Magazines/Third-class Mail	0.53	-0.29	0.23
Newspaper	0.53	-0.13	0.40
Office Paper	0.53	-0.48	0.04
Phonebooks	0.53	-0.13	0.40
Textbooks	0.53	-0.48	0.04
Dimensional Lumber	0.53	-0.02	0.51
Medium-density Fiberboard	0.53	-0.01	0.52
Food Waste	0.53	-0.19	0.34
Food Waste (meat only)	0.53	-0.19	0.34
Food Waste (non-meat)	0.53	-0.19	0.34
Beef	0.53	-0.19	0.34
Poultry	0.53	-0.19	0.34
Grains	0.53	-0.19	0.34
Bread	0.53	-0.19	0.34
Fruits and Vegetables	0.53	-0.19	0.34
Dairy Products	0.53	-0.19	0.34
Yard Trimmings	0.53	-0.07	0.46
Grass	0.53	-0.05	0.48
Leaves	0.53	-0.07	0.46
Branches	0.53	-0.10	0.43
Mixed Paper (general)	0.53	-0.30	0.22
Mixed Paper (primarily residential)	0.53	-0.29	0.23
Mixed Paper (primarily from offices)	0.53	-0.33	0.19
Mixed Metals	0.53	NA	0.53
Mixed Plastics	0.53	NA	0.53
Mixed Recyclables	0.53	-0.22	0.31
Mixed Organics	0.53	-0.13	0.40
Mixed MSW	0.53	-0.21	0.32
Carpet	0.53	NA	0.53
Personal Computers	0.53	NA	0.53
Clay Bricks	0.53	NA	0.53
Concrete	0.53	NA	0.53
Fly Ash	0.53	NA	0.53
Tires	0.53	NA	0.53
Asphalt Concrete	0.53	NA	0.53
Asphalt Shingles	0.53	NA	0.53
Drywall	0.53	NA	0.53
Fiberglass Insulation	0.53	NA	0.53
Vinyl Flooring	0.53	NA	0.53

Material/Product	Transportation to Landfill	Electric Utility Fuel Consumption	Net Energy (Post-Consumer)
Wood Flooring	0.53	NA	0.53

Note: Negative energy impacts = Energy savings. NA = Not applicable.

Exhibit 8-10: Net Energy Impacts from Source Reduction and MSW Management Options (Million Btu/Ton)

Material/Product	Source Reduction for Current Mix of Inputs	Recycling	Combustion	Landfilling
Aluminum Cans	-89.66	-152.76	0.63	0.53
Aluminum Ingot	-126.92	-113.85	0.63	0.53
Steel Cans	-29.85	-19.97	-17.10	0.53
Copper Wire	-122.32	-82.59	0.57	0.53
Glass	-6.87	-2.13	0.53	0.53
HDPE	-61.22	-50.36	-19.71	0.53
LDPE	-71.05	NA	-19.60	0.53
PET	-50.38	-32.05	-10.31	0.53
LLDPE	-66.38	NA	-19.67	0.53
PP	-66.63	NA	-19.67	0.53
PS	-75.02	NA	-17.72	0.53
PVC	-48.47	NA	-7.59	0.53
PLA	-29.83	NA	-8.08	0.53
Corrugated Containers	-22.25	-15.05	-6.75	0.21
Magazines/Third-class Mail	-33.20	-0.69	-4.97	0.23
Newspaper	-36.44	-16.49	-7.66	0.40
Office Paper	-36.57	-10.08	-6.51	0.04
Phonebooks	-40.14	-11.93	-7.66	0.40
Textbooks	-35.55	-1.03	-6.51	0.04
Dimensional Lumber	-3.65	0.59	-8.01	0.51
Medium-density Fiberboard	-11.85	0.86	-8.01	0.52
Food Waste	-14.56	0.58	-2.08	0.34
Food Waste (meat only)	-43.60	0.58	-2.08	0.34
Food Waste (non-meat)	-7.20	0.58	-2.08	0.34
Beef	-63.88	0.58	-2.08	0.34
Poultry	-26.48	0.58	-2.08	0.34
Grains	-5.62	0.58	-2.08	0.34
Bread	-6.51	0.58	-2.08	0.34
Fruits and Vegetables	-5.07	0.58	-2.08	0.34
Dairy Products	-14.27	0.58	-2.08	0.34
Yard Trimmings	NA	0.58	-2.51	0.46
Grass	NA	0.58	-2.51	0.48
Leaves	NA	0.58	-2.51	0.46
Branches	NA	0.58	-2.51	0.43
Mixed Paper (general)	-28.93	-20.37	-6.78	0.22
Mixed Paper (primarily residential)	-28.64	-20.37	-6.75	0.23
Mixed Paper (primarily from offices)	-73.26	-20.85	-6.21	0.19
Mixed Metals	-59.51	-66.64	-10.87	0.53
Mixed Plastics	-28.09	-39.25	-14.01	0.53
Mixed Recyclables	-26.53	-14.85	-6.68	0.31
Mixed Organics	NA	0.58	-2.28	0.40
Mixed MSW	NA	NA	-4.71	0.32
Carpet	-91.06	-21.57	-7.31	0.53
Personal Computers	-956.74	-29.24	-6.27	0.53
Clay Bricks	-5.13	NA	NA	0.53
Concrete	NA	-0.11	NA	0.53
Fly Ash	NA	-4.77	NA	0.53
Tires	-71.66	-3.67	-28.49	0.53
Asphalt Concrete	-1.68	-1.22	NA	0.53
Asphalt Shingles	-3.11	-2.46	-8.50	0.53
Drywall	-3.53	-2.65	NA	0.53
Fiberglass Insulation	-4.70	NA	NA	0.53

Material/Product	Source Reduction for Current Mix of Inputs	Recycling	Combustion	Landfilling
Vinyl Flooring	-10.73	NA	-7.59	0.53
Wood Flooring	-14.49	NA	-10.58	0.53

Note: Negative energy impacts = Energy savings. NA = Not applicable.
– = Zero impact.

Exhibit 8-11: Energy Impacts for MSW Management Options Compared to Landfilling (Million Btu/Ton)

Material/Product	Source Reduction Minus Landfilling		Recycling Minus Landfilling	Combustion Minus Landfilling
	Current Mix of Inputs	100% Virgin Inputs		
Aluminum Cans	-90.19	-201.06	-153.29	0.10
Aluminum Ingot	-127.44	-127.44	-114.37	0.10
Steel Cans	-30.37	-37.04	-20.49	-17.63
Copper Wire	-122.85	-123.84	-83.12	0.04
Glass	-7.40	-7.95	-2.65	0.00
HDPE	-61.75	-67.64	-50.88	-20.23
LDPE	-71.58	-71.58	-0.53	-20.13
PET	-50.91	-51.98	-32.58	-10.84
LLDPE	-66.91	-66.91	-0.53	-20.19
PP	-67.16	-67.16	-0.53	-20.20
PS	-75.54	-75.54	-0.53	-18.25
PVC	-48.99	-48.99	-0.53	-8.11
PLA	-30.36	-30.36	NA	-8.61
Corrugated Containers	-22.47	-27.32	-15.27	-6.97
Magazines/Third-class Mail	-33.43	-33.47	-0.92	-5.20
Newspaper	-36.83	-41.07	-16.88	-8.06
Office Paper	-36.62	-37.31	-10.12	-6.55
Phonebooks	-40.54	-40.54	-12.33	-8.06
Textbooks	-35.59	-35.65	-1.07	-6.55
Dimensional Lumber	-4.16	-4.16	0.08	-8.52
Medium-density Fiberboard	-12.37	-12.37	0.34	-8.53
Food Waste	-14.89	-14.89	0.25	-2.41
Food Waste (meat only)	-43.94	-43.94	0.25	-2.41
Food Waste (non-meat)	-7.53	-7.53	0.25	-2.41
Beef	-64.22	-64.22	0.25	-2.41
Poultry	-26.82	-26.82	0.25	-2.41
Grains	-5.95	-5.95	0.25	-2.41
Bread	-6.84	-6.84	0.25	-2.41
Fruits and Vegetables	-5.41	-5.41	0.25	-2.41
Dairy Products	-14.60	-14.60	0.25	-2.41
Yard Trimmings	NA	NA	0.12	-2.97
Grass	NA	NA	0.11	-2.98
Leaves	NA	NA	0.13	-2.96
Branches	NA	NA	0.15	-2.94
Mixed Paper (general)	-29.16	-34.28	-20.60	-7.00
Mixed Paper (primarily residential)	-28.87	-34.29	-20.60	-6.98
Mixed Paper (primarily from offices)	-73.45	-75.70	-21.04	-6.40
Mixed Metals	-60.04	-89.57	-67.17	-11.40
Mixed Plastics	-28.62	-29.56	-39.78	-14.53
Mixed Recyclables	NA	NA	-15.13	-6.95
Mixed Organics	NA	NA	0.18	-2.68
Mixed MSW	NA	NA	-0.32	-5.03
Carpet	-91.59	-91.59	-22.10	-7.84
Personal Computers	-957.27	-957.27	-29.77	-6.80
Clay Bricks	-5.66	-5.66	NA	NA
Concrete	NA	NA	-0.63	NA
Fly Ash	NA	NA	-5.29	NA
Tires	-72.19	-74.80	-4.20	-29.02
Asphalt Concrete	-2.21	-2.21	-1.75	-0.53
Asphalt Shingles	-3.64	-3.64	-2.99	-9.03
Drywall	-4.05	-4.05	-3.17	-0.53
Fiberglass Insulation	-5.23	-6.06	-0.53	-0.53

Material/Product	Source Reduction Minus Landfilling		Recycling Minus Landfilling	Combustion Minus Landfilling
	Current Mix of Inputs	100% Virgin Inputs		
Vinyl Flooring	-11.25	-11.25	-0.53	-8.11
Wood Flooring	-15.02	-15.02	-0.53	-11.10

Note: Negative energy impacts = Energy savings. NA = Not applicable.

8.5 References

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EPA. (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks.* U.S. Environmental Protection Agency (EPA). Retrieved October 22, 2008, from http://epa.gov/epawaste/conserve/tools/warm/SWMGHGreport.html#background

9 FOREST CARBON STORAGE

This chapter describes the development of material-specific estimates of changes in forest carbon storage in EPA's Waste Reduction Model (WARM). It summarizes the approach used to estimate changes in forest carbon storage in managed forests resulting from source reduction and recycling of wood and paper products.

9.1 A Summary of the Greenhouse Gas Implications of Forest Carbon Storage

Forests absorb (i.e., sequester) atmospheric carbon dioxide (CO_2) and store it in the form of cellulose and other materials. In the early stages of growth, trees store carbon rapidly; consequently, as tree growth slows, so does carbon sequestration. Trees naturally release carbon throughout their life cycle as they shed leaves, branches, nuts, fruit, and other materials, which then decay; carbon is also released when trees are cleared and processed or burned.

When paper and wood products are recycled or the production of these materials is avoided through source reduction, trees that otherwise would be harvested are left standing in forests. In the short term, this reduction in harvesting results in more carbon storage than would occur in the absence of the recycling or source reduction. Over the long term, when forest managers find they have more trees standing resulting from reduced harvesting, they will respond by planting fewer trees; therefore, while the carbon storage effect of source reduction and recycling is high in the short term, it is less pronounced in the long term.

WARM evaluates forest carbon storage implications for all wood and paper products, which include all of the paper types in WARM,[44] dimensional lumber, medium-density fiberboard (MDF), and hardwood flooring. Paper products are primarily nondurable goods, or goods that generally have a lifetime of less than three years (EPA, 2008, p. 76). Wood products such as dimensional lumber, MDF, and wood flooring are considered durable goods because they typically have a lifetime of much longer than three years (Skog, 2008). Because of the differences in harvesting practices, use, and service life of paper and wood products, EPA analyzes the forest carbon storage implications for paper products separately from wood products.

In the United States, uptake by forests has long exceeded release, a result of forest management activities and the reforestation of previously cleared areas. EPA estimated that the 2012 annual net carbon flux (i.e., the excess of uptake minus release) in U.S. forests was about 866.5 million metric tons of carbon dioxide equivalent ($MMTCO_2e$), which offset about 17 percent of U.S. energy-related CO_2 emissions. In addition, about 5,397 $MMTCO_2e$ was stored in wood products currently in use (e.g., wood in building structures and furniture, paper in books and periodicals) (EPA 2014a). Considering the effect of forest carbon sequestration on U.S. net GHG emissions, the data clearly showed that a thorough examination was warranted for use in WARM.

This chapter summarizes the methodology, approach, and results of EPA's analysis of forest carbon storage. The next section outlines the overall methodology, including the key components in the assessment of changes in forest carbon storage. Sections 3 and 4 summarize forest carbon storage estimates for source reduction and recycling for paper and wood products. Section 5 outlines the limitations associated with EPA's analysis of forest carbon storage.

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[44] Corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks and textbooks.

9.2 Forest Carbon Storage Methodology

EPA estimates the net change in forest carbon storage from source reduction or recycling of forest products by evaluating three components:

1. Changes in timber harvest (i.e., trees that have been cut from the forest) as a result of changes in demand for virgin wood.
2. Changes in forest stocks as a result of changes in harvest.
3. Changes in carbon storage in the in-use product pool (for durable wood products).

These three components taken together provide the net change in carbon storage resulting from recycling or source reduction of forest products. Exhibit 9-1 is a flow chart explaining the approach. First, for a forest product that is recycled or source reduced instead of being put in a landfill or combusted, WARM assumes that—if demand for forest products remains constant—recycling or reuse results in a reduction in the demand for virgin timber from forests. Second, this reduction in timber harvest results in a small increase in the stock of carbon that remains in U.S. forests. Third, durable wood products remain in use for many years,[45] and are themselves a significant source of carbon storage that is tracked in the U.S. GHG Inventory[46] (EPA, 2014a). Since source reduction reduces the amount of virgin wood products that enter the market, and remanufacturing wood products into recycled products results in some loss of

WARM's Approach to Forest Carbon Storage

WARM adopts a waste management perspective that assumes life-cycle boundaries start at the point of waste generation (i.e., the moment a product such as paper or dimensional lumber reaches its end-of-life stage), and the methodology examines the resulting life-cycle GHG implications of alternative material management pathways relative to a baseline waste management scenario.

To evaluate forest carbon storage, WARM first assesses the amount of wood that would have been harvested from the forest with no efforts to increase source reduction or recycling. This establishes a "business-as-usual" baseline of wood harvests. Next, WARM examines how increased source reduction or recycling reduces the demand for wood harvests from the forest by avoiding the use of wood or by conserving paper and wood products relative to this business-as-usual baseline. The forest carbon storage is equal to the amount of carbon contained in wood that is not harvested as a result of increased recycling or source reduction.

In other words, rather than evaluating the entire stock and flows of carbon into and out of forests in the United States, WARM evaluates the difference, or *marginal* change, in forest carbon storage resulting from efforts to increase source reduction or recycling beyond the business-as-usual baseline. This approach is consistent with WARM's purpose of evaluating the benefits of alternative management practices relative to baseline activities.

On average in the United States, timber harvests are more than compensated by replanting; therefore, baseline forest carbon withdrawals need to be considered as part of the overall carbon stocks-and-flows cycle for forest and harvested wood products. This methodology is consistent with and supported by the Intergovernmental Panel on Climate Change (IPCC) Inventory Guidelines (IPCC, 2006) that distinguish between biogenic carbon that is harvested on a sustainable basis versus non-sustainable harvest, and the fact that land use change and forestry provide a large net sink for GHG emissions in EPA's U.S. GHG Inventory (2014a).

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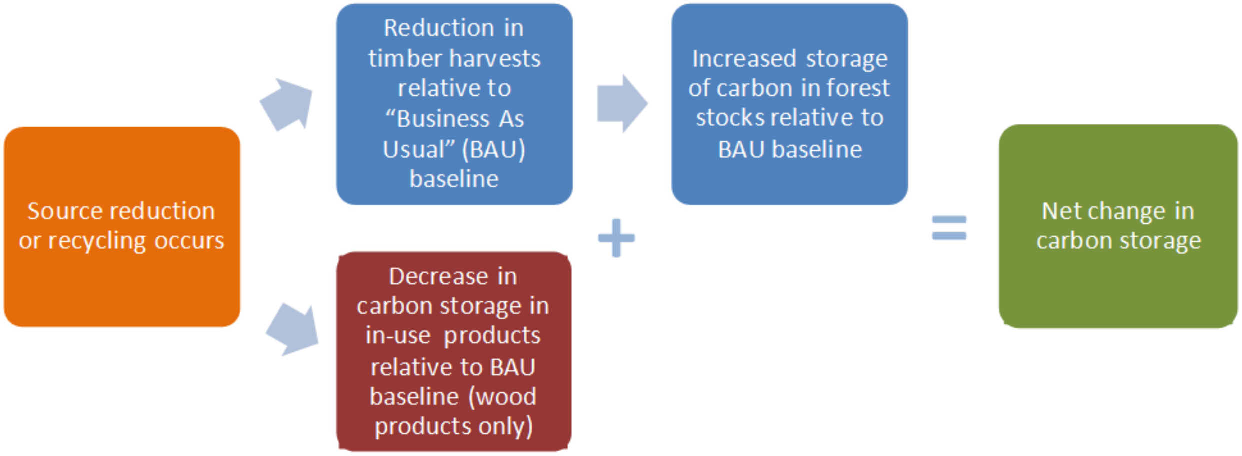
[45] For example, Skog (2008) estimates that the half-life of wood (i.e., the amount of time it takes for half of an initial amount of wood to reach the end-of-life stage) is 100 years in single-family housing and 30 years in other end uses.

[46] Durable wood products (also known as harvested wood products) accounted for 66.5 million metric tons of CO_2 of net carbon flux (equivalent to 18.1 million metric tons of carbon) in 2012. See Chapter 7 of the U.S. GHG Inventory (EPA, 2014a).

material, increasing source reduction or recycling decreases the amount of carbon stored in in-use products.

Consequently, for durable wood products, recycling and source reduction increase the amount of carbon that is stored in U.S. forests, but simultaneously they decrease the amount of carbon from virgin products that would have been stored in durable wood products. Together, these two factors equal the net change in carbon storage resulting from increased source reduction or recycling. Note that the decrease in carbon storage in in-use products applies only to durable (wood) products; WARM does not consider changes in the in-use product carbon pool for nondurable (paper) goods because these products have shorter lifetimes, typically less than three years, and the carbon in these goods cycles out of the in-use pool over a relatively short period.

Exhibit 9-1: Forest Carbon Storage Methodology



9.3 Forest Carbon Storage and Paper Products

Paper products in WARM include corrugated containers, magazines/third-class mail, newspapers, office paper, phonebooks, and textbooks. These products are short-lived, nondurable goods that are harvested primarily from forests that are grown for making wood pulp for paper production. This section describes the methodology used to evaluate the two relevant components of forest carbon storage, outlined in Section 9.2, for paper products: changes in timber harvest and changes in forest stock.

Paper types fall into two broad categories, mechanical- and chemical-pulp papers. Mechanical pulping involves grinding logs into wood fibers and mixing with hot water to form a pulp suspension. Chemical pulping, also known as kraft pulping, involves removing the surrounding lignin in the wood raw material during a cooking process. (Verband Deutscher Papierfabrikin e.V., 2008) Of the paper types modeled in WARM, mechanical pulp papers include newspaper and textbooks. Office paper, corrugated containers, textbooks, and magazines/third-class mail are considered chemical-pulp paper types.[47]

9.3.1 Effect of Source Reduction and Recycling on Timber Harvests

Several U.S. Department of Agriculture Forest Service (USDA FS) efforts have analyzed the relationship between paper recovery (i.e., recycling) rates and pulpwood harvests (i.e., wood harvested

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[47] In general, shipping and packaging containers, paper bags, and printing and writing papers are manufactured from chemical pulp, while newspaper, specialty papers, tissue, toweling, paperboard, and wallboard are produced from mechanical pulp (AF&PA, 2010a).

for paper production) based on data compiled by the American Forest and Paper Association (AF&PA) and the Forest Resources Association (FRA). AF&PA collects information on the mass of recovered paper and wood pulp consumed (AF&PA, 2005) and paper and paperboard production (AF&PA, 2004). FRA publishes information on the annual amount of pulpwood received at pulp mills (FRA, 2004). Based on this information, along with assumptions about moisture content,[48] Dr. Peter Ince of USDA FS developed the following equation to relate paper recovery to pulpwood harvests (Ince and McKeever, 1995):

$$PWH = X \times \{PP - [PR \times (1 - EX) \times Y]\} \qquad \text{(Eqn. 1)}$$

Where,

PWH = Pulpwood harvests at 0 percent moisture content, i.e., ovendry (short tons)
PP = Paper production at 3 percent moisture content (short tons)
PR = Paper recovery at 15 percent moisture content (short tons)
EX = Percentage of recovered paper that is exported
X = Process efficiency of converting ovendry pulpwood to paper and paperboard at 3 percent moisture content, which is the ratio of finished paper to pulp, and accounts for the portion of paper and paperboard that is water and fillers
Y = Process efficiency of converting recovered paper at 15 percent moisture to paper and paperboard at 3 percent moisture, which is the ratio of recovered paper to finished paper, and accounts for the water in recovered paper

The values of *X* and *Y* are based on process efficiency estimates provided by John Klungness (Research Chemical Engineer, USDA FS) and Ken Skog (Project Leader, Timber Demand and Technology Assessment Research, USDA FS). The value for *EX*, the export rate, is based on AF&PA statistics on U.S. recovered paper exports. In 2008, approximately 40 percent of recovered paper was exported from the United States (AF&PA, 2010b).[49]

EPA uses the relationship developed in Equation 1 to describe how a change in paper recovery affects pulpwood harvests. For example, if paper recovery increases by one short ton, by how much would pulpwood harvests be reduced to meet the same level of paper production in the United States? Exhibit 9-2 column (f) shows that increasing paper recovery by one short ton would reduce (i.e., avoid) pulpwood harvests by 0.58 short tons for mechanical pulp papers and by 0.89 short tons for chemical pulp papers. This difference results from the lower ratio of pulp to finished paper for chemical-pulp papers because the chemical pulping process in paper manufacturing removes lignin from the raw wood material.

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[48] The moisture contents are pulpwood as harvested, 50 percent; paper and paperboard, 3 percent; wood pulp consumed, 10 percent; and recovered paper consumed, 15 percent. Knowing the moisture content is important to accurately gauge carbon contents of these materials.

[49] EPA included the export rate in the calculation of avoided pulpwood harvest per ton of paper recovered because the WARM analysis focuses on the United States; therefore, EPA assumed the avoided pulpwood harvest was affected only by recovered paper that stays in the United States. Recovered paper that is exported will produce a different offset for pulpwood harvests in other countries because forest management practices outside of the United States are likely to be different. The inclusion of the exported recovered paper as a factor in calculating avoided pulpwood harvest per ton of paper recovered is a conservative assumption because it results in a smaller reduction in pulpwood harvests from increased paper recovery.

Exhibit 9-2: Relationship Between Paper Recovery (i.e., Recycling) and Pulpwood Harvest (Values of Eqn. 1 Parameters)

(a)	(b) Ratio of Pulp to Finished Paper	(c) *X* = Process Efficiency (c = 1/b)	(d) *Y* = Ratio of Recovered Paper to Finished Paper	(e) EX (%)	(f) Avoided Short Tons PWH per Short Ton Paper Recovered (f = c × d × [1 − e])
Mechanical Pulp	0.900	1.11	0.875	40	0.58
Chemical Pulp	0.475	2.11	0.700	40	0.89

For source reduction, the change in pulpwood harvests from source reducing paper can be calculated directly from the process efficiency (X) of mechanical and chemical pulp production. This is because source reduction, by reducing consumption of paper, directly reduces paper production (PP in Equation 1) and, consequently, the amount of pulpwood harvested. Based on the process efficiency estimates in

Exhibit 9-2, WARM estimates that one short ton of source reduction avoids 1.1 short tons of pulpwood harvests for mechanical pulp, and 2.11 short tons of chemical pulp.

9.3.2 Effect of Changes in Timber Harvests on Forest Carbon Stocks

EPA bases its analysis of carbon storage on model results provided by the USDA FS using its FORCARB II model of the U.S. forest sector. USDA FS models and data sets are the most thoroughly documented and peer-reviewed models available for characterizing and simulating the species composition, inventory, and growth of forests, and the Forest Service has used them to analyze GHG mitigation in support of a variety of policy analyses. FORCARB II is a USDA FS model that simulates the complex, dynamic nature of forest systems, including the interaction of various forest carbon pools, how carbon stocks in those pools change over time, and whether the response of forest carbon is linearly proportional to harvests. To explore these questions, USDA FS ran two enhanced recycling/source reduction pulpwood harvest scenarios in FORCARB II.

The base assumptions on pulpwood harvests are derived from the North American Pulp and Paper (NAPAP) model baseline projections developed for the Forest Service 2001 Resource Planning Act Timber Assessment. To investigate the effect of small and large changes in pulpwood harvests, the Forest Service modeled two reduced harvest scenarios, which involved decreasing pulpwood harvest by 6.7 million metric tons and 20.2 million metric tons for the period 2005 to 2009.[50] The Forest Service selected the values of 6.7 million and 20.2 million metric tons as representative low- and high-end reductions in pulpwood harvests based on the 50-percent paper recycling rate in 2005 (Freed et al., 2006). Harvests in all other periods were the same as the baseline.

The relative change in forest carbon storage per unit of reduced pulpwood harvest across the two decreased harvest scenarios is virtually identical (i.e., less than 1 percent), which suggests that the relationship between forest carbon storage and reduced pulpwood harvests is not affected by the size of the reduction in pulpwood harvests over the range investigated by the two scenarios.

For each scenario, the Forest Service calculated the change in carbon stocks compared with the base case; the change represents the carbon benefit of reduced harvests associated with recycling or source reduction. The change in metric tons of carbon equivalents (MTCE) is divided by the incremental metric tons of pulpwood harvested and multiplied by the weight ratio of CO_2 to carbon (44/12, or

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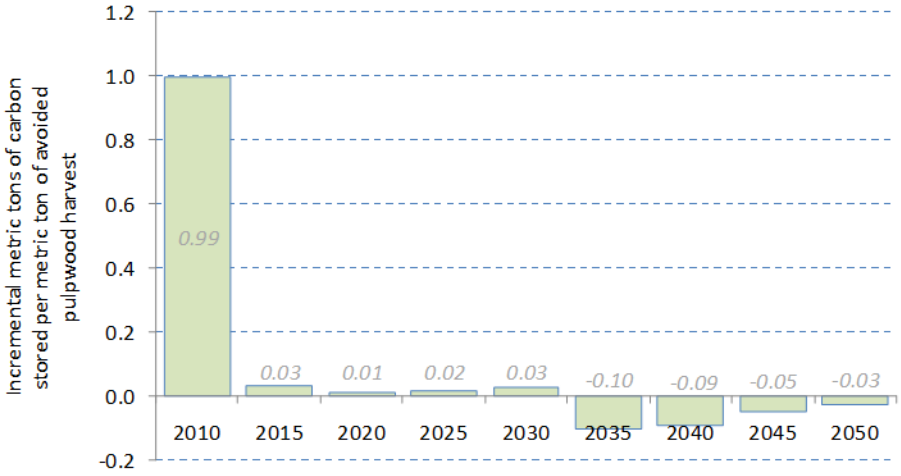
[50] EPA selected this timeframe because, at the time the EPA did the analysis, that period represented a short-term future time horizon over which reduced forest withdrawals could be evaluated against baseline projections.

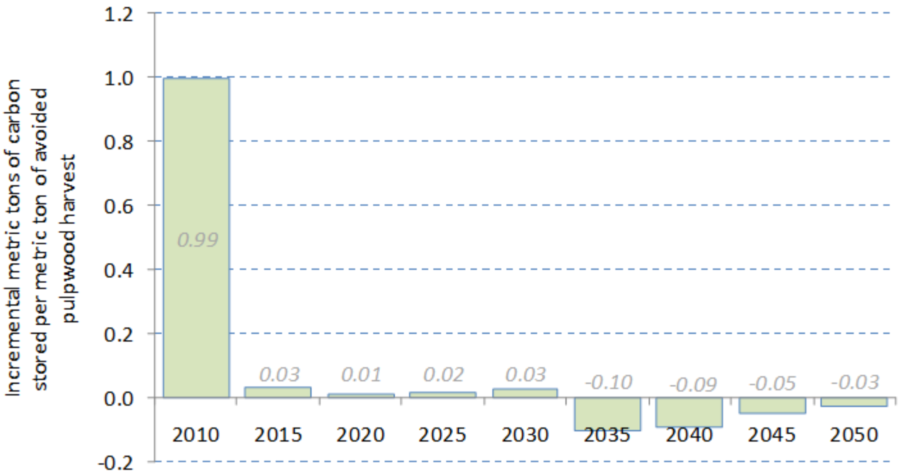
approximately 3.667) to yield results in units of $MTCO_2e$ per metric ton of pulpwood not harvested (i.e., the carbon storage rate). For more details, please refer to the conversions provided in Exhibit 9-4 and Exhibit 9-5.

As shown in Exhibit 9-3, the cumulative carbon storage rate starts at about 0.99 MTCE per metric ton pulpwood in 2010, increases to about 1.08 MTCE per metric ton pulpwood in 2030, and declines with time to about 0.81 MTCE per metric ton pulpwood in 2050. According to EPA's detailed analysis of the FORCARB II results, the primary effect of reduced pulpwood harvests is to increase carbon stored in live trees that otherwise would have been harvested (shown by the sharp increase in carbon storage in 2010). This effect is offset to a small degree by a decrease in carbon storage in the amount of downed wood in the forest. Carbon storage in dead trees, the forest floor, and forest understory increases slightly; carbon stored in forest soils has no effect. Most of the changes in each of these pools of forest carbon peak in 2010 and moderate somewhat over the next 40 years, although the increase in carbon storage in the forest floor peaks over a longer time period in 2030. After 2030, the amount of carbon stored in live trees begins to decline, causing a reduction in forest carbon storage. This decline likely reflects the effect of market forces, which result in less planting of new managed forests in response to a lower level of demand for pulpwood harvests.

Exhibit 9-3: Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest for (a) Incremental Change in Forest Carbon Storage and (b) Cumulative Change in Forest Carbon Storage Per Unit of Reduced Pulpwood Harvest



(a)



(b)

Note: Colored bar for 2020 represents the value EPA selected to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 6.7 million metric tons of pulpwood harvests reduced over the period 2005 to 2009.

Apparently the major driver of the net carbon storage estimate is the time it takes for the increase in carbon storage in live trees and the decrease in carbon storage in downed wood to begin to decline back toward baseline levels. Because the decrease in carbon storage in downed wood returns to baseline levels more quickly than the increase in carbon storage in live trees, the net change in carbon storage actually increases through 2030.

The FORCARB II results indicate that the effect of paper recycling or source reduction on carbon storage appears to be persistent (i.e., lasting at least for several decades). EPA chose to use the value for 2020 in the emission factors, or 1.04 MTCE per metric ton of pulpwood. The choice of 2020 represents a delay of about 5 to 15 years for the onset of incremental recycling, long enough to reflect the effects of the recycling program, but at a rate lower than the peak effect in 2030. As shown in Exhibit 9-3, the effect is relatively stable over time, so the choice of year does not have a significant effect.

For additional details on this methodology and a comparison of the FORCARB II results to those from other analyses, please see the *Revised Estimates of Effect of Paper Recycling on Forest Carbon* (Freed et al., 2006).

9.3.3 Changes in In-Use Product Carbon Pool

WARM does not consider changes in the in-use product carbon pool for nondurable goods because these products have shorter lifetimes, typically less than three years, and the carbon contained in these goods cycles out of the in-use pool over a relatively short period.

9.3.4 Net Change in Carbon Storage

To estimate the rate of forest carbon change per metric ton of paper recovery, multiply the rate of pulpwood harvest (*PWH*) per metric ton of paper recovery (*PRC*) (from Section 9.3.1) by the rate of forest carbon (*FC*) change per metric ton of pulpwood harvest (from Section 9.3.2), as shown in Exhibit 9-4. Exhibit 9-4 shows the net change in carbon storage per unit of increased paper product recycling, while Exhibit 9-5 shows the net change in carbon storage per unit of increased paper source reduction. The various paper grades fall into mechanical or chemical pulp categories as follows:

- Mechanical pulp papers: newspaper, telephone books.
- Chemical pulp papers: office paper, corrugated containers, textbooks, magazines/third class mail.

Note that the net change in carbon storage for recycling and source reduction of wood products (compared with paper products) is different, as discussed in Section 4.

Exhibit 9-4: Net Change in Carbon Storage per Unit of Increased Paper Product Recycling

(a)	(b)	(c)	(d)	(e)	(f)
Paper Product Recycled	**Reduction in Timber Harvest per Unit of Increased Recycling (Short Tons Timber/Short Ton of Wood) (from Section 9.3.1)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 9.3.2)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)**	**Change in Carbon Storage in In-use Products per Unit of Increased Paper Product Recycling ($MTCO_2e$/Short Ton)**	**Net Change in Carbon Storage per Unit of Increased Paper Product Recycling ($MTCO_2e$/Short Ton) (e = b × d + e)**
Mechanical pulp	0.58	1.04	3.46	NA	2.02
Chemical pulp	0.89	1.04	3.46	NA	3.06

NA = Not applicable.
One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.

Exhibit 9-5: Forest Carbon Storage from Source Reduction of Paper Products

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)
Material	**Mechanical or Chemical Pulp**	**Reduction in Timber Harvest per Unit of Increased Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 9.3.1)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 9.3.2)**	**Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (e = d x 0.907 x 3.667)**	**Net Change in Carbon Storage per Unit of Increased Source Reduction, 100% Virgin Inputs ($MTCO_2e$ /Short Ton) (f = c × e)**	**Virgin Inputs in the Current Mix of Inputs[a] (%)**	**Net Change in Carbon Storage per Unit of Increased Source Reduction, Current Mix ($MTCO_2e$ /Short Ton) (h = f × g)**
Corrugated Containers	Chemical	2.11	1.04	3.46	7.26	65.1	4.73
Magazines/ Third-class Mail	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Newspapers	Mechanical	1.11	1.04	3.46	3.83	77.0	2.95
Office Paper	Chemical	2.11	1.04	3.46	7.26	95.9	6.96
Phonebooks	Mechanical	1.11	1.04	3.46	3.83	100.0	3.83
Textbooks	Chemical	2.11	1.04	3.46	7.26	95.9	6.96

One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.
[a] Source: FAL (2003).

The net forest carbon storage for source reduction of paper products is shown in Exhibit 9-5. The reduction in timber harvest per unit of increased source reduction (Exhibit 9-5, column (c)) is the process efficiency of converting pulpwood to finished paper (i.e., 1/ratio of pulp to finished paper), as described in Section 3.1. The net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs or the current industry-average mix of virgin and recycled inputs (FAL, 2003). For source reduction that offsets paper produced from 100-percent virgin pulp, the net change in forest carbon storage is shown in Exhibit 9-5, column (e). For the case where source reduction offsets paper produced from the current mix of virgin and recycled inputs, however, WARM assumes that the net forest carbon effect is attributable only to the proportion of inputs that are virgin pulp, as shown in Exhibit 9-5, column (g). WARM makes this assumption because displacing recycled inputs, which have already been harvested from the forest, are unlikely to have a direct effect on forest carbon storage.

9.4 Forest Carbon Storage and Wood Products

Wood products in WARM include dimensional lumber, MDF, and wood flooring. These products are long-lived, durable goods that are harvested from sustainably managed soft- and hardwood forests. This section describes the methodology EPA uses to evaluate the three components of forest carbon storage, outlined in Section 9.2, for softwood products (i.e., dimensional lumber and MDF). The approach for evaluating forest carbon storage for hardwood flooring is similar and is provided in further detail in the Wood Flooring chapter.

9.4.1 Effect of Source Reduction and Recycling on Timber Harvests

To estimate the change in timber harvests that result from increased recycling and source reduction of softwood products, EPA uses estimates provided by Dr. Skog for the system efficiencies (on a weight basis) of producing wood products from virgin inputs or recycled inputs. Assuming that overall demand for softwood products is constant, increases in recycling will reduce timber harvests according to the following ratio:[51]

$$TH = X/Y \qquad \text{(Eqn. 2)}$$

Where,

TH = Change in timber harvests resulting from increased recycling of wood products

X = Process efficiency of converting virgin roundwood into finished wood product

Y = Process efficiency of converting recycled wood into finished wood product

Based on the estimates provided by Dr. Skog, EPA assumes that one short ton of finished wood product requires 1.1 short tons of virgin roundwood[52] (i.e., harvested logs, with or without bark), on average, or 1.25 short tons of recycled wood. According to this relationship, each additional short ton of wood products recycled will reduce the demand for virgin roundwood from timber forests by a ratio of 1.1/1.25 = 0.88 short tons.

The effect of source reduction on timber harvests can be calculated from the process efficiency (X) of wood products production, assuming that one short ton of source reduction completely offsets virgin roundwood harvests that otherwise would be harvested to produce one short ton of wood products. Section 9.5 discusses the sensitivity of the forest carbon storage results to this assumption.

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[51] Unlike EPA's consideration of paper products, WARM does not consider exports of recycled wood outside of the United States. In contrast with recovered paper, which is exported to other countries for recycling, recovered wood typically is not directly exported for recycling. Instead, finished wood products or wood packaging materials (such as pallets, skids, containers, crates, boxes, cases, bins, reels, and drums) may be manufactured from recycled materials in the United States for export (Ince 1995; FAO 2005).

[52] Harvested logs, with or without bark; roundwood may be round, spilt, or roughly squared (FAO, 1997).

Consequently, WARM estimates that one short ton of source reduction avoids 1.1 short tons of roundwood harvests for dimensional lumber and MDF wood products.

These values describe the change in timber harvests resulting from increased recycling and source reduction of softwood products. Together with the effects that changes in timber harvests have on forest carbon stocks (developed in Section 9.4.2), these two parameters describe how forest carbon storage changes as a result of increases in recycling and source reduction. The values developed in this section are also used to determine how source reduction and recycling affect carbon storage in in-use wood products, which is discussed in Section 9.4.3. The net changes in carbon storage from recycling and source reduction are calculated in Section 9.4.4, taking into account both changes in forest carbon storage and in-use product carbon storage.

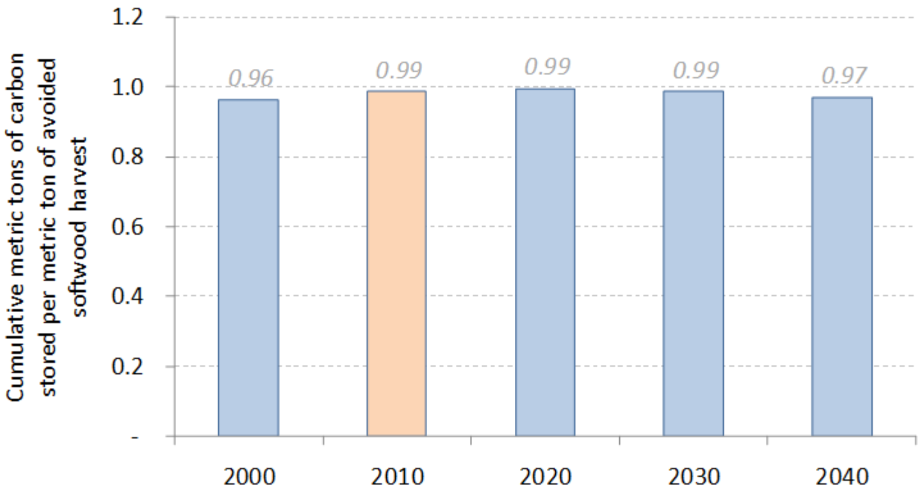
9.4.2 Effect of Changes in Timber Harvests on Forest Carbon Stocks

To investigate the change in forest carbon resulting from increased recycling and source reduction of wood products, EPA uses estimates developed from the USDA FS's FORCARB II model. The method for wood products is similar to the approach for paper described in Section 9.3.2. First, EPA applies a harvest scenario developed in consultation with Dr. Skog and Dr. Linda Heath at USDA FS. EPA determined that the majority of wood products are derived from softwood and evaluated an increased wood recycling/source reduction scenario corresponding to a 1.7-percent reduction in softwood harvest. The 1.7-percent reduction is a representative estimate of the reduction in softwood harvests that could be achieved with a national increase in wood product recycling above current levels.

This reduction is distributed throughout the USDA FS regions in proportion to baseline harvest for the period 1998 to 2007. The cumulative reduction in softwood harvest from the 1.7-percent reduced harvest scenario is 26.4 million short tons over this period.

The effect of this reduction in harvest is to increase carbon sequestration in forests. To be consistent with the approach for paper recycling and source reduction, EPA analyzed effects only for tree and understory components (and excluded forest floor and soils). Exhibit 9-6 displays the results of the analysis for wood products. The results show that every metric ton of avoided timber harvest results in 0.96 to 0.99 metric tons of forest carbon storage. For consistency with the paper recycling/source reduction analysis, EPA selected the forest carbon storage benefit in 2010, representing a delay of 5 to 15 years from the onset of the simulated period of incremental recycling. This period is consistent with the 5 to 15 year timeframe used in the paper forest carbon analysis in Section 9.3. Consequently, EPA estimates that a one-metric-ton reduction in timber harvests increases forest carbon storage by 0.99 metric tons.

Exhibit 9-6: Cumulative Change in Forest Carbon Storage per Unit of Reduced Timber Harvest



Note: Colored bar for 2010 represents the value EPA selects to estimate the forest carbon storage benefit in WARM's GHG emission factors. EPA calculated the results by dividing the change in forest carbon storage in each year by 24 million metric tons of pulpwood harvests reduced over the period 1998 to 2007.

9.4.3 Changes in In-Use Product Carbon Pool

The final step involves estimating the effects of increased wood product recycling on carbon storage in in-use wood products.

For recycling, based on the estimates developed in Section 9.4.1, EPA assumes that 1.25 short tons of recycled wood are required to produce one short ton of finished wood product; in other words, every short ton of wood recycled yields 0.8 short tons of finished wood product (i.e., 1/1.25 = 0.8), and 0.2 short tons of wood are lost from in-use products. For wood products, EPA assumes a carbon density of 0.48 MTCE per short ton of wood, corresponding to softwoods in Southeast and South Central pine forests (Birdsey, 1992). Consequently, the carbon loss from the product pool is given by:

(1 short ton recycled – 0.8 short tons retained) x 0.48 MTCE/short ton x 44/12 $MTCO_2e$/MTCE = 0.35 $MTCO_2e$/short ton

For source reduction of wood products, a short ton of wood offset by source reduction results in a decline in carbon that otherwise would have been stored in the in-use wood product.[53] This essentially represents a one-to-one relationship, where source reducing one short ton of wood avoids one short ton of wood that otherwise would have been manufactured into in-use products. Consequently, the change in the in-use product carbon pool from source reduction of one short ton of wood product is equal to the carbon density of the wood product, given by:

1 short ton source reduced x 0.48 MTCE/short ton x 44/12 $MTCO_2e$/MTCE = 1.77 $MTCO_2e$/short ton

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[53] Because dimensional lumber and MDF are not commonly manufactured from recycled inputs in the United States, WARM assumes that source reduction of wood products avoids virgin wood inputs only. This is a different approach than for source reduction for paper products, where the net change in forest carbon storage depends on whether the source reduction of paper products is assumed to displace paper that would have been produced from 100-percent virgin inputs, or the current industry-average mix of virgin and recycled inputs.

Both source reduction and recycling decrease the amount of carbon stored in in-use products; this decrease offsets some of the benefit of increasing storage in forests; see Section 2 for more details.

9.4.4 Net Change in Carbon Storage

Based on the estimates developed in the previous sections, Exhibit 9-7 shows the net change in forest carbon storage for recycling and source reduction of wood products. These results conclude that recycling and source reduction of one short ton of wood products corresponds to an increase in net carbon storage. In both cases, the increase in forest carbon storage is offset by a reduction in carbon storage in in-use products as a result of recycling or source reduction.

Exhibit 9-7: Net Change in Carbon Storage per Unit of Increased Wood Product Recycling

(a)	(b) Reduction in Timber Harvest per Unit of Increased Recycling or Source Reduction (Short Tons Timber/Short Ton of Wood) (from Section 9.4.1)	(c) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest (Metric Tons Forest Carbon/Metric Ton Timber) (from Section 9.4.2)	(d) Change in Forest Carbon Storage per Unit of Reduced Timber Harvest ($MTCO_2e$/ Short Ton Timber) (d = c x 0.907 x 3.667)	(e) Change in Carbon Storage in In-use Products per Unit of Increased Wood Product Recycling ($MTCO_2e$/Short Ton) (from Section 9.4.3)	(f) Net Change in Carbon Storage per Unit of Increased Wood Product Recycling ($MTCO_2e$/Short Ton) (e = b × d + e)
Recycling	0.88	0.99	3.29	-0.35	2.53
Source Reduction	1.1	0.99	3.29	-1.77	1.84

Note: Positive values denote an increase in carbon storage; negative values denote a decrease in carbon storage.
One metric ton = 0.907 short tons.
One metric ton of carbon = 3.667 metric tons of CO_2e.

9.5 Limitations

Several limitations are associated with the analysis. The forest product market is very complex, and EPA's simulation of some of the underlying economic relationships that affect the market simplifies some important interactions.

A general limitation of the analysis is that it does not account for any potential long-term changes in land use caused by a reduction in pulpwood or softwood demand, and landowners' choices to change land use from silviculture to other uses. If overall forest area is reduced, this would result in significant loss of carbon stocks. Hardie and Parks (1997) developed an area base model for use in Resource Planning Act assessments to help determine factors that influence land area change. They derived a model that estimated the elasticity of (a) forest land area change with respect to (b) pulpwood price change. They estimated the elasticity to be −0.10, but this was not significant at the 10-percent confidence level. This suggests that forest area change would be limited with a modest price change in pulpwood demand.

The following limitations relate to the estimate of forest carbon storage for paper products:

- Results are very sensitive to the assumption on paper exports (i.e., that paper exports comprise a constant proportion of total paper recovery). If all of the recovered paper is exported, none of the incremental recovery results in a corresponding reduction in U.S. pulpwood harvest. At the other extreme, if all of the incremental recovery results in a corresponding reduction in U.S.

pulpwood harvest, the storage factor would be higher. The results are also sensitive to assumptions on the moisture content and the carbon content of pulpwood, pulp, and paper.

- Also, this analysis does not consider the effect that decreases in pulpwood harvest may have on the supply curve for sawtimber, which could result in a potential increase in harvests of other wood products. This could result in a smaller reduction in harvest, offsetting some of the carbon storage benefit estimated here. Prestamon and Wear (2000) investigated how pulpwood and sawtimber supply would change with changes in prices for each. They estimated that non-industrial private forest and industry may increase sawtimber supply when the price for pulpwood increases—and the change is perceived as temporary—although the estimate was not statistically significant. The sawtimber supply, however, may decrease when the pulpwood price increases—and the change is perceived as permanent—but, once again, the estimate was not statistically significant. Given that the relationship between the price change for pulpwood and supply of sawtimber was not consistent and was often statistically insignificant, there is not compelling evidence to indicate that the omission of this effect is a significant limitation to the analysis.
- A related issue is that if the domestic harvest of pulpwood decreases, it could result in a decrease in the cost of domestic production, which could shift the balance between domestic paper production and imports to meet demand.

The following limitations relate to the estimate of forest carbon storage for wood products:

- The estimated changes in timber harvests resulting from increased recycling and source reduction are based on process efficiency estimates that assume overall demand for softwood products remains constant. Increased recycling or source reduction of wood products could increase or decrease demand for new wood products to the extent that these changes influence factors such as virgin wood-product prices. EPA has not explicitly modeled this effect because of the complexity of virgin wood-product markets and the fact that the current assumption provides a first-order estimate of the change in timber harvests from recycling and source reduction.
- Similarly, in-use product carbon storage is modeled based on first-order reductions in carbon storage associated with losses from recycling wood products and avoided in-use product carbon storage from source reduction of wood products. This analysis provides an estimate of the direct, first-order effects on the in-use carbon pool associated with recycling or source reduction of wood products.

As shown in Exhibit 9-3 and Exhibit 9-6, estimates of forest carbon storage resulting from increased paper recycling vary over time. As noted earlier, WARM applies a single point estimate reflecting a time period that best balances the competing criteria of (1) capturing the long-term forest carbon sequestration effects, and (2) limiting the uncertainty inherent in projections made well into the future. The variation in forest carbon storage estimates over time and the limitations of the analysis discussed earlier indicate considerable uncertainty in the point estimate selected. In comparison to the estimates of other types of GHG emissions and sinks developed in other parts of WARM, the magnitude of forest carbon sequestration is relatively high. Based on these forest carbon storage estimates, source reduction and recycling of paper are found to have substantial net GHG reductions. Because paper products make up the largest share of municipal waste generation (and the largest volumes of waste managed through recycling, landfill use, and combustion), it is important to bear in mind the uncertainty in the forest carbon sequestration values when evaluating the results of this analysis.

9.6 References

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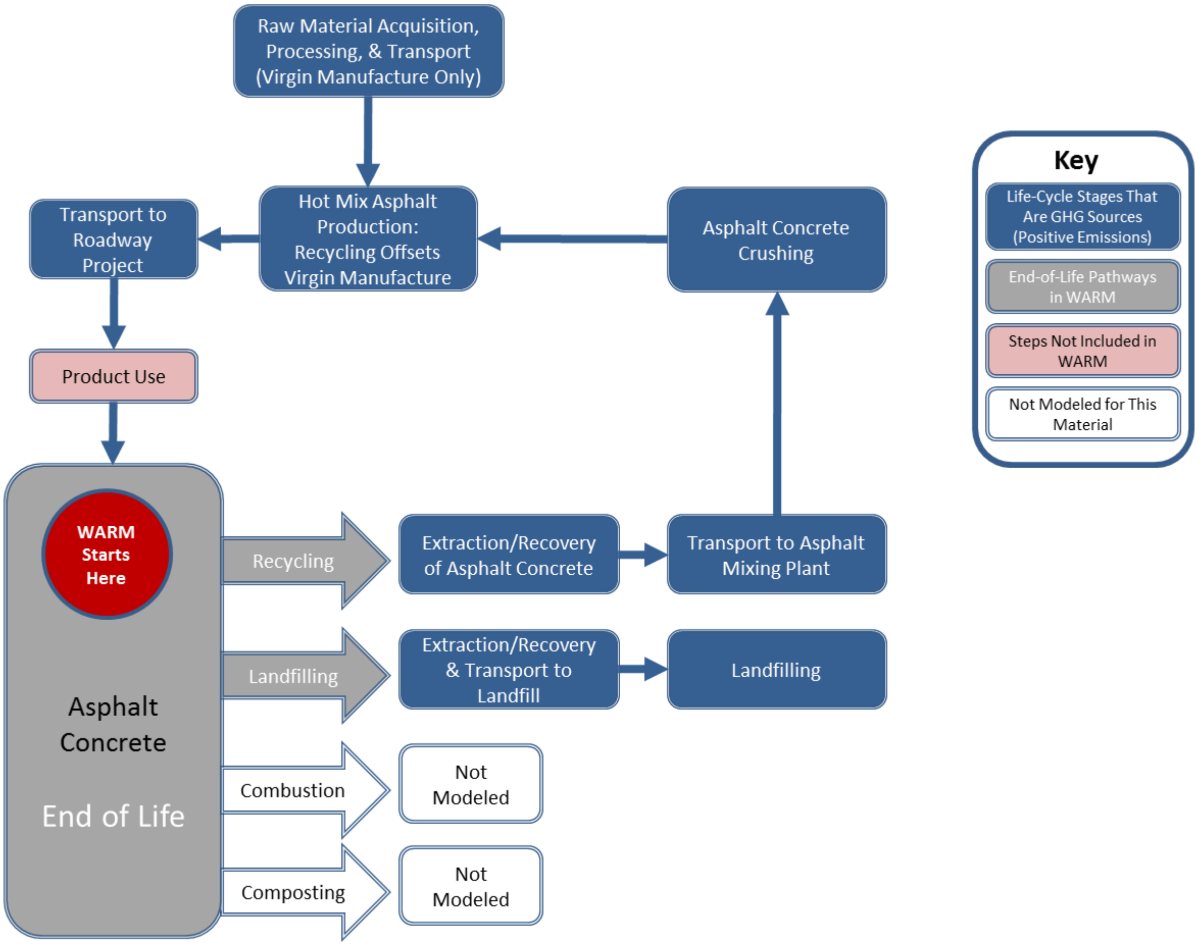
10 ASPHALT CONCRETE

10.1 Introduction to WARM and Asphalt Concrete

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for asphalt concrete beginning at the waste generation reference point.[54] EPA uses the WARM GHG emission factors to compare the net emissions associated with asphalt concrete in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 10-1 shows the general outline of materials management pathways for asphalt concrete in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, and Landfilling, see the chapters devoted to those processes.

Exhibit 10-1: Life Cycle of Asphalt Concrete in WARM



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

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

including pavement, base, and sub-base. The pavement layer, the surface layer, is made of either asphalt concrete or portland cement concrete.

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

10.2 Life-Cycle Assessment and Emission Factor Results

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

WARM does not consider composting or combustion for asphalt concrete. As Exhibit 10-2 illustrates, all of the GHG sources and sinks relevant to asphalt concrete in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 10-2: Asphalt Concrete GHG Sources and Sinks from Relevant Materials Management Pathways

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

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 10-2 and calculates net GHG emissions per short ton of asphalt concrete inputs. For more detailed methodology on emission factors, please see the following sections on individual waste management strategies. Exhibit 10-3 outlines the net GHG emissions for asphalt concrete under each materials management option.

Exhibit 10-3: Net Emissions for Asphalt Concrete under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Asphalt Concrete	-0.11	-0.08	NA	NA	0.04

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

10.3 Raw Materials Acquisition and Manufacturing

For asphalt concrete, GHG emissions associated with RMAM are (1) GHG emissions from energy used during the raw materials acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[55] Asphalt concrete is composed primarily of aggregate, which consists of hard, graduated fragments of sand, gravel, crushed stone, slag, rock dust, or powder and road-asphalt binder, a coproduct of petroleum refining (Exhibit 10-4). The process that energy GHG emissions result from is the manufacture of these main raw materials, plus the HMA production process. The production process involves sorting and drying the aggregate, heating the asphalt binder, and heating and applying the mixture. Aggregate material can be produced from numerous sources, including natural rock, reclaimed asphalt pavement (RAP), reclaimed concrete pavement (RCP), glass, fly ash, bottom ash, steel slag, recycled asphalt shingles, and crumb rubber. The transportation GHG emissions are generated from transportation associated with raw materials during manufacture and transportation to the roadway construction site. EPA assumes that non-energy process GHG emissions from making asphalt concrete are negligible because no data were available about non-energy emissions, and the majority of the asphalt concrete is aggregate, which has no non-energy emissions associated with its production.

Exhibit 10-4: Composition of Hot Mix Asphalt

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

Source: Hassan 2009.

10.4 Materials Management Methodologies

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

Reclaimed asphalt pavement from HMA can be either recycled in an open loop as aggregate for a variety of materials or it can be recycled in a closed loop to produce new HMA, which results in lower input quantities of both new aggregate and new asphalt binder; WARM examines only the closed-loop pathway. An estimated 80–85 percent of waste HMA is recycled to produce aggregate or HMA (Levis, 2008). Asphalt concrete can also be landfilled in a construction and demolition (C&D) landfill. Descriptions of life-cycle energy and GHG emissions data for virgin asphalt mixture are available from the Athena Sustainable Materials Institute (Athena, 2001) and in a technical report published by

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

Transportation Research Board (Hassan, 2009). This analysis considers source reduction, recycling, and landfilling for materials management of asphalt concrete.

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

10.4.1 Source Reduction

Virgin production of HMA is generalized to be a three-step process: (1) aggregate production, (2) road asphalt binder production, and (3) HMA production. Exhibit 10-5 summarizes the avoided emissions of source reducing virgin HMA. The avoided emissions associated with process energy and transportation energy are similar in magnitude, suggesting that the transportation of raw materials to the HMA plant and to the road site is as emissions-intensive as the actual production of the HMA itself. The following paragraphs give a further explanation of the process energy and transportation energy required for HMA production and avoided by source reduction. For more information on Source Reduction, please see the chapter on Source Reduction.

Exhibit 10-5: Source Reduction Emission Factors for Asphalt Concrete ($MTCO_2e$/Short Ton)

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

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

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

– = Zero emissions.

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

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

10.4.1.1 Developing the Emission Factor for Source Reduction of Asphalt Concrete

To calculate the avoided GHG emissions for asphalt concrete, EPA first looks at two components of GHG emissions from RMAM activities: (1) process energy and (2) transportation energy GHG emissions. No non-energy GHG emissions result from asphalt concrete RMAM activities. Exhibit 10-6 shows the results for each component and the total GHG emission factors for source reduction of asphalt concrete. A discussion of the methodology for estimating emissions from asphalt concrete manufactured from recycled materials can be found in the Recycling section.

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

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

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

Process energy includes the requirements to produce the raw material aggregate and asphalt binder to combine the aggregate and binder in an HMA plant and to produce the hot mix asphalt. By mass, most of the HMA is composed of aggregate and the remainder consists of asphalt binder (Exhibit 10-4). By far the most energy-intensive part of this process is the production of the asphalt binder. The HMA plant operations to produce the hot mix asphalt have more modest energy requirements, and the production of aggregate (extraction and processing of limestone, granite, and other stone) is even less energy intensive.

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

EPA obtained energy inputs for the manufacturing process of asphalt binder from the Athena Sustainable Materials Institute's Life Cycle Inventory for Road and Roofing Asphalt, prepared by Franklin Associates (Athena, 2001). For road asphalt binder production, we obtained data on virgin crude oil (which is a material input in manufacturing asphalt binder) from National Renewable Energy Laboratory's (NREL) U.S. Life Cycle Inventory (LCI) Database (NREL, 2009). EPA also took data on limestone manufacturing from the U.S. LCI Database (NREL, 2009). Finally, we obtained energy inputs for the production of HMA from aggregate and asphalt binder from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). We then multiplied the fuel consumption estimates by the fuel-specific carbon contents. The process energy used to produce asphalt concrete and the resulting emissions appear in Exhibit 10-7.

Exhibit 10-7: Process Energy GHG Emissions Calculations for Virgin Production of Asphalt Concrete

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO$_2$e/Short Ton)
Asphalt concrete	0.95	0.06

EPA obtained transportation energy requirements for the asphalt binder, aggregate, and HMA from the Canadian Program for Energy Conservation (Natural Resources Canada, 2005). We assume the asphalt concrete materials are transported by truck, based on the average transport distance requirements for two different types of roadway projects: Class I Roadway (rural secondary highway) and Class II Roadway (urban arterial roadway). For the production of virgin crude oil, we obtained transportation data from NREL (2009). The U.S. LCI Database assumes no transportation is associated with the manufacturing of limestone. The transportation energy and the resulting emissions used to produce and deliver the asphalt concrete to the roadway project appear in Exhibit 10-8.

Exhibit 10-8: Transportation Energy Emissions Calculations for Virgin Production of Asphalt Concrete

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Asphalt Concrete	0.73	0.05

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

10.4.2 Recycling

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

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

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

A recycled input credit is calculated for asphalt concrete by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the asphalt concrete from virgin inputs. GHG emissions associated with management (i.e., collection, transportation, and processing) of recycled asphalt concrete are included in the recycling credit calculation. Each component of the recycling emission factor as shown in Exhibit 10-9 is discussed in later paragraphs. For more information on recycling in general, see the Recycling chapter.

Exhibit 10-9: Recycling Emission Factor for Asphalt Concrete ($MTCO_2e$/Short Ton)

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

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

10.4.2.1 Developing the Emission Factor for Recycling of Asphalt Concrete

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

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

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

Step 1. *Calculate GHG emissions from virgin production of one short ton of asphalt concrete.* The GHG emissions from virgin production of asphalt concrete are provided in Exhibit 10-7 and Exhibit 10-8. EPA Calculates emissions from production of virgin asphalt concrete using the data sources and methodology also used to calculate the source reduction factor. EPA applies fuel-specific carbon coefficients to the process and transportation energy use data for virgin RMAM of asphalt concrete.

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

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

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Asphalt Concrete	0.41	0.03

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

Exhibit 10-11: Transportation Energy GHG Emissions Calculations for Recycled Production of Asphalt Concrete

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Asphalt Concrete	0.05	0.00

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

Step 3. *Calculate the difference in emissions between virgin and recycled production.* To calculate the GHG emissions implications of recycling one short ton of asphalt concrete, WARM subtracts the recycled product emissions (calculated in Step 2) from the virgin product emissions (calculated in Step 1) to calculate the GHG savings. These results appear in Exhibit 10-12.

Exhibit 10-12: Differences in Emissions between Recycled and Virgin Asphalt Concrete Manufacture ($MTCO_2e$/Short Ton)

Material/Product	Product Manufacture Using 100% Virgin Inputs ($MTCO_2e$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2e$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2e$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Asphalt Concrete	0.06	0.05	–	0.03	0.00	–	-0.03	-0.05	–

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

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. Processors discard this portion in either the recovery stage or the remanufacturing stage; and consequently, less than one short ton of new material generally is made from one short ton of recovered material. Material losses are quantified and translated into loss rates. The recycled input credits calculated earlier are, therefore, adjusted to account for any loss of product during the recycling process. Because the recovered asphalt concrete is valuable and typically recovered on-site, the retention rate for recovered asphalt concrete is quite high. We assume, therefore, that the loss rates for recycling asphalt concrete are less than 1 percent by weight (Levis, 2008), and we assume that the recycling retention rate is 100 percent. Thus we do not adjust the GHG emissions associated with recycling (i.e., the difference between virgin and recycled manufacture), as shown in Exhibit 10-12.

10.4.3 Composting

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

10.4.4 Combustion

While asphalt concrete does contain combustible materials in the form of petroleum-based components, industry and academic experts indicate that asphalt is not combusted as an end-of-life management pathway, nor would it be logical to do so (Hassan, 2009). The combustible components of asphalt concrete make up a relatively small percentage of the material (roughly 5 percent), meaning that a lot of energy would be wasted to heat up the non-combustible components at the facility (Levis, 2008). The uses for recycled asphalt also provide a more valuable end-use for the material than the value of energy recovery from combustion. Finally, emissions such as volatile organic compounds generated by combustion would provide emission control burdens at the facilities that outweigh the potential energy gains (Hassan, 2009). For these reasons, EPA does not include an emission factor in WARM for combustion of asphalt concrete.

10.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since asphalt concrete does not contain bio-degradable carbon, there are zero emissions from landfill methane, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling asphalt concrete. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for asphalt concrete is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. Exhibit 10-13 provides the net emission factor for landfilling asphalt concrete. For more information on Landfilling, please see the chapter on Landfilling.

Exhibit 10-13: Landfilling Emission Factor for Asphalt Concrete ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

10.5 Limitations

As indicated in Section 10.1, asphalt concrete is produced in a variety of mixtures, including hot mix, warm mix, cold mix, cut-back, mastic, and natural, each with distinct material and energy inputs. EPA chose to analyze hot mix asphalt because of its widespread use in U.S. roadway projects. Recent studies indicate that warm mix asphalt may provide significant energy and GHG savings to the asphalt industry because of lower heat requirements during production (Hassan, 2009). As data become available, it will be important to estimate the life-cycle GHG emissions from the production and use of other types of asphalt concrete.

10.6 References

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

Census Bureau. (2001). *Mining-Subject Series, Product Summary, U.S. Economic Census.* June 2001. Available online at: http://www.census.gov/prod/ec97/97n21s-ps.pdf

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Levis, J. W. (2008). *A Life-Cycle Analysis of Alternatives for the Management of Waste Hot-Mix Asphalt, Commercial Food Waste, and Construction and Demolition Waste*. North Carolina State University.

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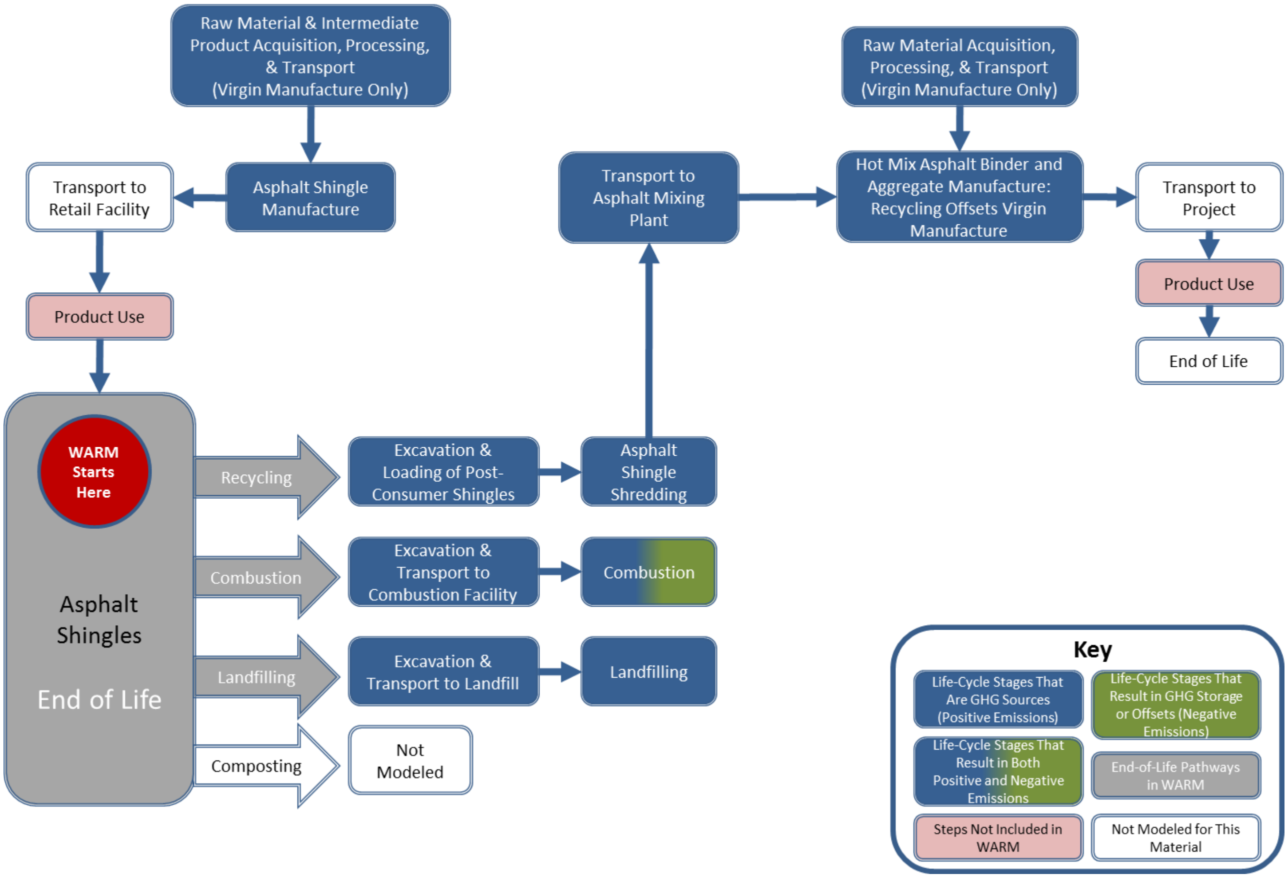
11 ASPHALT SHINGLES

11.1 Introduction to WARM and Asphalt Shingles

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for asphalt shingles beginning at the waste generation reference point.[56] The WARM GHG emission factors are used to compare the net emissions associated with asphalt shingles in the following four waste management alternatives: source reduction, recycling, combustion, and landfilling. Exhibit 11-1 shows the general outline of materials management pathways for asphalt shingles in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, Combustion, and Landfilling, see the chapters devoted to those processes.

Exhibit 11-1: Life Cycle of Asphalt Shingles in WARM



Asphalt shingles are used as a roofing material and are typically made of a felt mat saturated with asphalt. Small rock granules are added to one side of the shingle in order to protect against natural elements such as sun and rain. Depending on whether the shingle base is organic or fiberglass, the granules are composed of asphalt cement (19 to 36 percent by weight, respectively), a mineral stabilizer like limestone or dolomite (8 to 40 percent), and sand-sized mineral granules (20 to 38 percent), in addition to the organic or fiberglass felt backing (2 to 15 percent). The asphalt that is used in shingles is

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

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

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

11.2 Life-Cycle Assessment and Emission Factor Results

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

WARM does not consider composting for asphalt shingles. As Exhibit 11-2 illustrates, all of the GHG sources and sinks relevant to asphalt shingles in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life cycle assessment.

Exhibit 11-2: Asphalt Shingles GHG Sources and Sinks from Relevant Materials Management Pathways

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

NA = Not applicable.

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

Exhibit 11-3: Net Emissions for Asphalt Shingles under Each Materials Management Option (MTCO$_2$e/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Asphalt Shingles	-0.19	-0.09	NA	-0.34	0.04

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

11.3 Raw Materials Acquisition and Manufacturing

For asphalt shingles, GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the raw materials acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[57] For virgin asphalt shingles, process energy GHG emissions result from the manufacture of the main raw materials used in the manufacturing of asphalt shingles, including the fiberglass mat carrier sheet, the asphalt binder and coating, mineral surfacing and the stabilizer or filler. Process energy GHG emissions also include the actual roof shingles manufacturing process, which is a continuous process on an assembly line consisting of a dry and wet accumulator, coating, cooling/drying, shingle cutting and roll winder that builds the shingles from the raw materials (Athena, 2000). Transportation emissions are generated from transportation associated with raw materials, during manufacture and during transportation to the retail facility. EPA assumes that non-energy process GHG emissions from making asphalt shingles are negligible.

The RMAM calculation in WARM also incorporates "retail transportation," which incorporates the average truck, rail, water and other-modes transportation emissions required to transport asphalt shingles from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 11-4. Transportation emissions from the retail point to the consumer are not included. The miles travelled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 11-4: 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$_2$e/ Short Ton)
Asphalt Shingles	356	0.42	0.03

11.4 Materials Management Methodologies

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

Reclaimed asphalt shingles can be used to offset the production and transport of both aggregate and binder. Greenhouse gas savings are realized for source reduction, recycling and combustion, while

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

landfilling has a slightly positive emission factor due to the emissions from transportation to the landfill and operation of landfill equipment. It is interesting to note that the GHG savings for combustion are greater than for any other waste management alternative. This is because the asphalt shingles have significantly high energy content (BTU per ton) due to the asphalt cement coating. Asphalt shingles that are combusted can displace other fuels (i.e., refinery fuel gas) used in cement kilns. This application would prevent the combustion emissions associated with refinery fuel gas and offers significant GHG reduction potential as a waste management alternative to landfilling. This analysis considers source reduction, recycling, combustion, and landfilling for materials management of asphalt concrete.

11.4.1 Source Reduction

The type of production process used to produce asphalt shingles depends on whether the asphalt shingle is organic felt-based or fiberglass mat-based. The Athena database contains life-cycle information on both types (organic and fiberglass) of asphalt shingles (Athena, 2000). In general, the production of fiberglass mat-based asphalt shingles is less energy-intensive (and subsequently less GHG-intensive) than the production of organic paper felt-based asphalt shingles. This is because fiberglass mat does not absorb water used throughout the mat production (unlike the organic shingle counterparts). Thus, it is less energy-intensive to form glass mat since the drying of the mat is eliminated as a process step. As discussed earlier, the EPA included only fiberglass shingles in WARM because they make up the majority (82 percent) of the residential shingle market, and the market share is growing (HUD, 1999). The source reduction emission factor for fiberglass asphalt shingles is summarized in Exhibit 11-5. For more information, please see the chapter on Source Reduction.

Exhibit 11-5: Source Reduction Emission Factors for Asphalt Shingles ($MTCO_2e$/Short Ton)

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

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

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

– = Zero emissions.

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

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

11.4.1.1 Developing the Emission Factor for Source Reduction of Asphalt Shingles

To calculate the avoided GHG emissions for asphalt shingles, EPA first looks at two components of GHG emissions from RMAM activities: process energy and transportation energy GHG emissions. There are no non-energy GHG emissions from asphalt shingles RMAM activities. Exhibit 11-6 shows the results for each component and the total GHG emission factors for source reduction of asphalt shingles. More information on each component making up the final emission factor is provided below. The methodology for estimating emissions from asphalt shingles manufactured from recycled materials is discussed below in the Recycling section.

Exhibit 11-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Asphalt Shingles ($MTCO_2e$/Short Ton)

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

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

EPA used data from the Athena Sustainable Materials Institute (2000) to develop a source reduction emission factor for fiberglass shingles. These data include the energy (by fuel type) associated with the production of the primary raw materials as well as secondary processing to manufacture the actual shingles (i.e., the energy associated with the operations at the roofing plant itself). Precombustion energy is not included in Athena (2000) and was subsequently added to the raw process and transportation data fuel breakdown. The process energy used to produce asphalt shingles and the resulting emissions are shown in Exhibit 11-7.

Exhibit 11-7: Process Energy GHG Emissions Calculations for Virgin Production of Asphalt Shingles

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Asphalt Shingles	2.19	0.12

EPA also used transportation data from the Athena Sustainable Materials Institute (2000) to develop the asphalt shingles source reduction emission factor. These data again include transportation energy associated with the primary raw materials and the manufacturing process itself. The transportation energy used to produce asphalt shingles and the resulting emissions are shown in Exhibit 11-8.

Exhibit 11-8: Transportation Energy Emissions Calculations for Virgin Production of Asphalt Shingles

Material/Product	Transportation Energy per Ton Made from Virgin Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Asphalt Shingles	0.58	0.04

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

11.4.2 Recycling

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

Using asphalt shingles as a component in hot mix asphalt (HMA) is the most common process to which recycled shingles are added. Researchers at the University of Massachusetts have determined that HMA that consists of up to 7 percent recycled asphalt shingles shows no quality differences as compared to virgin HMA (Mallick, 2000). Waste shingles are ground, screened and filtered for contaminants. They are then usually fed into and mixed with aggregate before being added to virgin asphalt binder (CMRA, 2007a). In our analysis, we assume that the ground asphalt shingles displace the production of virgin asphalt binder and aggregate, taking into account the asphalt and aggregate content of the shingles as shown in Exhibit 11-9.

Exhibit 11-9: Typical Composition of Asphalt Shingles

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

Source: CMRA, 2007a.

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

A "recycled input credit" is calculated for asphalt shingles by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing virgin asphalt binder and aggregate, taking into account the asphalt and aggregate content of the shingles. GHG emissions associated with management (i.e., collection, transportation and processing) of recycled asphalt shingles are included in the recycling credit calculation. Each component of the recycling emission factor as provided in Exhibit 11-10 is discussed further in section 11.4.2.1. For more information on recycling in general, see the Recycling chapter.

Exhibit 11-10: Recycling Emission Factor for Asphalt Shingles (MTCO$_2$e/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Asphalt Shingles	–	–	-0.11	0.01	–	NA	-0.09

– = Zero emissions.

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

11.4.2.1 Developing the Emission Factor for Recycling of Asphalt Shingles

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

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

Step 1. *Calculate emissions from the recycling of one short ton of asphalt shingles.* The GHG emissions from recycling asphalt shingles are provided in Exhibit 11-7 and Exhibit 11-8.

EPA estimates the energy associated with excavating, loading and shredding the post-consumer asphalt shingles using data from Dr. Kimberly Cochran (Cochran, 2006). We assume that the machinery is operated using diesel fuel. The emissions for the process of excavating, loading and shredding the post-consumer asphalt shingles in preparation for use in hot mix asphalt are shown in Exhibit 11-11.

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

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Asphalt Shingles	0.04	0.00

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

Exhibit 11-12: Transportation Energy GHG Emissions Calculations for Recycled Production of Asphalt Shingles

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Asphalt Shingles	0.08	0.01

Step 2. *Calculate GHG emissions for production of components of hot mix asphalt.* Exhibit 11-13 and Exhibit 11-14 provide the process and transportation emissions associated with producing hot mix asphalt components.

EPA assumes that the recycled asphalt shingles will avoid the production of virgin asphalt binder and aggregate based on the relative percent virgin asphalt binder and aggregate as shown in Exhibit 11-9. We estimate the emissions associated with the production of virgin asphalt binder using the data and methodology discussed in the Asphalt Concrete chapter. Specifically, we obtained energy inputs for the manufacturing process of asphalt binder from the Athena Sustainable Materials Institute's *Life Cycle Inventory for Road and Roofing Asphalt*, prepared by Franklin Associates (Athena, 2001). To estimate the emissions associated with virgin production of aggregate, we obtained emission factors discussed in the Concrete chapter for virgin aggregate production.

For example, since fiberglass shingles contain 22 percent "asphalt cement" per short ton, we assume that each ton of recovered asphalt shingles could avoid the production-related GHG emissions of virgin asphalt binder adjusted by this percentage. The "weighted" emission factors in Exhibit 11-13 and Exhibit 11-14 show the avoided GHG emissions associated with using recycled asphalt shingles in hot mix asphalt to displace virgin asphalt binder and aggregate.

Exhibit 11-13: Process Energy Emissions for Components of Hot Mix Asphalt

Material/Product	Process Energy Emissions ($MTCO_2e$/Short Ton)	Typical Composition as Shown in Exhibit 11-9 (%)	Weighted Process Energy Emissions ($MTCO_2e$/Short Ton)
Virgin Asphalt Binder	0.54	22%	0.12
Aggregate	0.00	38%	0.00

Exhibit 11-14: Transportation Energy emissions for Components of Hot Mix Asphalt

Material/Product	Transportation Energy Emissions ($MTCO_2e$/Short Ton)	Typical Composition as Shown in Exhibit 11-9 (%)	Weighted $MTCO_2e$/Short Ton
Virgin Asphalt Binder	0.05	22%	0.01
Aggregate	0.01	38%	0.01

Step 3. *Calculate the avoided hot mix asphalt emissions using recycled asphalt shingles.* To calculate the GHG emissions implications of recycling one short ton of asphalt shingles, WARM subtracts the virgin asphalt binder and aggregate avoided emissions (calculated in Step 2) from the recycling process emissions (calculated in Step 1) to obtain the GHG savings. These results are shown in Exhibit 11-15.

Exhibit 11-15: Differences in Emissions between Recycled and Virgin Asphalt Shingles Manufacture ($MTCO_2e$/Short Ton)

Material/ Product	Product Manufacture Using 100% Virgin Inputs ($MTCO_2e$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2e$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2e$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Asphalt Shingles	0.12	0.07	–	0.00	0.03	–	-0.12	-0.04	–

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

Step 4. *Adjust the emissions differences to account for recycling losses.* When any material is recovered for recycling, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the remanufacturing stage. Consequently, less than 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. Since data were unavailable for the losses associated with recovered asphalt shingles, WARM assumes a 7.2 percent loss rate for asphalt shingles recycling based on the average residue percent of throughput across all multi-material material recovery facilities (MRF) (Berenyi, 2007). The differences in emissions from virgin versus recycled process energy and transportation energy are adjusted to account for loss rates by multiplying the final three columns of Exhibit 11-15 by 92.8 percent, the amount of material retained after losses (i.e., 100 percent input – 7.2 percent lost = 92.8 percent retained).

11.4.3 Composting

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

11.4.4 Combustion

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

Since C&D waste is typically not combusted in standard combustion facilities because of various impurities that are present, EPA assumes that asphalt shingles are combusted in cement kilns (CMRA, 2007a). We obtained data on the energy content of asphalt shingles from the Construction Materials Recycling Association (CMRA, 2007a). We used carbon coefficients for oil and lubricants taken from the *U.S. Inventory of Greenhouse Gas Emissions and Sinks* as a proxy to calculate combustion emissions associated with the combustion of fiberglass-based shingles (EPA, 2014). Similarly, we calculated offset emissions using the carbon coefficients for refinery fuel gas typically used in cement kilns, taking into account the amount of shingles needed to generate a similar amount of energy. Greenhouse gas benefits are shown in Exhibit 11-16.

Exhibit 11-16: Components of the Combustion Net Emission Factor for Asphalt Shingles ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Asphalt Shingles	–	0.03	0.65	0.04	-1.05	–	-0.34

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

11.4.4.1 Developing the Emission Factor for Combustion of Asphalt Shingles

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 0.04 $MTCO_2e$ for one short ton of asphalt shingles (FAL, 1994).

CO_2 from Combustion and N_2O from Combustion: Carbon coefficients for oil and lubricants are based on the *U.S. Inventory of Greenhouse Gas Emissions and Sinks* as a proxy to calculate combustion emissions associated with the combustion of fiberglass-based shingles in cement kilns (EPA, 2014). Emissions of N_2O are also included in the combustion factor.

Avoided Utility Emissions: Since asphalt shingles are not typically combusted in waste-to-energy (WTE) combustion facilities, EPA modeled the combustion of asphalt shingles as avoiding the combustion of refinery fuel gas typically combusted in cement kilns. The energy content and carbon content of refinery fuel gas are based on data from the American Petroleum Institute and the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, respectively (API, 2004; EPA, 2014). Using the energy content per ton of fiberglass shingles in comparison to the energy and carbon content of refinery fuel gas, EPA calculated the avoided GHG emissions associated with combusting fiberglass shingles instead of refinery fuel gas in cement kilns.

Exhibit 11-17: Avoided Emissions from Combustion of Asphalt Shingles in Cement Kilns

(a)	(b) Energy Content (Million Btu/Short Ton)	(c) Carbon Content (kg C/ Million Btu)[a]	(d) Short Tons of Shingles Required/Short Ton Refinery Fuel Gas	(e) Avoided Emissions ($MTCO_2e$/Short Ton Asphalt Shingles) (e = c adjusted per ton/d)
Refinery Fuel Gas	37.5	32.65	NA	NA
Fiberglass Shingles	8.8	20.24	4.26	1.05

Source: New Mexico Environment Department Solid Waste Bureau, 2010.
NA = Not applicable.
[a] The carbon content for refinery fuel gas is adjusted to mass based on the assumption that 250 gallons of refinery fuel gas weigh 1 ton.

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

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

11.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since asphalt shingles do not biodegrade, there are zero emissions from landfill methane, zero landfill carbon storage and zero avoided utility emissions associated with landfilling asphalt shingles. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the landfilling emission factor for asphalt shingles is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. For further information, please refer to the chapter on Landfilling. Exhibit 11-18 provides the net emission factor for landfilling asphalt shingles.

Exhibit 11-18: Landfilling Emission Factor for Asphalt Shingles ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Asphalt Shingles	–	0.04	–	–	–	0.04

– = Zero emissions.

11.5 Limitations

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

11.6 References

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12 CARPET

12.1 Introduction to WARM and Carpet

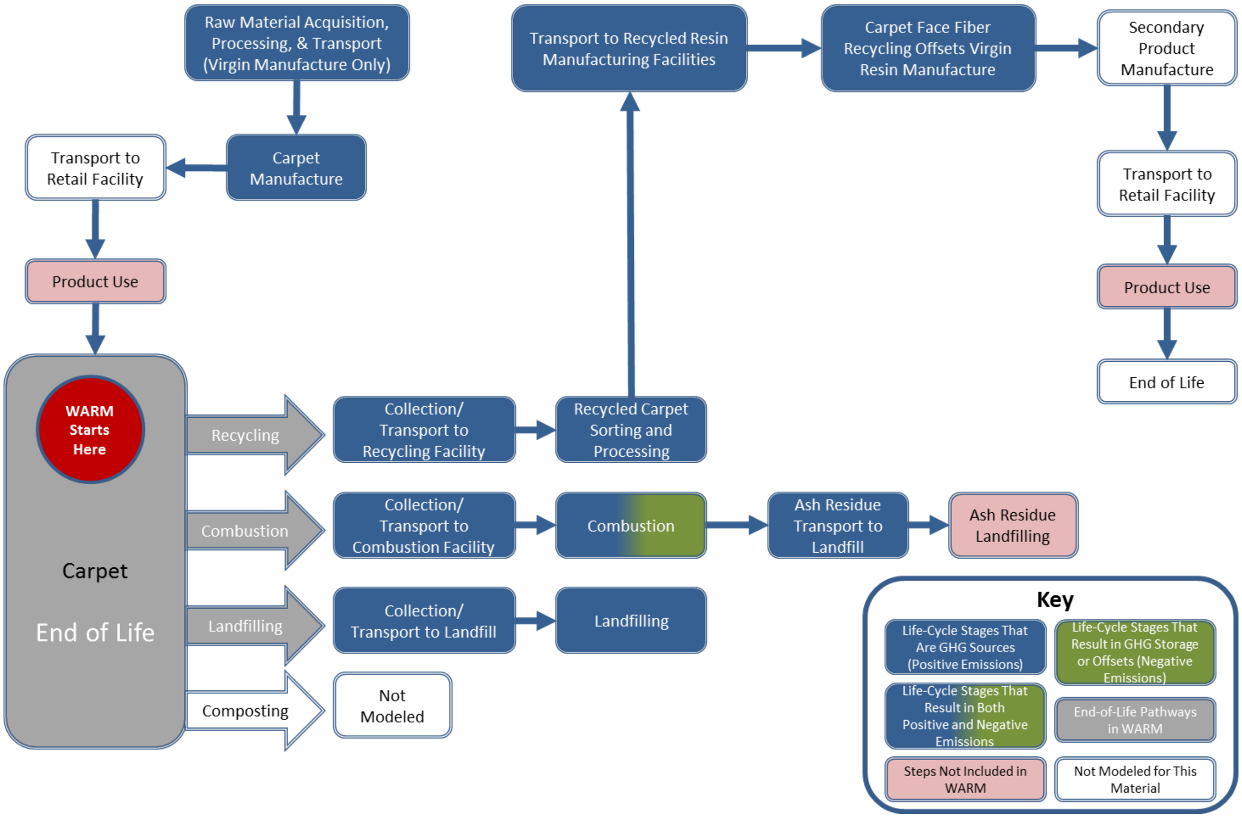
This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for carpet beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with carpet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

At the end of its useful life, carpet can be recovered for recycling, sent to a landfill or combusted. Landfilling is the most commonly selected waste management option for carpet. According to EPA (2011), 9 percent of carpet is recycled annually. Efforts by industry, EPA, and other organizations over the past few years have increased the fraction of waste carpet that is recycled.

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

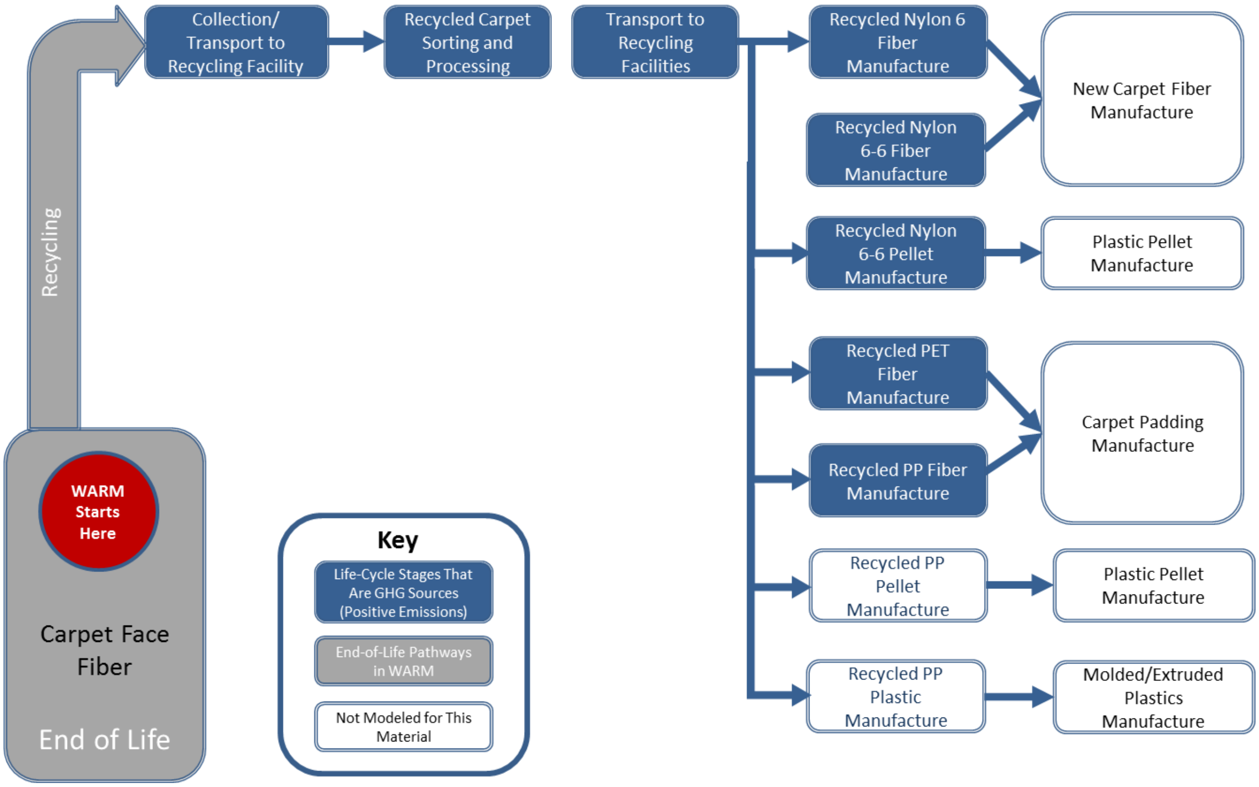
Exhibit 12-1 shows the general outline of materials management pathways in WARM and how they are modeled for carpet. Recycling carpet is an open-loop process, meaning that components are recycled into secondary materials such as carpet pad, molded products and carpet backing. In WARM, the life-cycle energy and material requirements for converting recycled carpet into these various secondary end products were unavailable (Realff, 2010a). Therefore, in the recycling pathway, the recycling benefits for carpet incorporate the avoided manufacture of the various virgin plastic resins only. Carpet is collected curbside and at special recovery events, or individuals can bring it to designated drop-off sites. Once carpet has been collected for recycling, it is sent to material recovery facilities that specialize in separating and recovering materials from carpet. Building on Exhibit 12-1, a more detailed flow diagram of the recycling pathway for carpet is provided in Exhibit 12-2.

Exhibit 12-1: Life Cycle of Carpet in WARM



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

Exhibit 12-2: Detailed Recycling Flows for Carpet in WARM



12.2 Life-Cycle Assessment and Emission Factor Results

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

WARM includes source reduction, recycling, landfilling, and combustion pathways for materials management of carpet. As Exhibit 12-3 illustrates, most of the GHG emissions from end-of-life management of carpet occur from waste management of this product, while most of the GHG savings occur from offsetting upstream raw materials acquisition and the manufacturing of other secondary materials that are recovered from carpet.

Exhibit 12-3: Carpet GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Carpet	GHG Sources and Sinks Relevant to Carpet		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End-of-Life
Source Reduction	**Offsets** - Transport of raw materials and intermediate products - Virgin process energy - Virgin process non-energy - Transport of carpet to point of sale	NA	NA
Recycling	**Emissions** - Transport of recycled materials - Recycled process energy - Recycled process non-energy **Offsets** - Emissions from producing Nylon 6, Nylon 6-6, PET and PP plastic resins from virgin material	NA	**Emissions** - Collection of carpet and transportation to recycling center - De-manufacturing and reprocessing recovered carpet
Landfilling	NA	NA	**Emissions** - Transport to landfill - Landfilling machinery
Combustion	NA	NA	**Emissions** - Transport to WTE facility - Combustion-related CO_2 **Offsets** - Avoided electric utility emissions

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 12-4 and calculates net GHG emissions per short ton of carpet inputs. For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

Exhibit 12-4: Net Emissions for Carpet under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) GHG Emissions For Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Landfilling Emissions	Net Combustion Emissions
Carpet	-3.83	-2.36	NA	0.04	1.10

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

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

NA = Not applicable.

12.3 Raw Materials Acquisition and Manufacturing

The components of nylon broadloom residential carpet in this analysis include: face fiber, primary and secondary backing and latex used for attaching the backings. The face fiber used for nylon carpet is typically made of a combination of Nylon 6, Nylon 6-6, Polyethylene terephthalate (PET) and Polypropylene (PP). For the purpose of developing an emission factor that represents “typical” broadloom residential carpet, WARM reflects the market share of each material in the carpet industry. Carpet backing for broadloom carpet typically consists of polypropylene (PP). For latex used to adhere carpet backings, EPA modeled styrene butadiene, the most common latex used for this purpose. Styrene butadiene latex is commonly compounded with a filler such as calcium carbonate (limestone). Inputs to the manufacture of nylon, PP and styrene butadiene are crude oil and/or natural gas. Exhibit 12-5 provides the assumed material composition of the typical carpet used for this analysis (FAL, 2002, Realff, 2011b).

Exhibit 12-5: Material Composition of One Short Ton of Carpet

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

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

The main polymers that are used for the face fiber are Nylon 6-6, Nylon 6, PET, and PP with very small amounts of wool and a growing interest in the use of bio-based fibers. The average proportion of each of these plastic resins in carpet face fibers is provided in Exhibit 12-6. These components are recovered and recycled in different ways, each consuming different amounts of energy. For example, Nylon 6 face fiber is recycled mostly through depolymerization, whereas Nylon 6-6 face fiber is recycled mainly through shaving the fiber followed by remelting and extrusion.

Exhibit 12-6: Residential Face Fiber Mix 1995-2000

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

Source: Realff, 2011b

The process used to turn the components in Exhibit 12-5 into a finished carpet may include weaving, tufting, needlepunching and/or knitting. According to the Carpet and Rug Institute, 95 percent of carpet produced in the United States is tufted (CRI, 2010). During tufting, face pile yarns are rapidly sewn into a primary backing by a wide multineedled machine. After the face pile yarns are sewn into the primary backing, a layer of latex is used to secure a secondary backing, which adds strength and dimensional stability to the carpet.

12.4 Materials Management Methodologies

This analysis considers source reduction, recycling, landfilling, and combustion of carpet. It is important to note that carpet is not recycled into new carpet; instead, it is recycled in an open loop process. The life-cycle assessment of carpet disposal must take into account the variety of second-generation products made from recycled carpet. Information on carpet recycling and the resulting second-generation products is sparse; however, EPA has modeled pathways for which consistent data are available for recycled carpet components. As described previously, due to unavailable life-cycle data on the manufacture of second-generation products from recycled carpet, EPA modeled only the remanufacture of the various virgin plastic resins (i.e., one step before the resins are used to manufacture the second-generation products such as carpet pad, molded products and carpet backing). Please see Exhibit 12-2 for the process flow diagram that illustrates these boundaries.

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

12.4.1 Source Reduction

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

Exhibit 12-7 outlines the GHG emission factor for source reducing carpet. GHG benefits of source reduction are calculated as the avoided emissions from raw materials acquisition and manufacturing (RMAM) of new carpet.

Exhibit 12-7: Source Reduction Emission Factor for Carpet ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Carpet	-3.83	-3.83	NA	NA	-3.83	-3.83

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.
NA = Not applicable.

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

12.4.1.1 Developing the Emission Factor for Source Reduction of Carpet

To calculate the avoided GHG emissions for carpet, EPA looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and process non-energy GHG emissions. Exhibit 12-8 shows the results for each component and the total GHG emission factor for source reduction. More information on each component making up the final emission factor is provided in the remainder of this section.

Exhibit 12-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Carpet ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Carpet	3.23	0.10	0.50	3.83

FAL (2002) reports the amount of energy required to produce one short ton of carpet as 60.32 million Btu. FAL (2002) also provided the fuel mix that makes up this energy estimate. To estimate GHG emissions, EPA multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. Summing the resulting GHG emissions, by fuel type, gives the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in carpet manufacture (Exhibit 12-9).

Exhibit 12-9: Process Energy GHG Emissions Calculations for Virgin Production of Carpet

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Carpet	60.32	3.23

Transportation energy emissions come from fossil fuels used to transport carpet raw materials and intermediate products. The methodology for estimating these emissions is the same as that for process energy emissions. Based upon estimated total carpet transportation energy in Btu, EPA calculates the total emissions using fuel-specific carbon coefficients (Exhibit 12-10).

Exhibit 12-10: Transportation Energy Emissions Calculations for Virgin Production of Carpet

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Carpet	1.36	0.10

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

Process non-energy GHG emissions occur during manufacture but are not related to combusting fuel for energy. For carpet, non-energy GHGs are emitted in the use of solvents or chemical treatments. FAL provided data on GHG emissions from non-energy-related processes in units of pounds of native gas (2002). We convert pounds of gas per 1,000 lbs of carpet to metric tons of gas per short ton of carpet and then multiply that by the ratio of carbon to gas to produce the emission factor in $MTCO_2e$ per short ton of carpet, as detailed in the example below, showing the calculation of CH_4 process non-energy emissions for carpet. Exhibit 12-11 shows the components for estimating process non-energy GHG emissions for carpet.

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

$$0.0025 \text{ MT } CH_4/\text{short ton carpet} \times 25 \text{ MTCO}_2\text{e/metric ton } CH_4 = 0.06 \text{ MTCO}_2\text{e/short ton carpet}$$

Exhibit 12-11: Process Non-Energy Emissions Calculations for Virgin Production of Carpet

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Carpet	0.01	0.00	–	–	0.00	0.50

– = Zero emissions.

12.4.2 Recycling

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

Exhibit 12-12: Recycling Emission Factor for Carpet ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Sequestration	Net Emissions (Post-Consumer)
Carpet	NA	NA	-1.41	-0.01	-0.94	NA	-2.36

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

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

NA = Not applicable.

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

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

EPA calculates the GHG benefits of recycling carpet by comparing the difference between the emissions associated with manufacturing a short ton of each of the four resins derived from recycled carpet and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. WARM assumes that both recycled Nylon 6-6 fiber and Nylon 6-6 pellets displace the virgin production of Nylon 6-6 resin. These results are then weighted by the distribution shown in Exhibit 12-13 to obtain a composite emission factor for recycling one short ton of carpet. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy.

Exhibit 12-13: Secondary Resins Produced from Recycled Carpet Fibers

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

Source: Realff, 2011b

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

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

We apply fuel-specific carbon coefficients to the life-cycle data for virgin RMAM of each secondary resin (FAL, 2010, Plastics Europe, 2005). The life-cycle data for virgin production of Nylon 6 and Nylon 6-6 were unavailable for production of these resins in the United States. Thus, life-cycle data for the production of these resins in the European context were used as a proxy (Plastics Europe, 2005). Life-cycle data for the production of PET and PP resins are the same as used in the development of the PET and PP emission factors in WARM (FAL, 2011). The upstream life-cycle data also incorporate transportation and process non-energy data. The calculations for virgin process, transportation and process non-energy emissions for the secondary resins are presented in Exhibit 12-14, Exhibit 12-15, and Exhibit 12-16, respectively.

Exhibit 12-14: Process Energy GHG Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton Carpet)
Nylon 6	112.16	6.60
Nylon 6-6	122.40	7.45
PET	28.43	1.75
PP	23.72	1.17

Exhibit 12-15: Transportation Energy Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton Carpet)
Nylon 6	1.05	0.07
Nylon 6-6	0.82	0.05
PET	1.00	0.07
PP	2.36	0.13

Exhibit 12-16: Process Non-Energy Emissions Calculations for Virgin Production of Carpet Secondary Resins

Material/Product	CO_2 Emissions (MT/Short Ton Carpet)	CH_4 Emissions (MT/Short Ton Carpet)	CF_4 Emissions (MT/Short Ton Carpet)	C_2F_6 Emissions (MT/Short Ton Carpet)	N_2O Emissions (MT/Short Ton Carpet)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Nylon 6	1.04	0.00	–	–	0.01	3.43
Nylon 6-6	0.84	0.00	–	–	0.00	1.08
PET	0.27	0.00	–	–	–	0.39
PP	0.07	0.01	–	–	0.00	0.21

– = Zero emissions.

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

EPA then applies the same carbon coefficients to the energy data for the production of the secondary resin production from recycled carpet. Personal correspondence with Dr. Matthew Realff (2011a) indicated that no non-energy process emissions occur in recycled production of secondary resins from carpet. Exhibit 12-17 and Exhibit 12-18 present the emission calculation components for recycled secondary product process energy emissions and transportation energy emissions, respectively.

Exhibit 12-17: Process Energy GHG Emissions Calculations for Recycled Production of Carpet Secondary Resins

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions (MTCO$_2$e/Short Ton)
Nylon 6 Fiber	74.24	3.93
Nylon 6-6 Fiber	3.13	0.16
Nylon 6-6 Pellet	13.39	0.71
PET Fiber	1.24	0.07
PP Fiber	10.55	0.56

Exhibit 12-18: Transportation Energy GHG Emissions Calculations for Recycled Production of Carpet Secondary Resins

Material/Product	Transportation Energy per Short Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions (MTCO$_2$e/Short Ton)
Nylon 6 Fiber	0.85	0.06
Nylon 6-6 Fiber	2.56	0.19
Nylon 6-6 Pellet	3.67	0.00
PET Fiber	3.24	0.00
PP Fiber	0.84	0.00

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

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

To calculate the GHG reductions associated with replacing virgin production with recycled production of secondary products, we then subtract the emissions from recycled production (Step 2) from the emissions from virgin production (Step 1). These results are shown in Exhibit 12-19.

Exhibit 12-19: Differences in Emissions between Recycled and Virgin Carpet Manufacture (MTCO$_2$e/Short Ton)

Material/ Product	Product Manufacture Using 100% Virgin Inputs (MTCO$_2$e/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO$_2$e/Short Ton)			Difference Between Virgin and Recycled Manufacture (MTCO$_2$e/Short Ton)		
	Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy
Nylon 6 Fiber	6.60	0.07	3.43	3.93	0.06	–	-2.67	-0.01	-3.43
Nylon 6-6 Fiber	7.45	0.05	1.08	0.16	0.19	–	-7.28	0.13	-1.08
Nylon 6-6 Pellet	7.45	0.05	1.08	0.71	0.00	–	-6.74	-0.05	-1.08
PET Fiber	1.75	0.07	0.39	0.07	0.00	–	-1.69	-0.07	-0.39
PP Fiber	1.17	0.13	0.21	0.56	0.00	–	-0.61	-0.13	-0.21

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

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

For almost every material that gets recycled, some portion of the recovered material is unsuitable for use as a recycled input. This portion is discarded either in the recovery stage or in the manufacturing stage. Consequently, less than one ton of new material is typically made from one ton of recovered materials. Material losses are quantified and translated into loss rates. Exhibit 12-20 shows the relative amounts of each plastic resin recovered from a given ton of recycled carpet and their end uses. Associated with each of these end uses are different recycling routes. For example Nylon 6 face fiber is recycled mostly through depolymerization, whereas Nylon 6-6 face fiber is recycled mainly through shaving the fiber followed by remelting and extrusion.

The distribution of end uses for carpet material is shown in Exhibit 12-20 and illustrates the total amount of plastic resins recovered and ultimately remanufactured per 1000 kg of recycled carpet. Note that the recovery and remanufacture of plastic resins per 1000 kg of incoming carpet material is less than 50 percent by mass indicating a high loss rate for recycling carpet. Furthermore, due to lack of data, EPA did not factor in the recovery of plastic pellets and molded plastics made from recovered PP resin. Exhibit 12-21 shows the recovery rates for each plastic resin recovered from carpet face fiber. The recovery rates add up to less than 100 percent due to the low overall recovery rate outlined in Exhibit 12-20.

Exhibit 12-20: End uses for recycled carpet based on 1000 kg of incoming carpet material

	Per 1000 kg Recycled Carpet				
Material/Product	**Total**	**Nylon 6**	**Nylon 6-6**	**PET**	**PP**
New Carpet	233.3	207.5	25.8	–	–-
Plastic Pellets	171.1	–	88.6	–	82.5*
Molded or Extruded Plastics	25.9	–	–	–	25.9*
Carpet Padding	62.2	–	–	29.6	33.1
Total Polymer Weight	**492.5**	**207.5**	**114.4**	**29.6**	**141.5**

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

Source: Realff, 2011b

Each product's process energy, transportation energy and process non-energy emissions are weighted by the percentages in Exhibit 12-21 and then they are summed as shown in the final column of Exhibit 12-22.

Exhibit 12-21: Calculation of Adjusted GHG Savings for Carpet Recycled into Secondary Products

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

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

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

Exhibit 12-22: Carpet Recycling Emission Factors (MTCO$_2$e/Short Ton)

	Recycled Input Credit for Recycling One Short Ton of Carpet			
Material/Product	**Weighted Process Energy (MTCO$_2$e/Short Ton Product)**	**Weighted Transport Energy (MTCO$_2$e/Short Ton Product)**	**Weighted Process Non-Energy (MTCO$_2$e/Short Ton Product)**	**Total (MTCO$_2$e/Short Ton Product)**
Nylon 6 Fiber	-0.55	-0.00	-0.80	-1.35
Nylon 6-6 Fiber	-0.19	0.00	-0.03	-0.21

Material/Product	Recycled Input Credit for Recycling One Short Ton of Carpet			
	Weighted Process Energy ($MTCO_2e$/Short Ton Product)	Weighted Transport Energy ($MTCO_2e$/Short Ton Product)	Weighted Process Non-Energy ($MTCO_2e$/Short Ton Product)	Total ($MTCO_2e$/Short Ton Product)
Nylon 6-6 Pellet	-0.60	-0.00	-0.10	-0.70
PET Fiber	-0.05	-0.00	-0.01	-0.06
PP Fiber	-0.02	-0.00	-0.01	-0.03
Carpet Total	**-1.41**	**-0.01**	**-0.94**	**-2.36**

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

12.4.3 Composting

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

12.4.4 Combustion

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

For further information on combustion, see the Combustion chapter. Because WARM's analysis begins with materials at end-of-life, emissions from RMAM are zero. Exhibit 12-23 shows the components of the emission factor for combustion of carpet. Further discussion on the development of each piece of the emission factor is discussed below.

Exhibit 12-23: Components of the Combustion Net Emission Factor for Carpet ($MTCO_2e$/Short Ton)

Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
–	0.03	1.67	–	-0.59	–	1.10

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

12.4.4.1 Developing the Emission Factor for Combustion of Carpet

EPA estimates that carpet has a weighted carbon content of 51 percent and that 98 percent of that carbon is converted to CO_2 during combustion. These estimates are based on the carbon that is contained within the various plastics and the limestone in carpet. These carbon contents and resulting direct CO_2 emissions from combustion of carbon in carpet are presented in Exhibit 12-24.

Exhibit 12-24: Carpet Combustion Emission Factor Calculation

Components	% of Total Weight	Carbon Content	Carbon Content % of Total Weight	Carbon Converted to CO_2 during Combustion	Total $MTCO_2e$/Short Ton
Styrene-butadiene (latex)	10%	90%	9%	98%	0.29
Limestone	37%	12%	4%	98%	0.13
Backing Fiber (PP)	11%	86%	9%	98%	0.29

Components	% of Total Weight	Carbon Content	Carbon Content % of Total Weight	Carbon Converted to CO_2 during Combustion	Total $MTCO_2e$/Short Ton
Face Fibers:					
Nylon 6 and Nylon 6-6	28%	64%	18%	98%	0.59
PP	8%	86%	7%	98%	0.23
PET	6%	63%	4%	98%	0.13
Carpet (Sum)	**NA**	**NA**	**51%**	**98%**	**1.67**

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

EPA estimates CO_2 emissions from transporting carpet to the WTE plant and transporting ash from the WTE plant to the landfill using data provided by FAL (2002). Transportation-related CO_2 emissions were estimated to be 0.03 $MTCO_2e$ per short ton of carpet combusted.

Most utility power plants use fossil fuels to produce electricity, and the electricity produced at a WTE plant reduces the demand for fossil-derived electricity. As a result, the combustion emission factor for carpet includes avoided GHG emissions from utilities. We calculate the avoided utility CO_2 emissions based on the energy content of carpet, the combustion efficiency of the WTE plant including transmission and distribution losses, and the national average carbon-intensity of electricity produced by non-baseload power plants. EPA utilized the energy content from recent analysis, which presents the energy content that is more representative of the current carpet composition (Realff, 2010b). Exhibit 12-25 shows the estimated utility offset from combustion of carpet.

Exhibit 12-25: Utility GHG Emissions Offset from Combustion of Carpet

(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) ($e = b \times c \times d$)
Carpet	15.2*	17.8%	0.22	0.59

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

12.4.5 Landfilling

Typically, the emission factor for landfilling is composed of four parts: landfill CH_4; CO_2 emissions from transportation and landfill equipment; landfill carbon storage; and avoided electric utility emissions. However, as with other non-biodegradable materials in WARM, there are zero landfill methane emissions, landfill carbon storage or avoided utility emissions associated with landfilling carpet, as shown in Exhibit 12-26. GHG emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling carpet represents only the transportation emissions associated with collecting the waste and operating the landfill equipment. For more information on landfilling, refer to the Landfilling chapter.

Exhibit 12-26: Landfilling Emission Factor for Carpet ($MTCO_2e$/Short Ton)

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)
–	0.04	NA	NA	NA	0.04

NA = Not applicable.
– = Zero emissions.

12.5 Limitations

As outlined in the Recycling section (12.4.2), the open-loop recycling process is a complicated end-of-life process for carpet. There are some limitations associated with modeling the GHG emissions from open-loop carpet recycling, including limited availability of representative life-cycle inventory (LCI) data for carpet and the materials recovered from them.

Given the complex open-loop recycling process and a lack of more complete information on carpet recycling, the recycling factor for carpet is subject to important limitations. A primary data gap is the availability of representative LCI data for carpet in the closed-loop recycling process, and the materials recovered from them in the open-loop recycling process. For this analysis, we use life-cycle data to represent the recovery of various plastic resins from recycled carpet but do not incorporate the additional energy and material requirements for converting these plastic resins into secondary products. Since the WARM carpet emission factor was initially developed, manufacturers have increased their capacity to recycle carpet into different end products including new carpet, plastic pellets, molded plastics and carpet padding. According to the CARE Annual Report for 2009, 47 percent of carpet recovered for recycling is used to manufacture new carpet, 35 percent was used to manufacture plastic pellets, 13 percent was used to manufacture carpet padding, and 5 percent was used to manufacture molded or extruded plastics (CARE, 2009). Updated LCI data on the conversion of plastic resins into final secondary products for carpet could have important effects on our results for the recycling benefits associated with carpet. EPA is investigating the availability of data necessary to develop a more representative open-loop recycling emission factor for carpet.

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

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

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

12.6 References

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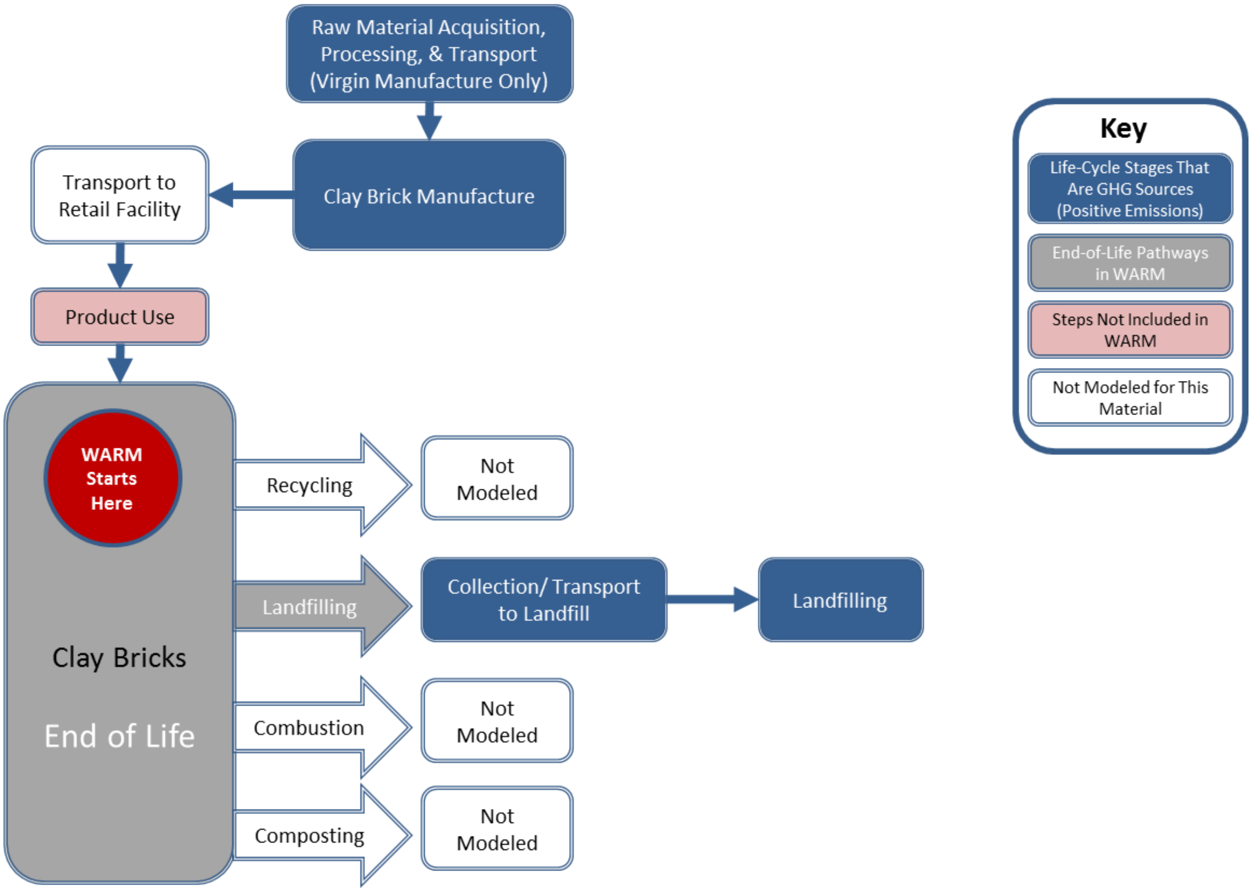
13 CLAY BRICKS

13.1 Introduction to WARM and Clay Bricks

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for clay bricks beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with clay bricks in the following waste management alternatives: source reduction and landfilling. Exhibit 13-1 shows the general outline of materials management pathways for clay bricks in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction and Landfilling, see the chapters devoted to these processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 13-1: Life Cycle of Clay Bricks in WARM



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

Clay bricks can be salvaged and reused, enabling source reduction of virgin clay bricks. It may also be possible to recycle broken or damaged clay bricks during the manufacturing process, although

EPA did not locate sufficient data to model a recycling pathway for management of clay bricks. Because clay bricks are inert and non-combustible, they cannot be composted or incinerated for energy recovery.

13.2 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.[58] For most materials, recycling and source reduction are the two materials management options that impact their upstream production and consequently are the only pathways that include upstream GHG emissions. Since WARM does not evaluate a recycling pathway for management of clay bricks, source reduction is the only pathway that affects upstream GHG emissions from clay bricks. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

As Exhibit 13-2 illustrates, the GHG sources relevant to clay bricks in this analysis are contained in the raw materials acquisition and manufacturing portion and end of life portions of the life cycle. WARM does not evaluate recycling, composting or combustion as life-cycle pathways for clay bricks because recycling is not a common practice and the data on recycling of clay bricks are limited, and clay bricks cannot be combusted or composted.

Exhibit 13-2: Clay Bricks GHG Sources and Sinks from Relevant Materials Management Pathways

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

NA = Not applicable.

13.3 Raw Materials Acquisition and Manufacturing

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are: (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[59] For clay bricks, process energy GHG emissions result from acquiring the raw clay used in manufacture and the firing process used to produce clay bricks. Transportation

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[58] 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.

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

emissions are generated from transporting raw materials to the brick manufacturing facility. EPA assumes that non-energy process GHG emissions are negligible because no data source consulted indicated the presence of these emissions.

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

13.4 Materials Management Methodologies

WARM evaluates GHG sources and sinks from source reduction and landfilling of clay bricks. Exhibit 13-3 provides the net GHG emissions per short ton of clay bricks for each of these materials management pathways. Source reduction avoids GHG emissions because it offsets emissions from manufacturing processes and transportation of raw materials. Landfilling results in GHG emissions from transporting clay bricks to the landfill and operation of landfill equipment. More details on the methodologies for developing these emission factors are provided in sections 13.4.1 through 13.4.5.

Exhibit 13-3: Net Emissions for Clay Bricks under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Clay Bricks	-0.27	NA	NA	NA	0.04

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

13.4.1 Source Reduction

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the postconsumer waste are avoided. In WARM, source reduction of clay bricks involves reusing old bricks that have been salvaged at end of life. Because reused bricks may lack the strength and durability of new bricks, the reuse of bricks is not appropriate for all brick structures. This is why the U.S. Green Building Council (USGBC) recommends that reused bricks not be used in exterior structures in cold climates, as cold temperatures can exacerbate existing weaknesses in reused bricks (Webster, 2002). Clay bricks are sometimes reused in such decorative or non-structural applications as brick fireplaces, hearths, patios, etc.[60]

As discussed previously, under the measurement convention used in this analysis, source reduction for clay bricks has negative raw material and manufacturing GHG emissions (i.e., it avoids emissions attributable to production) and zero end-of-life management GHG emissions. The overall source reduction emission factors for clay bricks are shown in Exhibit 13-4.

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

Exhibit 13-4: Source Reduction Emission Factor for Clay Bricks ($MTCO_2e$/Short Ton)

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

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

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

NA = Not applicable.

Because EPA assumes that clay bricks are always produced from 100 percent virgin materials, the GHG emission factor for "100 percent virgin inputs" is equal to the factor for the "current mix" of virgin and recycled inputs. Post-consumer emissions are the emissions associated with materials management pathways that could occur at end-of-life. When source reducing carpet, there are no post-consumer emissions because production of the material is avoided in the first place, and the avoided carpet never becomes post-consumer. There are no changes in forest carbon storage since clay bricks contain no paper or wood and therefore do not influence forest carbon stocks. For more information on this topic, please see the chapter on Source Reduction.

13.4.1.1 Developing the Emission Factor for Source Reduction of Clay Bricks

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

Avoided Process Energy Emissions: Process energy GHG emissions result from both the direct combustion of fossil fuels and the upstream emissions associated with the production of fuels and electricity (i.e., "pre-combustion" energy).[61] An estimated 5.1 million Btu of total energy are required to produce one ton of clay bricks (Athena, 1998).[62] To calculate process energy emissions, we determine the national-average mix of fuels used to manufacture clay bricks. We then multiply the amount of each fuel consumed by the fuel's GHG emissions intensity (i.e., GHG emissions per Btu of fuel consumed) to obtain CO_2 and CH_4 emissions for each fuel (EPA, 2014). Total process energy GHG emissions are calculated as the sum of GHG emissions, including both CO_2 and CH_4, from all of the fuel types used in the production of one ton of clay bricks. Results of these calculations are provided in Exhibit 13-5.

Exhibit 13-5: Process Energy GHG Emissions Calculations for Virgin Production of Clay Bricks

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Clay Bricks	5.10	0.27

Avoided Transportation Energy Emissions: Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for clay brick production. The methodology for estimating these emissions is the same as the one used for process energy emissions. Total transportation energy emissions are calculated based upon an estimate of total clay brick

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

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

transportation energy and the corresponding fuel mix (Athena, 1998) and using fuel-specific coefficients for CO_2 and CH_4 (EPA, 2014). The related GHG emissions are provided in Exhibit 13-6.

Exhibit 13-6: Transportation Energy Emissions Calculations for Virgin Production of Clay Bricks

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Clay Bricks	0.03	0.00

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

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

13.4.2 Recycling

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Research indicates that there is very little postconsumer recycling of bricks (Athena, 1998). Likewise, almost all bricks in the United States are made from virgin materials, so EPA has not analyzed the impacts of using recycled material in brick manufacture.[63]

13.4.3 Composting

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

13.4.4 Combustion

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

13.4.5 Landfilling

In general, GHG impacts from landfilling consist of landfill CH_4 emissions; CO_2 emissions from transportation and landfill equipment operation; landfill carbon storage; and avoided utility emissions that are offset by landfill gas energy recovery. However, because clay bricks do not contain carbon-based materials or degrade in landfills, they do not produce CH_4 emissions or result in carbon storage in landfills. Therefore, the landfilling emission factor only accounts for transportation emissions: transportation of clay bricks to a landfill and operation of landfill equipment result in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes. This information is summarized in Exhibit 13-7. For more information on this topic, please see the chapter on Landfilling.

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[63] Athena (1998) describes the recycling of old clay bricks as feasible but not widely practiced at this time. Athena also notes that 4 to 8 percent of the volume of raw materials used in brick production is made up of damaged, finished ware that has been recycled back into raw materials. Because these inputs reflect pre-consumer recycling, not post-consumer recycling, the energy associated with manufacturing brick with these inputs would still be considered “virgin” in our nomenclature. Based on the information provided by Athena, it appears that there is very little (if any) recycled-content brick being produced. Therefore, this analysis assumes that virgin production is the same as production using the current mix (nearly 100 percent virgin inputs).

Exhibit 13-7: Landfilling Emission Factor for Clay Bricks ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

13.5 Limitations

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

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

13.6 References

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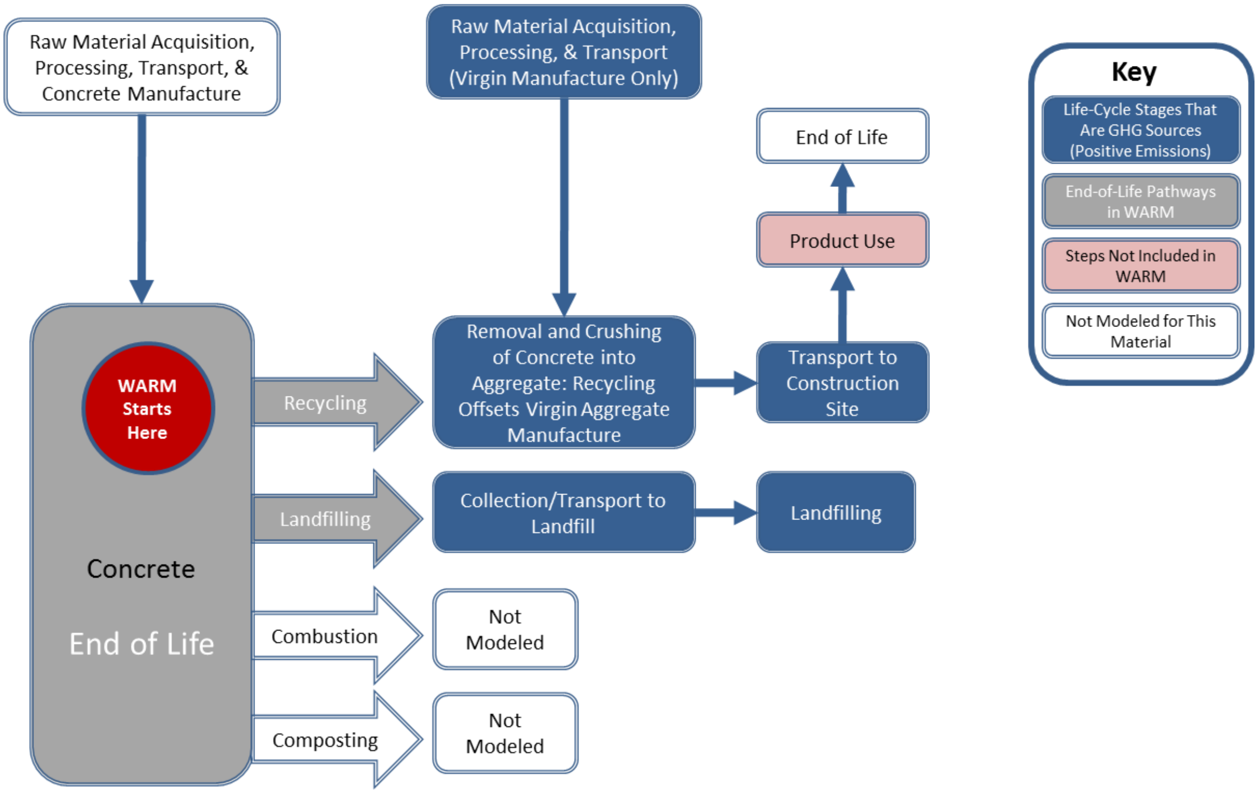
14 CONCRETE

14.1 Introduction to WARM and Concrete

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for concrete beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with concrete in the following two waste management alternatives: recycling and landfilling. Exhibit 14-1 shows the general outline of materials management pathways for concrete in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Recycling and Landfilling, see the chapters devoted to these processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 14-1: Life-cycle of Concrete in WARM



Concrete is a high-volume, low-cost building material produced by mixing cement, water and coarse and fine aggregates. Its use is nearly universal in modern construction, as it is an essential component of roads, foundations, high-rises, dams and other staples of the developed landscape. Approximately 578 million tons of concrete[64] were produced in 2011 and approximately 200 million tons of waste concrete are generated annually from construction and demolition (C&D) and public works

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

projects (Turley, 2002; Wilburn and Goonan, 1998). According to Turley (2002) and Wilburn and Goonan (1998), an estimated 50 to 60 percent of waste concrete is recycled, while the remainder is landfilled.

14.2 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.[65]

As Exhibit 14-2 illustrates, most of the GHG sources relevant to concrete in this analysis are contained in the raw materials acquisition and manufacturing and end of life sections of the life cycle assessment. WARM does not consider source reduction, composting or combustion as life-cycle pathways for concrete. Of note, the recycling emission factor represents the GHG impacts of manufacturing concrete using recycled concrete in place of the virgin aggregate component. The landfilling emission factor reflects the GHG impacts of disposing of concrete in a landfill. Because concrete does not generate methane in a landfill, the emission factor is the emissions from transporting the concrete to the landfill and operating the landfill equipment.

Exhibit 14-2: Concrete GHG Sources and Sinks from Relevant Materials Management Pathways

MSW Management Strategies for Concrete	GHG Sources and Sinks Relevant to Concrete		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	Not modeled in WARM		
Recycling	**Offsets** • Transport of raw materials and products • Virgin aggregate mining and production process energy	NA	**Emissions** • Collection and transportation to processing facility • Sorting and processing energy
Composting	Not applicable because concrete cannot be composted		
Combustion	Not applicable because concrete cannot be combusted		
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 14-2 and calculates net GHG emissions per short ton of concrete inputs for each materials management alternative (see Exhibit 14-3). For additional discussion on the detailed methodology used to develop these emission factors, please see sections 14.3 and 14.4 on individual waste management strategies.

Exhibit 14-3: Net Emissions for Concrete under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Concrete	NA	-0.01	NA	NA	0.04

NA = Not applicable.

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

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[65] 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.

14.3 Raw Materials Acquisition and Manufacturing

In general, GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[66] For the recycling emission factor, WARM compares the impact of producing aggregate from recycled concrete to the impact of producing virgin aggregate. In WARM, concrete is considered to be essentially a byproduct of the demolition of buildings and other concrete structures. Since the structures were created for themselves, and not for the purpose of being turned into aggregate, WARM considers that there are no manufacturing or combustion emissions associated with concrete before end of life. Hence, no RMAM emissions are considered in the life-cycle analysis of concrete in WARM. However, we do note that the production of concrete is a greenhouse-gas- and energy-intensive process.

14.4 Materials Management Methodologies

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 14-2 and calculates net GHG emissions per short ton of concrete. This analysis considers recycling and landfilling as possible materials management options for concrete. Recycling of concrete leads to reductions in GHG emissions since it avoids manufacture of virgin aggregate. Landfilling has a slightly positive emission factor due to the emissions from landfill operation equipment.

14.4.1 Source Reduction

When a material is source reduced (i.e., less of the material is made), GHG emissions associated with making the material and managing the postconsumer waste are avoided. Although concrete may be reused or used in ways that could reduce the overall demand for new concrete structures, the benefits of this type of activity have not yet been quantified. Therefore, WARM does not include an emission factor for source reduction.

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

14.4.2 Recycling

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. The Construction Materials Recycling Association (CMRA, 2010) indicates that approximately 140 million tons of concrete are recycled annually in the United States. WARM investigates the GHG impacts associated with reusing crushed concrete in place of virgin aggregate, an open-loop recycling process.[67] Virgin aggregates, which include crushed stone, gravel and sand, are used in a wide variety of construction applications, such as road base and fill, and as an ingredient in concrete and asphalt pavement. When structures are demolished, the waste concrete can be crushed and reused in place of virgin aggregate, reducing the GHG emissions associated with producing concrete using virgin aggregate material. Therefore, the GHG benefit of using recycled

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

[67] Concrete may be recycled in a “closed-loop” by being crushed and reused as aggregate in new concrete. The recycling process is believed to rehydrate some cement in the used concrete, thus reducing the need for cement in the new concrete, resulting in additional GHG benefits. However, sufficient data to quantify this additional benefit are not available at this point.

concrete results from the avoided emissions associated with mining and processing aggregate that concrete is replacing.[68]

More than 2 billion tons of aggregates are consumed each year in the United States, with an estimated 5 percent coming from recycled sources such as asphalt pavement and concrete (USGS, 2000). The U.S. Geological Survey (USGS) estimates that, of the concrete recycled in 1997, at least 83 percent was used in applications that typically employ virgin aggregate: 68 percent of all recycled product was used as road base, 9 percent in asphalt hot mixes, and 6 percent in new concrete mixes. Non-aggregate uses of recycled concrete included 7 percent as general fill, 3 percent as high-value riprap, and 7 percent as other (USGS, 2000.) As tipping fees at landfills increase in many urban areas and recycling techniques continue to improve, concrete recycling is expected to become even more popular.

The calculation of the concrete emission factor involves estimating the emissions associated with production and transportation of one ton of virgin input (aggregate) versus one ton of recycled input (i.e., crushed concrete) individually, and then determining the difference in emissions between recycled and virgin production. The GHG emissions associated with these steps result from the consumption of fossil fuels used in the production and transport of aggregate (combustion energy), as well as the upstream energy (pre-combustion energy) required to obtain these fuels. The concrete recycling emission factor is made up of two components: process energy and transportation energy. No process non-energy emissions occur. Exhibit 14-4 presents a summary of these components. The following sections contain descriptions of how each component is calculated.

Exhibit 14-4: Recycling Emission Factor for Concrete ($MTCO_2e$/Short Ton)

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

NA = Not applicable.

– = Zero emissions.

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

14.4.2.1 Developing the Emission Factor for Recycling Concrete

EPA calculates the benefits of recycling by comparing the difference between the emissions associated with producing one short ton of recycled concrete aggregate and the emissions from producing one short ton of virgin aggregate. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy. Since process non-energy emissions for production of both virgin aggregate and recycled concrete are considered to be zero, this component is not considered in the discussion below.

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

Step 1. *Calculate emissions from virgin production of aggregate.* GHG emissions from the combustion of fossil fuels are attributed to both process energy (required to extract and process raw

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

materials such as coarse aggregate and sand) and transportation energy (required to transport virgin aggregate to the job site where it is used.) Emissions associated with transporting the virgin or recycled materials to the consumer, in the case of aggregates, are a driving factor in the GHG impacts of end-of-life concrete management options. EPA estimates the total energy required to produce one short ton of aggregate as 0.0429 million Btu.[69] WARM applies fuel-specific carbon content and fugitive CH_4 emissions coefficients to the energy data for production of (one ton of) virgin aggregate, in order to obtain total process energy GHG emissions, including CO_2 and CH_4. This estimate is then summed with the emissions from transportation energy to calculate the total emissions from virgin production of aggregate. Both process and transportation energy estimates for virgin aggregate production were calculated from data in U.S. Census Bureau (1997), as detailed in EPA (2003).

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

Exhibit 14-5 and Exhibit 14-6 present the process and transportation energy and associated emissions for virgin and recycled manufacture of aggregate.

Exhibit 14-5: Process Energy GHG Emission Calculations for Concrete

Material/Product	Process Energy per Short Ton Aggregate (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Virgin Aggregate	0.05	0.00
Recycled Aggregate (Crushed Concrete)	0.04	0.00

Exhibit 14-6: Transportation Energy GHG Emission Calculations for Concrete

Material/Product	Transportation Energy per Short Ton Aggregate (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Virgin Aggregate	0.19	0.01
Recycled Aggregate (Crushed Concrete)	0.09	0.01

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

Step 3. *Calculate the difference in emissions between virgin and recycled aggregate production.* We then subtract the recycled product emissions (Step 2) from the virgin product emissions (Step 1) to get the GHG savings for using recycled concrete in place of virgin aggregate. These results are shown in Exhibit 14-7.

Exhibit 14-7: Differences in Emissions between Recycled and Virgin Concrete Manufacture ($MTCO_2e$/Short Ton)

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

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

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[69] This total represents the sum of pre-combustion and combustion process energy. Please refer to Appendix B of EPA 2003 for more details on how the total energy per ton of aggregate was calculated.

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

14.4.3 Composting

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

14.4.4 Combustion

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

14.4.5 Landfilling

In general, GHG emissions from landfilling consist of landfill CH_4; CO_2 emissions from transportation and landfill equipment operation; landfill carbon storage; and avoided utility emissions that are offset by landfill gas energy recovery. However, since concrete is not subject to aerobic bacterial degradation and does not degrade in landfills, it does not produce any CH_4 emissions associated with landfilling concrete. Studies have indicated that, over time, the cement portion of concrete is capable of absorbing CO_2 (Gadja, 2001). The amount of carbon stored is affected by age, cement content and the amount of exposed surface area. While this effect would represent landfill carbon storage when concrete is deposited in a landfill, the results of this with respect to the emission factor are difficult to quantify and are considered to be beyond the scope of WARM. Therefore, WARM only counts transportation emissions: transportation of concrete to a landfill and operation of landfill equipment result in anthropogenic CO_2 emissions due to the combustion of fossil fuels in the vehicles used to haul and move the wastes. This information is summarized in Exhibit 14-8. For more information on this topic, please see the chapter on Landfilling.

Exhibit 14-8: Landfilling Emission Factor for Concrete ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

14.5 Limitations

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

- Landfill carbon storage by the cement component of concrete deposited in a landfill is difficult to quantify and considered to be beyond the scope of WARM. Better data and more information on this storage process would help enhance the landfill emission factor.
- There is a current lack of sufficient data to quantify the GHG benefits of “closed-loop” recycling of concrete. Concrete may be recycled and reused as aggregate in new concrete such that it

rehydrates some cement in the used concrete, thus reducing the need for cement in the new concrete, and resulting in additional GHG benefits. More information related to a decrease in need for virgin cement due to this kind of recycling would help improve the recycling emission factor.

If updated information could be obtained to address these limitations, the life-cycle emission factor for concrete could be further refined. It is important that we continue to assess the assumptions and data used to develop the emission factors. As the combustion processes, manufacturing processes and recycling processes change in the future, these changes will be incorporated into revised emission factors. In addition, it should be noted that these results are designed to represent national average data. The actual GHG impacts of recycling or landfilling concrete will vary, depending on individual circumstances.

14.6 References

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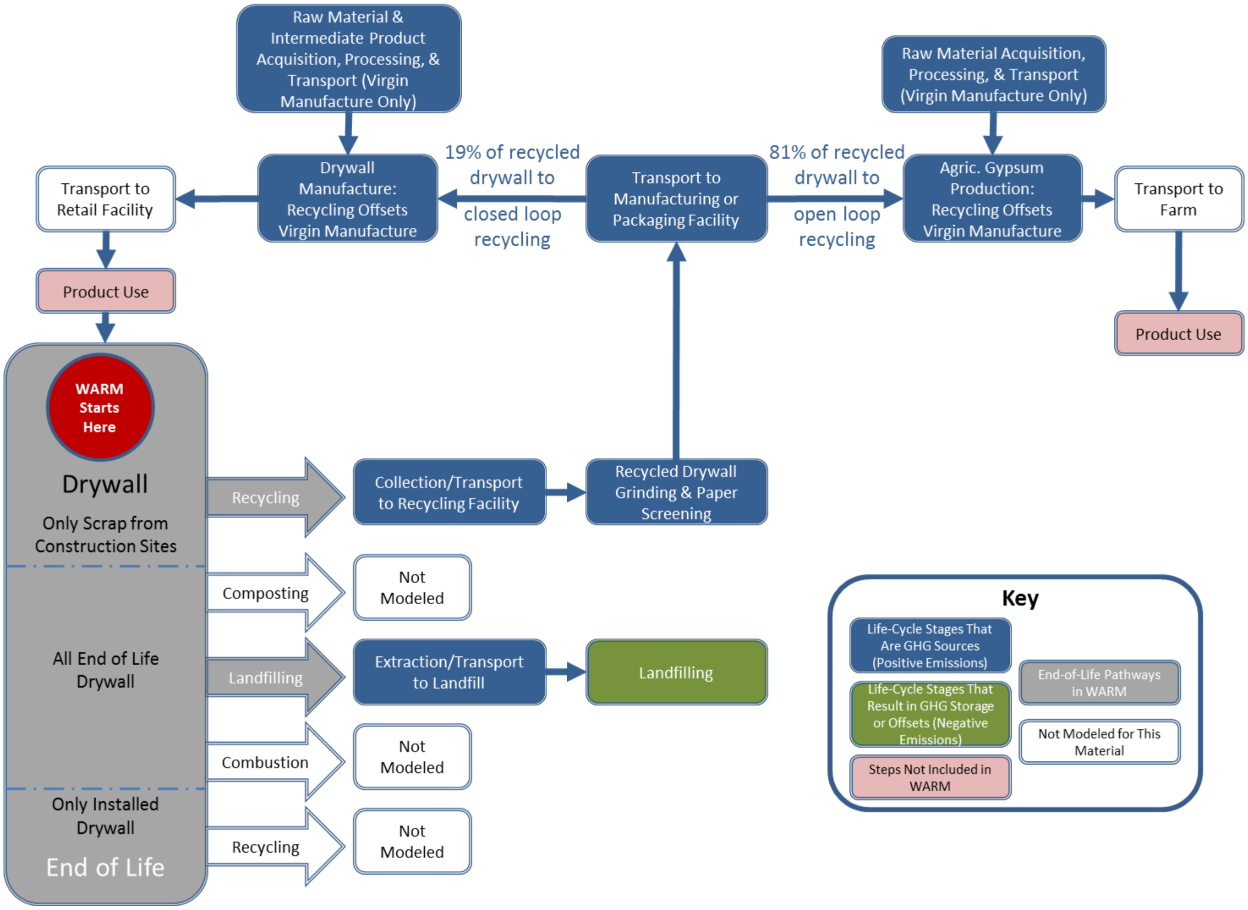
15 DRYWALL

15.1 Introduction to WARM and Drywall

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for drywall beginning at the waste generation reference point.[70] The WARM GHG emission factors are used to compare the net emissions associated with drywall in the following three waste management alternatives: source reduction, recycling, and landfilling. Exhibit 15-1 shows the general outline of materials management pathways for drywall in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, and Landfilling, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 15-1: Life Cycle of Drywall in WARM



Drywall, also known as wallboard, gypsum board or plaster board, is manufactured from gypsum plaster and a paper covering. Exhibit 15-2 presents the sources of drywall entering the waste stream.

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[70] EPA would like to thank Rik Master of USG Corporation for his efforts at improving these estimates.

Exhibit 15-2: Composition of the Drywall Waste Stream

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

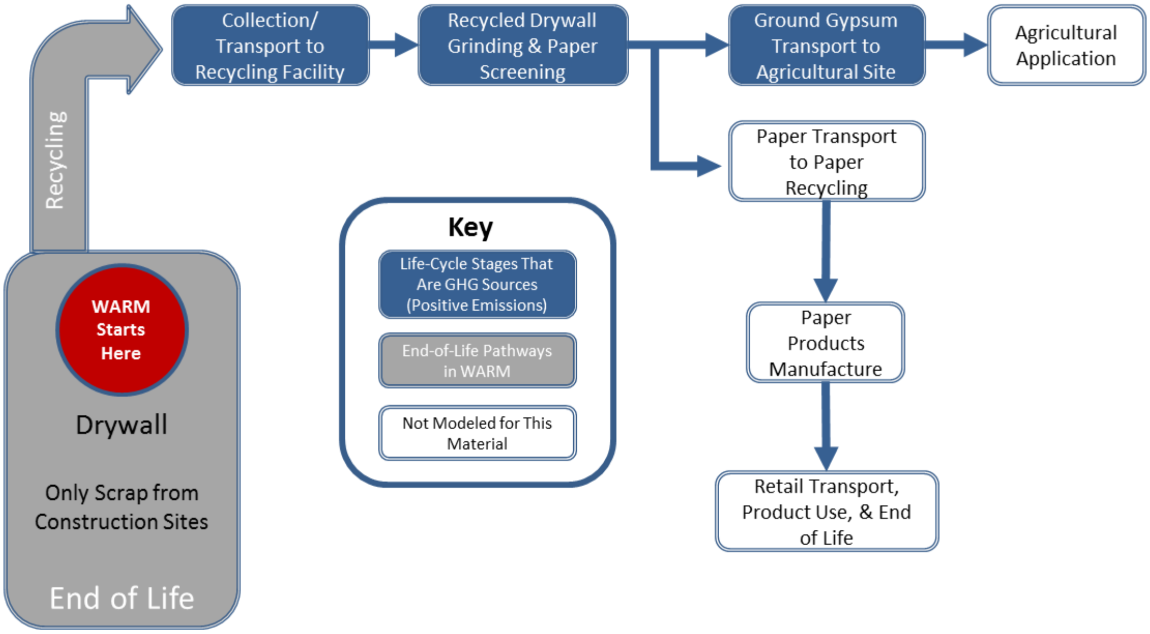
Source: CIWMB (2009b).

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

Most drywall is currently disposed of in landfills (Master, 2009). This disposal pathway can be problematic; if water is admitted to the landfill, under certain conditions the drywall may produce hydrogen sulfide gas. Additionally, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by communications with Dr. Morton Barlaz. Incineration can produce sulfur dioxide gas, and is banned in some states (CIWMB, 2009b). Drywall is sometimes accepted at composting facilities, but it is used as an additive to compost, rather than a true compost input (please see section 15.4.3). For this reason, WARM does not include a composting emission factor for drywall. However, users interested in the GHG implications of sending drywall to a composting facility can use the recycling factor as a proxy (again, see section 15.4.3).

Drywall, however, is sometimes recycled into agricultural products, new drywall, a component of cement and some other uses. Sometimes the gypsum and paper are disposed of together, but they are also sometimes separated out during the recycling process, creating a somewhat more complicated life-cycle pathway (refer to Exhibit 15-1 for the primary lifecycle pathways of the gypsum and paper used in drywall). Recycling drywall is an open-loop process, meaning that components are recycled into secondary materials such as agricultural amendments and paper products. Building on Exhibit 15-1, a more detailed flow diagram showing the open-loop recycling pathways of drywall is provided in Exhibit 15-3.

Exhibit 15-3: Detailed Recycling Flows for Drywall in WARM



15.2 Lifecycle Assessment and Emission Factor Results

The streamlined life-cycle GHG analysis in WARM focuses on the waste generation point, or the moment a material is discarded, as the reference point and only considers upstream GHG emissions when the production of new materials is affected by materials management decisions.[71] Recycling and Source Reduction are the two materials management options that impact the upstream production of materials and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not consider composting or combustion for drywall. As Exhibit 15-4 illustrates, the GHG sources and sinks relevant to drywall in this analysis are contained in all three sections of the life cycle assessment: raw materials acquisition and manufacturing (RMAM), changes in forest or soil carbon storage, and materials management.

Exhibit 15-4: Drywall GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Drywall	GHG Sources and Sinks Relevant to Drywall		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Avoided raw material acquisition of gypsum • Avoided manufacturing of wallboard, including paper facing • Avoided transportation of raw gypsum	NA	NA

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

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 15-4 and calculates net GHG emissions per short ton of drywall inputs. For more detailed methodology on emission factors, please see sections 4.1 through 4.5. Exhibit 15-5 outlines the net GHG emissions for drywall under each materials management option.

Exhibit 15-5: Net Emissions for Drywall under Each Materials Management Option (MTCO$_2$e/Short Ton)

Material/ Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Drywall	-0.21	0.03	0.03	NA	-0.04

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

15.3 Raw Materials Acquisition and Manufacturing

GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[72] For drywall, process energy GHG emissions result from acquiring the virgin gypsum used in manufacture, as well as the manufacturing processes used to prepare the stucco and paper facings, and to produce the actual wallboards. Transportation emissions are generated from

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

transporting raw materials to the drywall manufacturing facility. Due to the nature of the processes and materials used to manufacture drywall, there are no non-energy process emissions.

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

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

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

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water and other-modes transportation emissions required to transport drywall from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 15-6. Transportation emissions from the retail point to the consumer are not included. The miles traveled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and greenhouse gas emissions from the Management of Selected Materials (EPA, 1998).

Exhibit 15-6: Retail Transportation Energy Use and GHG Emissions

Material/Product	Average Miles per Shipment	Retail Transportation Energy per Short Ton of Product (Million Btu)	Retail Transportation Emissions ($MTCO_2e$/ Short Ton)
Drywall	356	0.35	0.03

15.4 Materials Management Methodologies

WARM evaluates GHG sources and sinks from source reduction, recycling, and landfilling of drywall. Exhibit 15-7 provides the net GHG emissions per short ton of drywall for each of these materials management pathways. Source reduction avoids GHG emissions because it offsets emissions from manufacturing processes and transportation of raw materials. Landfilling results in GHG emissions from the transport of drywall to the landfill and operation of landfill equipment. Recycling drywall into new drywall or using it for agricultural purposes results in positive net emissions, but fewer emissions than would be obtained from landfilling the material. More details on the methodologies for developing these emission factors are provided in sections 4.1 through 4.5.

EPA used data on drywall manufacturing from the Athena Sustainable Materials Institute (Venta, 1997), which assumes that drywall is manufactured with 85 percent virgin gypsum, 6 percent synthetic gypsum, 5 percent gypsum recycled from manufacturing waste (internal recycling) and 4 percent recycled gypsum from construction sites (Venta, 1997, Table 9.3). Because EPA was unable to disaggregate the energy data for each source of gypsum, the 100 percent "virgin" drywall estimates in fact represent this composition. However, since most drywall likely contains at least some synthetic and/or recycled gypsum, this composition likely approximates an upper bound for virgin gypsum in drywall. Also, the paper facing used in drywall is made from recycled paper. The "virgin" drywall estimates therefore reflect the use of recycled paper rather than virgin paper. The "current mix" of drywall production reflects these same percentages.

15.4.1 Source Reduction

Reducing the amount of drywall wasted at construction sites, or the amount of drywall and other wall finishing products needed, results in emission reductions. The benefits of source-reducing drywall come primarily from avoided emissions from the manufacturing process, and also from avoided transportation emissions. Avoided raw material acquisition presents some small additional savings. The avoided emissions are summarized in Exhibit 15-7. For more information on this topic, please see the chapter on Source Reduction.

Exhibit 15-7: Source Reduction Emission Factors for Drywall ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs[a]	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Drywall	-0.21	-0.21	NA	NA	-0.21	-0.21

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

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

NA = Not applicable.

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

15.4.1.1 Developing the Emission Factor for Source Reduction of Drywall

The approach and data sources used to calculate the emission factor for source reduction of drywall are summarized in the following paragraphs for each of the three categories of GHG emissions: process energy (pre-combustion and combustion), transportation energy and process non-energy emissions. Exhibit 15-8 shows the results for each component and the total GHG emission factors for source reduction of drywall.

Exhibit 15-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Drywall ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Drywall	0.18	0.03	–	0.21

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

– = Zero emissions.

Avoided Process Energy. Process energy GHG emissions result from the direct combustion of fossil fuels used to extract raw materials and to manufacture the stucco, the paper facing and the drywall boards themselves. Process energy also includes the upstream emissions associated with the production of fuels and electricity (i.e., “pre-combustion” energy).[73] EPA obtained data on raw material extraction, and drywall and paper manufacturing from Venta (1997). While these data are several years old, they represent the most complete dataset available at the time these emissions factors were developed.

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

- Raw material creation—13 percent
- Raw material transportation—3 percent
- Wallboard manufacturing—85 percent[74]

Because the Venta (1997) estimates do not include the pre-combustion energy of the fuels, EPA added pre-combustion values based on pre-combustion estimates by fuel types cited in FAL (2007). Total process energy GHG emissions are calculated as the sum of GHG emissions, including both CO_2 and CH_4, from all of the fuel types used in the production of one ton of drywall. Results of these calculations are provided in Exhibit 15-9.

Exhibit 15-9: Process Energy GHG Emissions Calculations for Virgin Production of Drywall

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Drywall	3.08	0.18

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

While the U.S. Census Bureau (2004) provides transportation data on the transport of raw gypsum, WARM uses transportation data from use estimates provided by R. Master (personal communication, February 26, 2010) for raw gypsum because, among the estimates currently available, these appear to be the most recent and most relevant to the United States. EPA obtained transportation data on finished products from the Census Bureau (2004). The related GHG emissions are provided in Exhibit 15-10.

Exhibit 15-10: Transportation Energy Emissions Calculations for Virgin Production of Drywall

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Drywall	0.10	0.01

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 15-6.

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

[74] Derived from Master (2010).

15.4.2 Recycling

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Drywall is modeled as being recycled in a semi-open loop, since some drywall is recycled back into drywall (closed loop), and some is recycled into agricultural gypsum (open loop). This section describes the development of the recycling emission factor for drywall, which is shown in the final column of Exhibit 15-11. For more information about this topic, please refer to the Recycling chapter.

Exhibit 15-11: Recycling Emission Factor for Drywall ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Drywall	–	–	0.01	0.02	–	–	0.03

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

15.4.2.1 Developing the Emission Factor for Recycling of Drywall

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

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

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

Most recycled drywall is used for a variety of agricultural purposes. For example, the gypsum can be used as a soil conditioner, as it helps increase soil water infiltration and adds calcium and sulfur to the soil. The paper backing, meanwhile, can be recovered and used as animal bedding. Drywall is also recycled back into new wallboard and is possibly used in concrete manufacture. WARM assumes that 19 percent of recycled drywall is recycled into new drywall (closed-loop recycling), and 81 percent is recycled for agricultural purposes (open-loop recycling) (derived from Master, 2009) as illustrated in Exhibit 15-12. There is conflicting evidence about the extent to which recycled gypsum is used in cement manufacture. Due to a lack of information, EPA has not included cement manufacture as a recycling pathway for drywall in WARM. However, as the recycled gypsum would likely displace virgin gypsum, savings from avoided raw material extraction and transportation and avoided landfilling emissions would likely be similar to those raw material and landfilling savings experienced when recycling gypsum into agricultural products and new drywall.

Exhibit 15-12: Assumed End-Uses of Recycled Drywall

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

Source: Derived from Master (2009).

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

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

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

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

Exhibit 15-13: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Agricultural Gypsum (MTCO$_2$e/Short Ton)

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

– = Zero emissions.

Step 2: *Calculate emissions for recycled production of drywall and agricultural gypsum.* EPA applied the same fuel-specific carbon coefficients to the process energy required to recycle drywall. EPA obtained information on gypsum recycling from WRAP (2008), which estimates that recycling one metric ton of waste wallboard requires 9.9 kWh of electricity and 0.09 liters of diesel. Because these estimates represent data from the United Kingdom, where renovation/demolition waste drywall is more commonly recycled than in the United States, these estimates reflect a small amount of post-construction wallboard recycling. Because this type of recycling would require additional processing, these estimates may slightly overstate the energy requirements to recycle construction waste drywall. Process energy emissions are shown in Exhibit 15-14.

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

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

Exhibit 15-14: Process Energy GHG Emissions Calculations for Recycled Production

Product/Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Drywall	3.19	0.18
Agricultural Gypsum	0.12	0.01

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

Product/Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Drywall	0.02	0.00
Agricultural Gypsum	–	–

– = Zero emissions.

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 15-6.

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

Step 4: Adjust the emissions differences to account for recycling losses. Material losses occur in both the recovery and manufacturing stages of recycling. The loss rate represents the percentage of end-of-life drywall collected for recycling that is lost during the recycling process, and ultimately disposed of. WARM assumes a 0.2 percent loss rate for drywall recycling (WRAP, 2008). The differences in emissions from virgin versus recycled process energy and transportation energy are adjusted to account for loss rates by multiplying the final three columns of Exhibit 15-16 by 99.8 percent, the amount of material retained after losses (i.e., 100 percent input – 0.2 percent lost = 99.8 percent retained).

Exhibit 15-16: Differences in Emissions between Recycled and Virgin Manufacture ($MTCO_2e$/Short Ton)

	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)		
Product/ Material	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Drywall	0.18	0.01	–	0.18	0.00	–	0.01	-0.01	–
Agricultural Gypsum	0.00	0.01	–	0.01	–	–	0.01	-0.01	–

– = Zero emissions.

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

15.4.3 Composting

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

Drywall is composed primarily of gypsum, which is an inorganic substance and therefore cannot become compost. Instead, drywall is generally added to the compost mix *after* the compost has been created. It is added to compost because gypsum can supply important nutrients to plants. When drywall is sent to a composting facility, therefore, it is actually used as an *additive to* compost, rather than turned *into* compost. More information about drywall recycling can be found at http://www.cdrecycling.org/drywall-recycling.

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

15.4.4 Combustion

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

15.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. Because gypsum is inorganic and does not contain biogenic carbon, there are zero emissions from landfill methane, zero landfill carbon storage and zero avoided utility emissions associated with landfilling gypsum. However, the paper facing on drywall is organic, resulting in some carbon sequestration. While the paper facing would separately generate landfill methane emissions, the sulfate in wallboard is estimated to reduce methane generation, as bacteria use sulfate preferentially to the pathway that results in methane, as suggested by Dr. Morton Barlaz. As such, methane yield from gypsum board is likely to be negligible and is therefore assumed to be zero in WARM. EPA obtained data on the moisture content and carbon storage factor for drywall from Barlaz and Staley (2009). In addition to those emissions, EPA assumes the standard WARM landfilling emissions related to transportation and equipment use. The carbon sequestration benefits outweigh the transportation emissions, resulting in net carbon storage in the landfill, as illustrated in Exhibit 15-17. For more information, please see the chapter on Landfilling.

Exhibit 15-17: Landfilling Emission Factor for Drywall ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Drywall	–	0.04	–	–	-0.08	-0.04

– = Zero emissions.

15.5 Limitations

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

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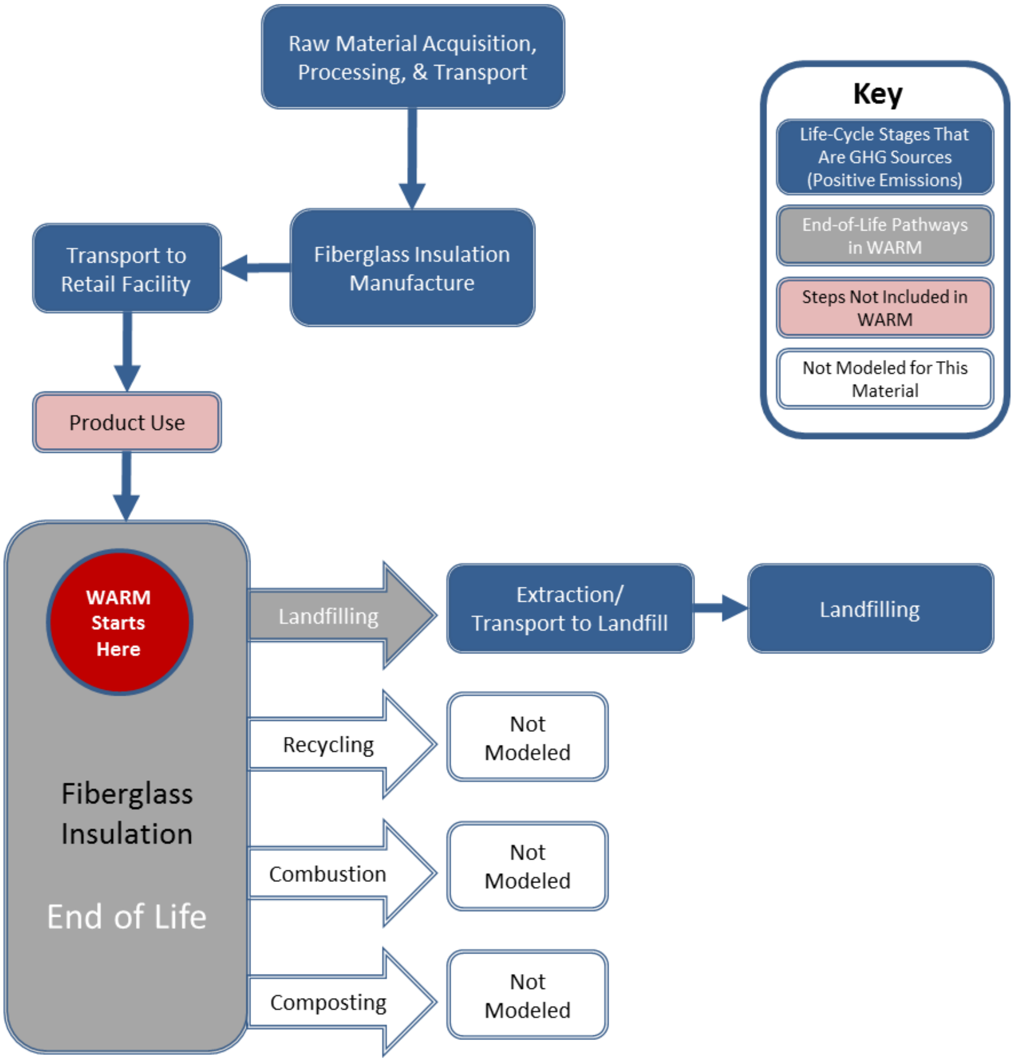
16 FIBERGLASS INSULATION

16.1 Introduction to WARM and Fiberglass Insulation

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for fiberglass insulation beginning at the waste generation reference point.[75] The WARM GHG emission factors are used to compare the net emissions associated with fiberglass insulation in the following two waste management alternatives: source reduction and landfilling. Exhibit 16-1 shows the general outline of materials management pathways for fiberglass insulation in WARM. For background information on the general purpose and function of WARM emission factors, see the General Guidance chapter. For more information on Source Reduction and Landfilling, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 16-1: Life Cycle of Fiberglass Insulation in WARM



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[75] EPA would like to thank Mr. Scott Miller of Knauf Insulation for his efforts at improving these estimates.

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

16.2 Life-Cycle Assessment and Emission Factor Results

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

WARM only has emission factors for landfilling and source reduction for fiberglass insulation. Fiberglass insulation is neither combusted nor composted. It *is* reusable in that it can be easily removed and re-installed (NAIMA, 2007); the extent to which this is actually done, however, is not known. As Exhibit 16-2 illustrates, all of the GHG sources and sinks relevant to fiberglass insulation in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life cycle.

Exhibit 16-2: Fiberglass Insulation GHG Sources and Sinks from Relevant Materials Management Pathways

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

NA =Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 16-2 and calculates the net GHG emissions per short ton of fiberglass insulation. For more detailed methodology on emission factors, please see the sections below on individual waste management strategies. Exhibit 16-3 outlines the net GHG emissions for fiberglass insulation under each materials management option.

Exhibit 16-3: Net Emissions for Fiberglass Insulation under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Fiberglass Insulation	-0.38	NA	NA	NA	0.04

NA =Not applicable.

16.3 Raw Materials Acquisition and Manufacturing

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

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

Exhibit 16-4 shows the proportion of materials assumed in WARM; this calculation was derived using Lippiatt (2007) and Miller (2010). Fiberglass generally uses cullet from recycled plate glass, but the Glass Packaging Institute (cited in NAIMA, 2007, p. 5) notes that “fiberglass insulation is the largest secondary market for recycled glass containers.”

Exhibit 16-4: Material Composition of Fiberglass, by Weight

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

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

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

The RMAM calculation in WARM also incorporates “retail transportation,” which includes the average truck, rail, water and other-modes transportation emissions required to transport fiberglass insulation from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 16-5, and are calculated using data on average shipping distances and modes from the Bureau of Transportation Statistics (2013) and on typical transportation fuel efficiencies from EPA (1998). Transportation emissions from the retail point to the consumer are not included.

Exhibit 16-5: 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)
Fiberglass Insulation	356	0. 35	0.03

16.4 Materials Management Methodologies

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

16.4.1 Source Reduction

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

Exhibit 16-6 outlines the source reduction emission factor for fiberglass insulation. GHG benefits of source reduction are calculated as the emissions savings from avoided raw materials acquisition and manufacturing (see section 3) of fiberglass insulation produced from a "current mix" of virgin and recycled inputs. Fiberglass insulation is usually not manufactured from 100 percent virgin inputs, and is rarely manufactured from 100 percent recycled inputs. WARM assumes that, on average, the "current mix" of fiberglass is composed of 40 percent recycled glass content.

Exhibit 16-6: Source Reduction Emission Factors for Fiberglass Insulation ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Fiberglass Insulation	-0.38	-0.49	NA	NA	-0.38	-0.49

NA = Not applicable.

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

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

16.4.1.1 Developing the Emission Factor for Source Reduction of Fiberglass Insulation

To produce fiberglass insulation, energy is used both in the acquisition of raw materials and in the manufacturing process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2. In addition, manufacturing fiberglass insulation also results in process non-energy CO_2 emissions from the heating of carbonates (soda ash and limestone). Hence, the RMAM component consists of process energy, non-process energy and transport emissions in the acquisition and manufacturing of raw materials, as shown in Exhibit 16-7. Please note that the tables in this section reflect the "current mix" of inputs, as fiberglass insulation usually contains recycled glass cullet.

Exhibit 16-7: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Fiberglass Insulation ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Fiberglass Insulation	0.27	0.06	0.15	0.49

Avoided Process Energy. To calculate this factor, EPA first obtained an estimate of the amount of energy required to acquire and produce one short ton of fiberglass insulation. Lippiatt (2007) provides estimates on the percent of each of the raw materials needed for manufacturing fiberglass, which include borax, soda ash, limestone, sand, glass cullet and binder coatings; EPA adjusts these percentages to increase the portion of recycled cullet from 34 to 40 percent, based on information received from Miller (2010). EPA obtained raw material acquisition data from the National Renewable Energy Laboratory (NREL, 2009) for soda ash and limestone, and from Athena (2000) for sand. NREL also provided estimates for borax, but these estimates include energy requirements of the infrastructure that were outside the boundaries of a WARM analysis; therefore, WARM allocates the fraction of borax in fiberglass among soda ash, limestone and sand on a proportional basis. Lippiatt (2007) also provides information on binder coatings. However, binder coatings represent a small component of fiberglass insulation (5 percent), and additional information on binder coating manufacture was not available; therefore, WARM does not include binder coatings in this analysis. NREL (2009), Lippiatt (2007) and Athena (2000) all provided energy estimates by fuel type.

Next, we multiply the fuel consumption (in Btu) by the fuel-specific carbon content. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in fiberglass insulation production. The process energy used to produce fiberglass insulation and the resulting emissions are shown in Exhibit 16-8.

Exhibit 16-8: Process Energy GHG Emissions Calculations for Virgin Production of Fiberglass Insulation

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Fiberglass Insulation	4.74	0.27

Avoided Transportation Energy. Transportation energy emissions occur when fossil fuels are used to transport raw materials and intermediate products for fiberglass insulation production. The methodology for estimating these emissions is the same as the one used for process energy emissions. EPA obtained transportation distances of raw materials from Lippiatt (2007). The assumed current mix of raw material inputs (including glass cullet) indicates that the materials are transported approximately 187 miles on a weighted average basis. EPA assumes they are transported by truck, and applies the standard WARM estimate of 0.0118 gallons diesel consumed per ton-mile. We estimated retail transportation using U.S. Census Bureau (2007), as shown in Exhibit 16-5. The calculations for estimating the transportation energy emission factor are shown in Exhibit 16-9.

Exhibit 16-9: Transportation Energy Emissions Calculations for Virgin Production of Fiberglass Insulation

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Fiberglass Insulation	0.44	0.03

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 16-5.

Avoided Non-Process Energy. Non-energy GHG emissions occur during manufacturing but are not related to consuming fuel for energy. For fiberglass insulation, non-energy CO_2 emissions (based on data from ICF (1994)) are emitted in the virgin glass manufacturing process during the melting and refining stages from the heating of carbonates (soda ash and limestone). This number is then multiplied by 95 percent, which is the approximate glass content of fiberglass insulation, and then by 60 percent, the approximate content of the glass that comes from raw materials. Exhibit 16-10 shows the components for estimating process non-energy GHG emissions for fiberglass insulation.

Exhibit 16-10: Process Non-Energy Emissions Calculations for Virgin Production of Fiberglass Insulation

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Fiberglass Insulation	0.15	–	–	–	–	0.15

– = Zero emissions.

16.4.2 Recycling

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

16.4.3 Composting

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

16.4.4 Combustion

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

16.4.5 Landfilling

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

Exhibit 16-11. For more information, please see the chapter on Landfilling.

Exhibit 16-11: Landfilling Emission Factor for Fiberglass Insulation ($MTCO_2e$/Short Ton)

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

– = Zero Emissions.

16.5 Limitations

Although this analysis is based upon best available life-cycle data, it does have certain limitations. EPA was unable to obtain sufficient life-cycle information on the raw material acquisition of borax, which represents about 8 percent of fiberglass raw materials by weight. Therefore, the analysis does not account for the emissions associated with obtaining and processing borax.

Furthermore, drywall contains a small amount of binder coatings—materials for which EPA was unable to obtain life-cycle information. Therefore, EPA's analysis does not consider the life-cycle GHG impact of binder coatings, which represent about 5 percent of fiberglass insulation by weight.

16.6 References

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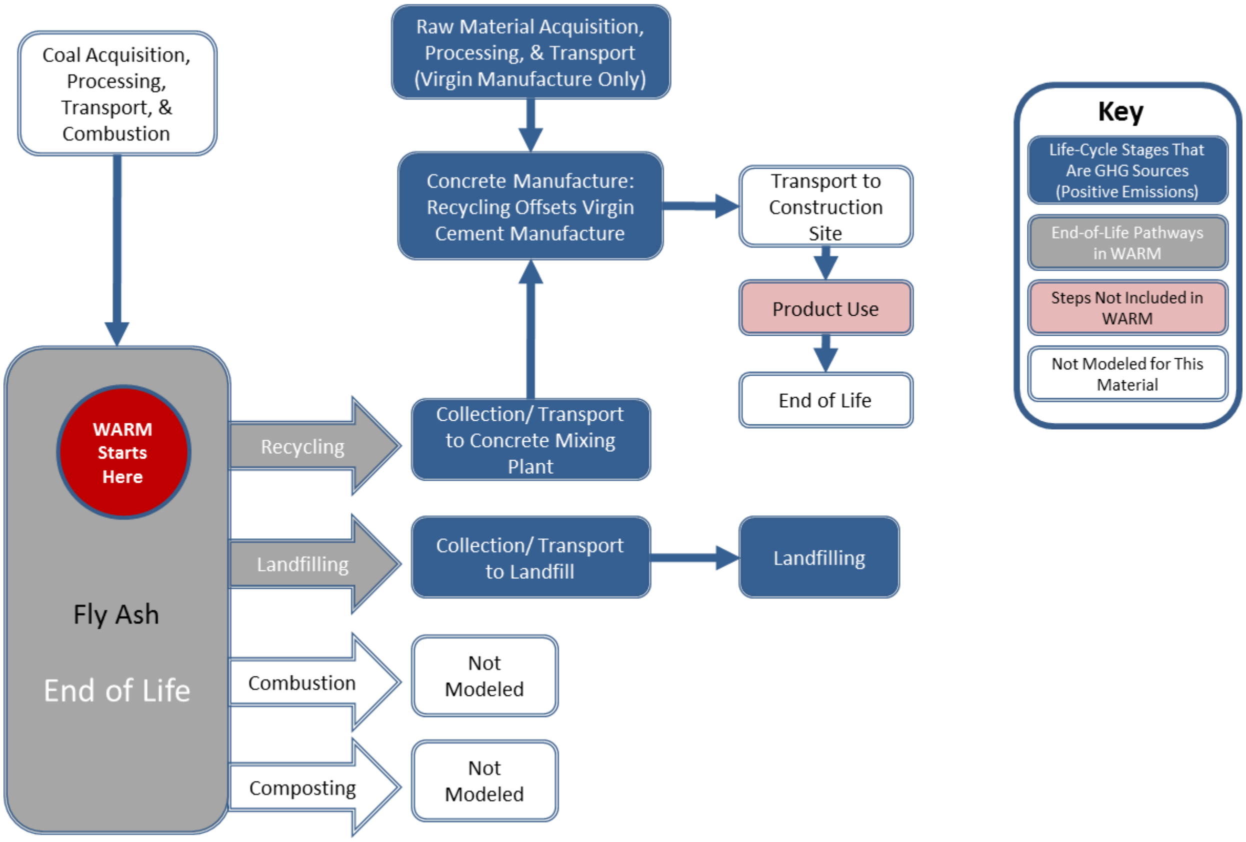
17 FLY ASH

17.1 Introduction to WARM and Fly Ash

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for fly ash beginning at the waste generation reference point. Fly ash is generated as a byproduct of coal combustion and is used as a replacement for cement in concrete, among other uses. The WARM GHG emission factors are used to compare the net emissions associated with management of fly ash in the following two materials management alternatives: recycling and landfilling. Exhibit 17-1 shows the general outline of materials management pathways for fly ash in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Recycling and Landfilling, see the chapters devoted to these processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 17-1: Life Cycle of Fly Ash in WARM



Coal-based electricity generation results in the production of significant quantities of coal combustion products (CCP) (see Exhibit 17-2). Fly ash is a CCP possessing unique characteristics that allow it to be used ton-for-ton as a substitute for portland cement in making concrete. Through the reuse of fly ash, the GHG emissions associated with the production of portland cement are avoided.

Exhibit 17-2: Fly Ash Generation and Reuse in the United States, 2012

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

Source: ACAA (2013).

17.2 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.[76]

As Exhibit 17-3 illustrates, most of the GHG sources relevant to fly ash in this analysis are contained in the raw materials acquisition and manufacturing and materials management sections of the life cycle. WARM does not consider source reduction, composting or combustion as life-cycle pathways for fly ash. The recycling emission factor represents the GHG impacts of manufacturing concrete with recycled fly ash in place of portland cement. The landfilling emission factor reflects the GHG impacts of disposing fly ash in a landfill. Because fly ash does not generate methane in a landfill, the emission factor reflects the emissions associated with transporting the fly ash to the landfill and operating the landfill equipment. As shown in Exhibit 17-3, all of the GHG sources relevant to fly ash in this analysis are contained in the materials management section of the life cycle assessment.

Exhibit 17-3: Fly Ash GHG Sources and Sinks from Relevant Materials Management Pathways

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

NA = Not available.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 17-3 and calculates net GHG emissions per short ton of fly ash inputs (see Exhibit 17-4). For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

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

Exhibit 17-4: Net Emissions for Fly Ash under Each Materials Management Option ($MTCO_2e$/Short Ton)

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

NA = Not applicable.

17.3 Raw Materials Acquisition and Manufacturing

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[77] Because fly ash is a byproduct (waste) of the process of combusting coal for electricity, WARM considers that there are no manufacturing or combustion emissions associated with fly ash itself. In this respect, fly ash is unlike most other materials in WARM for which EPA has developed emission factors. Because the intent is not to burn coal to produce fly ash, but rather to burn coal to produce power, the fly ash would be produced in any case. Therefore, from WARM's perspective, the emissions associated with burning coal would be allocated to the power production process, and not to the production of coal ash. Hence, no RMAM emissions are considered in the life-cycle analysis of fly ash in WARM.

17.4 Materials Management Methodologies

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 17-3 and calculates net GHG emissions per short ton of fly ash. Recycling fly ash leads to reductions in GHG emissions since it avoids energy-intensive manufacture of portland cement. Landfilling has a slightly positive emission factor due to the emissions from transportation of the ash and landfill operation equipment.

17.4.1 Source Reduction

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

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

17.4.2 Recycling

When a material is recycled, it is used in place of virgin inputs in the manufacturing process, rather than being disposed of and managed as waste. Given its byproduct nature, fly ash cannot be recycled in a closed loop and is thus different from most of the other materials considered in the WARM emission factor analysis. Instead, it is recycled in an open loop, replacing cement in the production of concrete.[78] Therefore, the GHG benefits of using fly ash are equivalent to the emissions associated with the manufacture of the quantity of cement that is replaced by fly ash, minus emissions associated with transporting the ash to a concrete manufacturing facility.

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

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

Portland cement, a material with GHG-intensive production, is the most common binding ingredient in concrete. As a pozzolan—a siliceous material that in a finely divided form reacts with lime and water to form compounds with cementitious properties (ACAA, 2003)—fly ash may be used to replace a portion of the portland cement in concrete. When used in concrete applications, fly ash typically composes 15–35 percent by weight of all cementitious material in the concrete mix. In high-performance applications, fly ash may account for up to 70 percent (NRC, 2000).

The calculation of the fly ash emission factor involves estimating the emissions associated with production of one ton of virgin cement and one ton of recycled inputs (i.e., fly ash) individually, and then determining the difference in emissions between recycled and virgin production. The fly ash recycling emission factor is made up of three components: process energy, transportation energy and non-energy emissions. Exhibit 17-5 presents a summary of these components. The following sections contain descriptions of how each component is calculated.

Exhibit 17-5: Components of the Fly Ash Recycling Emission Factor ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

17.4.2.1 Developing the Emission Factor for the Recycling of Fly Ash

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

Cement Production. To produce cement, calcium carbonate ($CaCO_3$) is heated in a kiln at a temperature of approximately 1,300° C (2,400° F), thus breaking the calcium carbonate into lime (CaO) and carbon dioxide (CO_2) in a process known as calcination. This CO_2 is emitted to the atmosphere and silica-containing materials are added to the lime to produce the intermediate product, clinker. The clinker is then allowed to cool and is mixed with a small amount of gypsum to produce portland cement (EPA, 2014). The large amounts of energy required to drive this process are generated by the combustion of fossil fuels, which result in GHG process energy emissions. Additionally, fossil fuels are also required to extract and refine the fuels used in the cement manufacturing process (i.e., “pre-combustion” energy).

To estimate process emissions, we first obtain an estimate of the total energy required to produce one ton of cement, which is reported as 4.77 million Btu (PCA, 2003).[79] Next, WARM determines the fraction of this total energy that is associated with the various fuel types. Each fuel’s share of energy is then multiplied by that fuel’s carbon content to obtain CO_2 emissions for each fuel. EPA then conducts a similar analysis for fugitive methane (CH_4) emissions, using fuel-specific CH_4 coefficients. Finally, total process energy GHG emissions are calculated as the sum of GHG emissions, including both CO_2 and CH_4, from all of the fuel types used in the production of one ton of cement.

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

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

than 3–4 percent) carbon content may be used in concrete without any additional processing. In the past, most U.S. fly ash has fallen into this category. However, at power plants that have instituted new NO_x emissions controls or that inject activated carbon to control mercury emissions, the carbon content (5–9 percent) may be too high for the fly ash to be used without further processing. However, this analysis does not include energy associated with fly ash processing because this process currently takes place on a limited scale. Therefore, the process energy and non-energy emissions for manufacturing fly ash are assumed to be zero.

Hence, the benefits from using fly ash as a recycled product instead of virgin cement in concrete result in negative emissions. Exhibit 17-6 provides the process energy emissions from production of cement and fly ash as calculated in WARM.

Exhibit 17-6: Process Energy GHG Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Cement	4.77	0.42
Fly ash	–	–

– = Zero emissions.

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

Because the transportation energy emissions for virgin cement and recycled fly ash are calculated to be identical (see Exhibit 17-7), the transportation energy emissions associated with fly ash recycling are estimated to be zero.

Exhibit 17-7: Transportation Energy Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Cement	0.10	0.01
Fly Ash	0.10	0.01

Cement production results in non-energy industrial process GHG emissions in the form of CO_2 emitted during the calcination step. To calculate the process non-energy emissions, the molecular weight of CO_2 is divided by the molecular weight of CaO to determine the ratio of CO_2 emitted to lime produced. This ratio is then multiplied by the lime content of cement to determine the ratio of CO_2 emitted to concrete produced. It is assumed that the average lime content of clinker is 65 percent and the average clinker content of portland cement is 95 percent (IPCC/UNEP/OECD/IEA, 1997). The results are adjusted by a 2-percent cement kiln dust (CKD) correction factor, in accordance with the IPCC's Good Practice Guidance (IPCC, 2000). This calculation resulted in a process non-energy emission factor of 0.45 $MTCO_2e$ per ton portland cement.

Exhibit 17-8 provides the calculations for each source of emissions from non-energy processes. Exhibit 17-9 shows the calculation of the emission factor for use of recycled fly ash in place of virgin cement.

Exhibit 17-8: Process Non-Energy Emissions Calculations for Virgin Production of Cement and Recycled Use of Fly Ash

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Cement	0.45	–	–	–	–	0.45
Fly ash	–	–	–	–	–	–

– = Zero emissions.

Exhibit 17-9: Difference in Emissions between Virgin Cement Production and Recycled Fly Ash Use ($MTCO_2e$/Short Ton)

Material/ Product	Virgin Cement Production ($MTCO_2e$/Short Ton)			Recycled Fly Ash Use ($MTCO_2e$/Short Ton)			Difference Between Virgin Cement Production and Recycled Fly Ash Use ($MTCO_2e$/Short Ton)		
	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Fly Ash/ Cement	0.42	0.01	0.45	–	0.01	–	-0.42	–	-0.45

– = Zero emissions.

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

17.4.3 Composting

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

17.4.4 Combustion

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

17.4.5 Landfilling

Landfilling is the most common waste management option for fly ash and a majority of the fly ash generated in the United States each year is disposed of in landfills (see Exhibit 17-2). Fly ash is typically placed in specialized fly ash landfills situated and built to prevent trace elements in the fly ash from leaching into drinking water supplies (EPRI, 1998). Although the construction of these specialized landfills requires energy and thus results in GHG emissions, the emissions from landfill construction are considered to be beyond the scope of this analysis; thus, the WARM landfill emission factor excludes these emissions.

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

GHG emissions generated by transportation to the landfill. WARM assumes the standard landfill transportation factor. This information is summarized in Exhibit 17-10.

Exhibit 17-10: Landfilling Emission Factor for Fly Ash ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

For more information, please see the chapter on Landfilling.

17.5 Limitations

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

- It does not consider emissions from construction of special leak-proof landfills for fly ash.
- It does not include energy associated with the processing of fly ash with high carbon content (5–9 percent) because this process currently takes place on a limited scale.
- Although this analysis is based upon the best available life-cycle data, uncertainties do exist in the final emission factors. It is important that we continue to assess the assumptions and data used to develop the emission factors. As the combustion processes, manufacturing processes and recycling processes change in the future, these changes will be incorporated into revised emission factors. In addition, it should be noted that these results are designed to represent national average data. The actual GHG impacts of recycling or landfilling fly ash will vary depending on individual circumstances.

17.6 References

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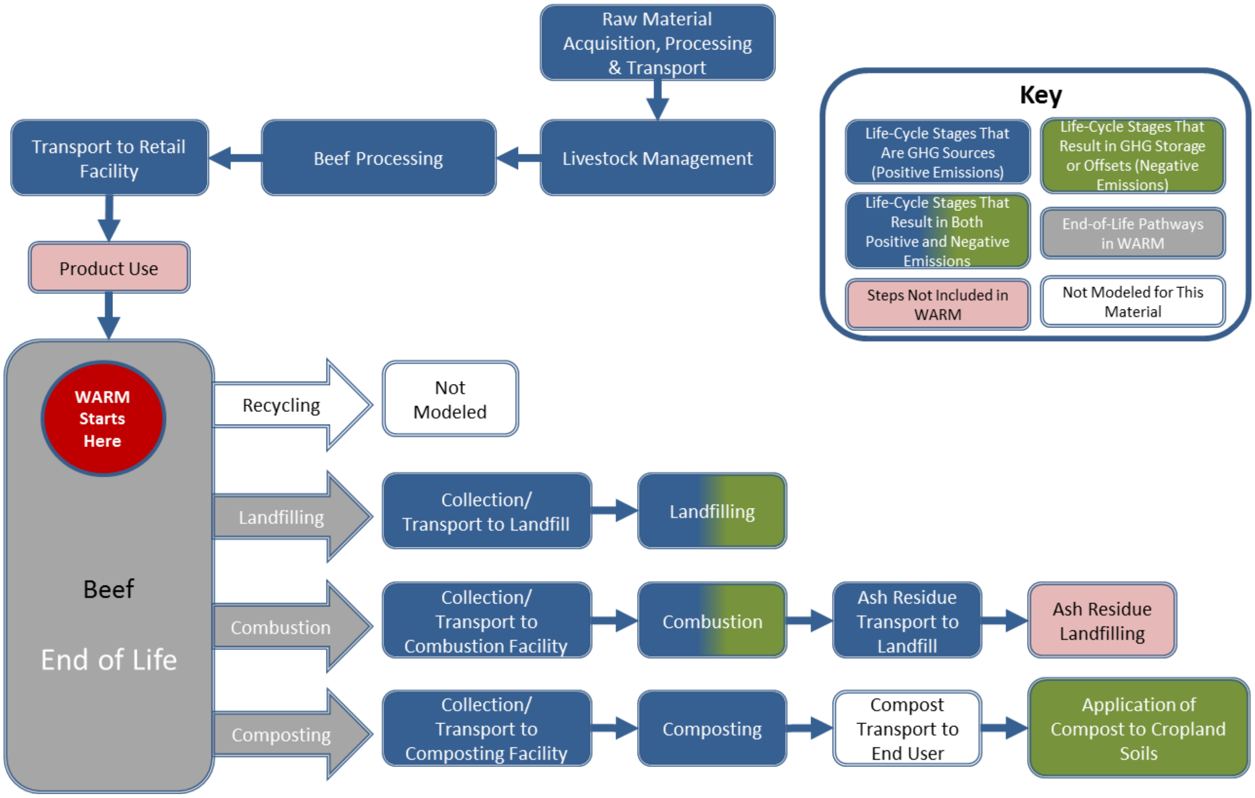
18 FOOD WASTE

18.1 Introduction to WARM and Food Waste

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for food waste—including beef, poultry, grains, bread, fruits and vegetables, and dairy products—beginning at the point of waste generation.[80] The WARM GHG emission factors are used to compare the net emissions associated with these six organic material types in the following four materials management options: source reduction, composting, landfilling, and combustion. Exhibit 18-1, Exhibit 18-2, Exhibit 18-3, Exhibit 18-4, Exhibit 18-5, and Exhibit 18-6 illustrate the general life cycles and materials management pathways modeled in WARM for beef, poultry, grains, bread, fruits and vegetables, and dairy products, respectively. In each life-cycle diagram, the end-of-life pathways are the same for each material, with only the upstream raw material and production stages differing across food waste types. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Composting, 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 18-1: Life Cycle of Beef in WARM



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[80] Source reduction factors for grains, bread, fruits and vegetables, and dairy products were incorporated into WARM version 13 in June 2014; source reduction factors for beef and poultry were added as part of an update to WARM version 13 in March 2015.

Exhibit 18-2: Life Cycle of Poultry in WARM

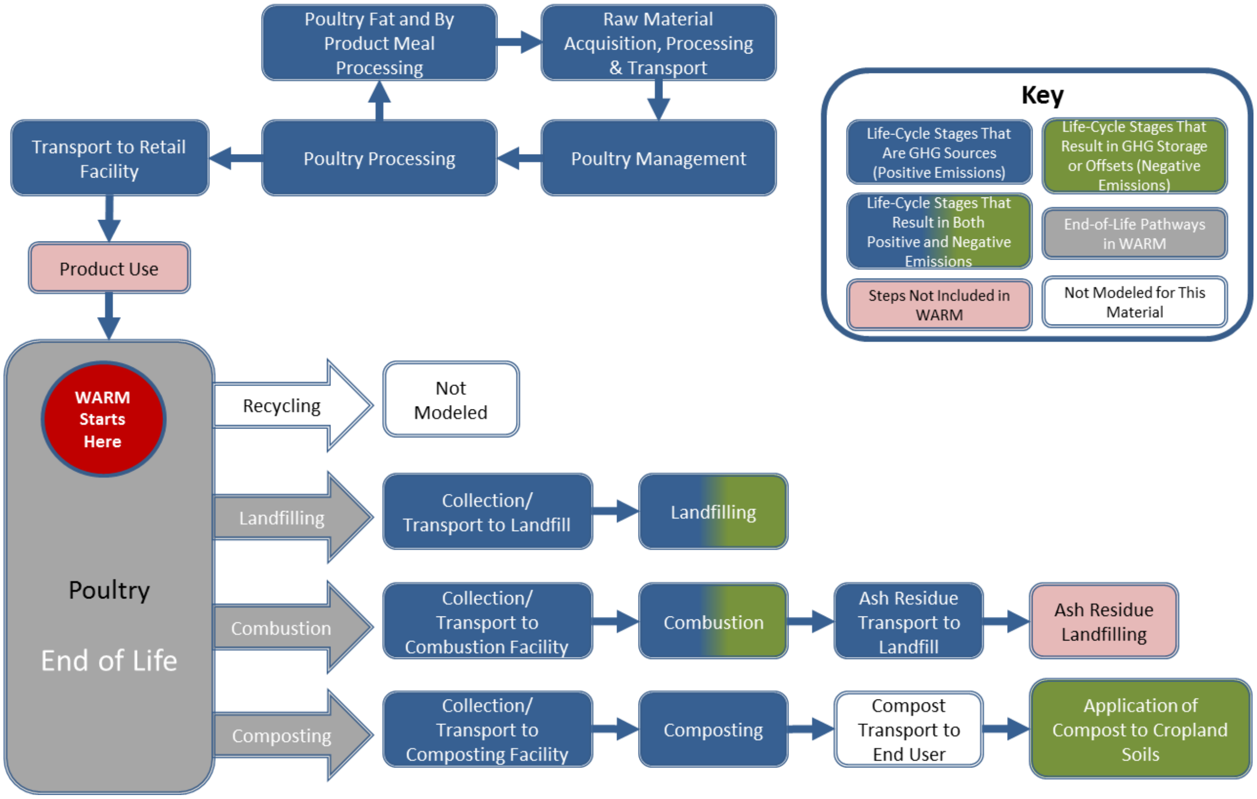


Exhibit 18-3: Life Cycle of Grains in WARM

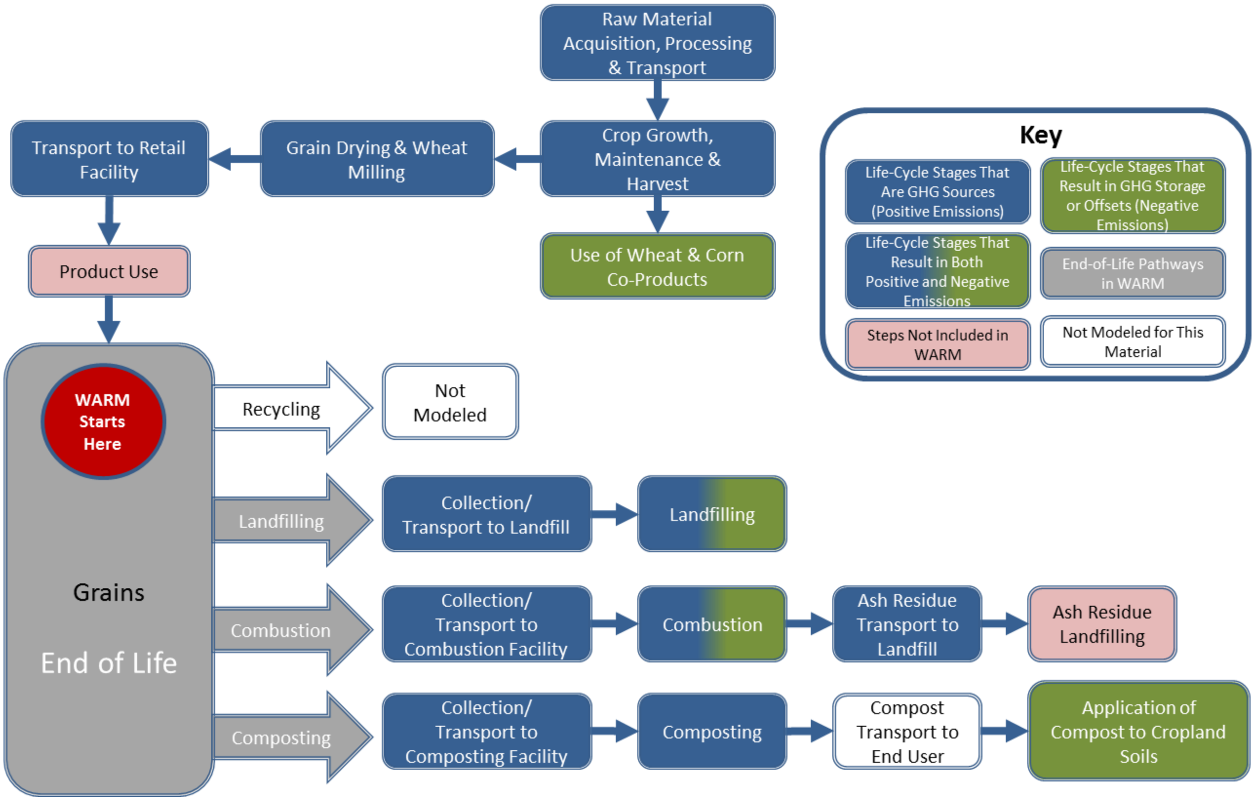


Exhibit 18-4: Life Cycle of Bread in WARM

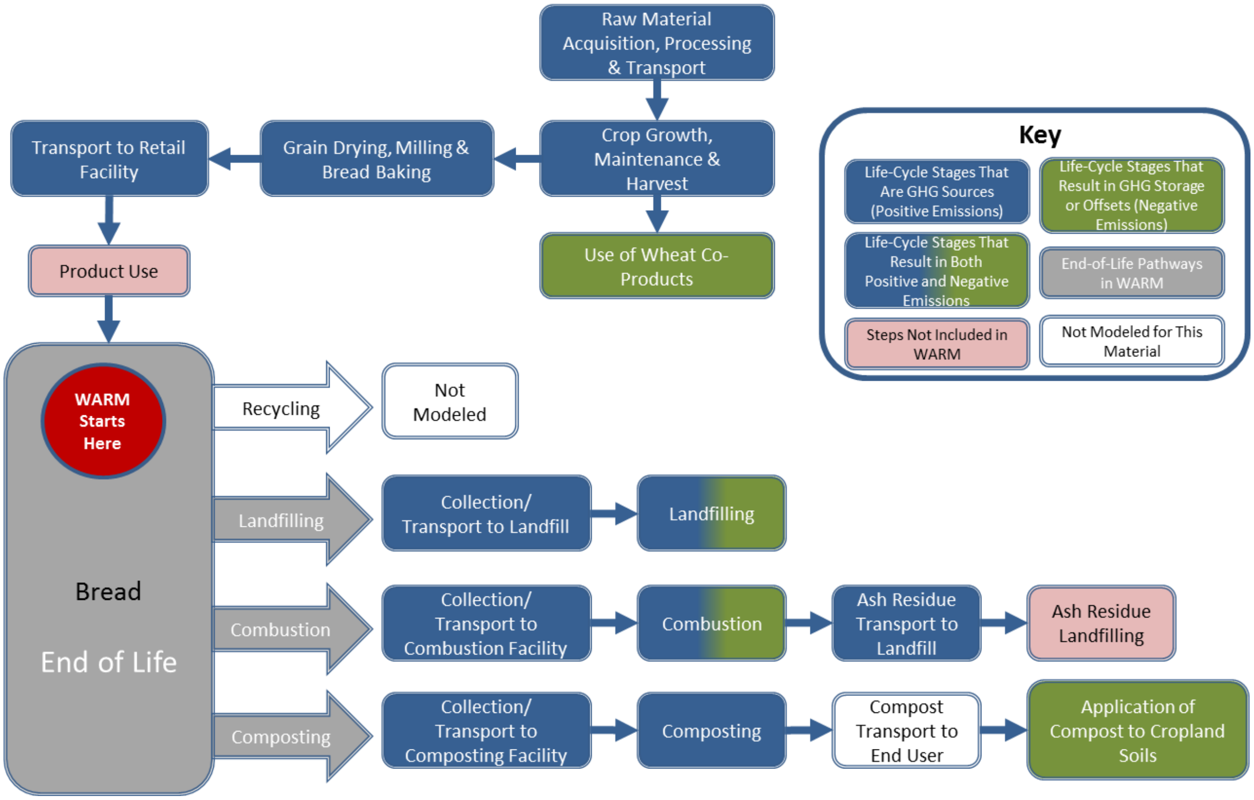


Exhibit 18-5: Life Cycle of Fruits and Vegetables in WARM

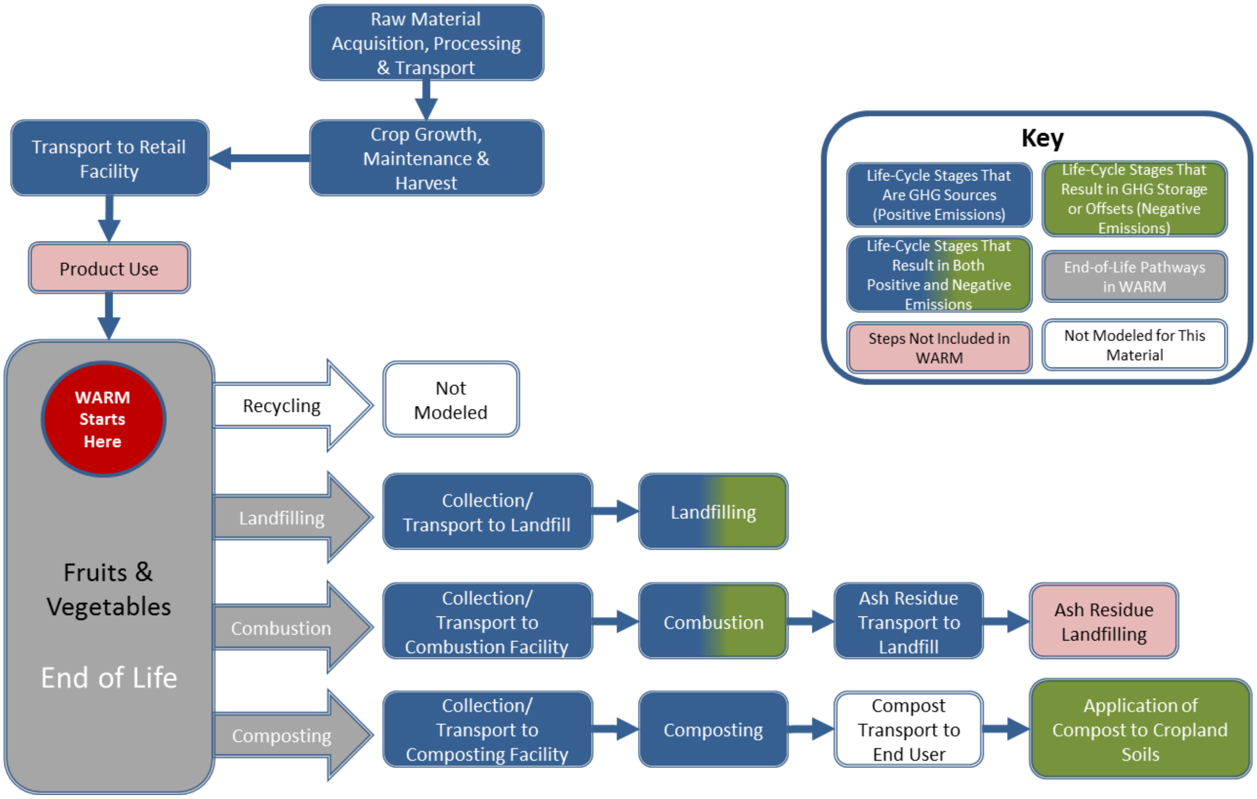
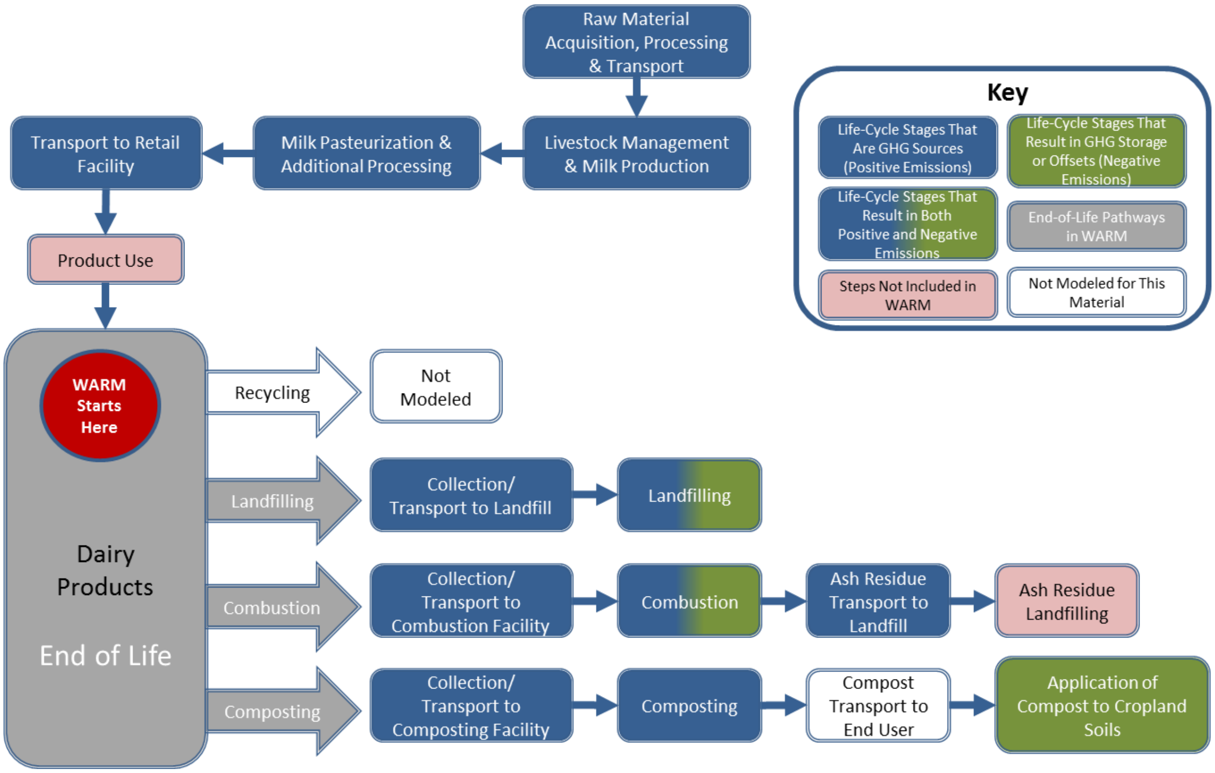


Exhibit 18-6: Life Cycle of Dairy Products in WARM



Food waste falls under the category of “organics” in WARM. Although paper, wood products and plastics are organic materials in the chemical sense, these categories of materials have very different life-cycle and end-of-life characteristics than food waste and are treated separately in the municipal solid waste (MSW) stream. Beef, poultry, grains, bread, fruits and vegetables, and dairy products include uneaten and prepared food from residences, commercial and non-commercial establishments, and industrial sources (USDA 2012b).

WARM also calculates emission factors for four mixed waste categories that include food waste. These mixed waste categories are provided to represent different types of common food wastes and to estimate emissions from a range of organic materials in wastes modeled by WARM users. Mixed food waste is also likely to include individual food waste components not currently modeled in WARM (e.g., meat types like pork). For more information on “proxies” that can be used to represent other food types not included in WARM, see the guidance document “Using WARM Emission Factors for Materials and Pathways Not in WARM.” The mixed waste categories that include food waste are:

- “Food waste”, which is a weighted average of the five main food type emission factors developed for WARM: beef, poultry, grains, fruits and vegetables, and dairy products.[81] The weighting is based on the relative shares of these five categories in the U.S. food waste stream, according to the U.S. Department of Agriculture (USDA) Economic Research Service (ERS) *Food Availability (per Capita) Data System - 2010,* and as shown in column (c) of Exhibit 18-7.
- “Food waste (meat only)”, which is a weighted average of the two meat food type emission factors developed for WARM: beef and poultry. The weighting is based on the relative shares of

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[81] Bread is an extension of the grains emission factor and represents wheat flour that is processed into bread; therefore, it is not included as a separate component in the weighted average food waste categories in WARM.

these two categories in the U.S. food waste stream according to USDA (2012b) and therefore not meant to be representative of emissions from other types of meat.

- "Food waste (non-meat)", which is a weighted average of the three non-meat food type emission factors developed for WARM: grains, fruits and vegetables, and dairy products. The weighting is based on the relative shares of these three categories in the U.S. food waste stream according to USDA (2012b).
- The "mixed organics category", which is a weighted average of the food waste and yard trimmings emission factors. The weighting is based on the relative shares of these two categories in the waste stream, according to the latest version of EPA's annual report, *Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures*, and as shown in column (c) of Exhibit 18-8.[82] For the mixed organics category, WARM models the waste management pathways relevant to both food waste and yard trimmings (i.e., landfilling, combustion, and composting).

Exhibit 18-7: Relative Shares of Categories of Food Waste Modeled in WARM in the Waste Stream in 2010

(a) Material		**(b) % of Total Food Waste Generation**	**(c) Weighted Percentage in WARM**
Modeled in WARM	Beef	5.5%	9.3%
	Poultry	6.5%	11.0%
	Grains	7.8%	13.1%
	Fruits and Vegetables	29.3%	49.1%
	Dairy Products	10.3%	17.7%
	Total Modeled in WARM	*59.4%*	*100%*
Other Types	Other meats[a]	4.2%	NA
	Other poultry[b]	1.1%	
	Other grains	0.3%	
	Other fruits and vegetables	19.9%	
	Other dairy products	0.3%	
	Other foods[c]	14.8%	
All Foods	*Total*	*100%*	

[a] Includes veal, pork, and lamb.
[b] Includes turkey.
[c] Includes eggs, fish, shellfish, peanuts, tree nuts, coconut, caloric sweeteners, added fats and oils, and dairy fats.
Source: USDA 2012b.

Exhibit 18-8: Relative Shares of Yard Trimmings and Food Waste in the Waste Stream in 2012

(a) Material	**(b) Generation (Short Tons)**	**(c) % of Total Organics Generation**	**(d) Recovery (Short Tons)**	**(e) Recovery Rate**
Food Waste	36,430,000	52%	1,740,000	4.8%
Yard Trimmings	33,960,000	48%	19,590,000	57.7%

Source: EPA 2014b.

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[82] Note that, unlike for other materials in WARM, the "food waste" and "mixed organics" categories are based on relative shares among materials *generated* rather than *recovered*. For food waste, this is because detailed data on the types of foods recovered in the United States are currently unavailable. For mixed organics, WARM assumes that users interested in composting would be dealing with a food waste and mixed organics category that is closer to the current rate of generation, rather than the current rate of recovery. Since the fraction of recovered food waste is so low, if the shares of yard trimmings and food waste recovered were used, the mixed organics factor would be essentially the same as the yard trimmings factor, rather than a mix of organic materials.

18.2 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.[83] 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.

As Exhibit 18-9 illustrates, all of the GHG sources relevant to food waste in this analysis fall under the raw materials acquisition and manufacturing and end-of-life sections of the life cycle. WARM does not include recycling as a management option for food waste, as food waste cannot be recycled in the traditional sense.

Exhibit 18-9: Food Waste GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Organics	**GHG Sources and Sinks Relevant to Food Waste**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Transport of raw materials and products • Raw material acquisition • Production energy • Production process non-energy • Transport of food productions to retail	NA	NA
Recycling	Not applicable since food waste cannot be recycled		
Composting	NA	**Offsets** • Increase in soil carbon storage	**Emissions** • Transport to compost facility • Compost machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related nitrous oxide **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas combustion • Landfill carbon storage

NA = Not applicable

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 18-9 to calculate net GHG emissions per short ton of food waste materials generated. GHG emissions arising from the consumer's

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[83] 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.

use of any product are not considered in WARM's life-cycle boundaries. Exhibit 18-10 presents the net GHG emission factors for each materials management strategy calculated in WARM for food waste. Note that while a detailed analysis of food type-specific upstream GHG emissions has been conducted in WARM, EPA has not yet analyzed differences in GHG emissions by food type in the composting, combustion, and landfilling pathways. Therefore, the emission factors for those pathways are the same for each food waste type.

Additional discussion on the detailed methodology used to develop these emission factors may be found in Section 18.4.

Exhibit 18-10: Net Emissions for Food Waste and Mixed Organics under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material	Net Source Reduction Emissions	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Food Waste	-3.66	NA	-0.15	-0.12	0.71
Food Waste (non-meat)	-0.76	NA	-0.15	-0.12	0.71
Food Waste (meat only)	-15.10	NA	-0.15	-0.12	0.71
Beef	-30.05	NA	-0.15	-0.12	0.71
Poultry	-2.47	NA	-0.15	-0.12	0.71
Grains	-0.62	NA	-0.15	-0.12	0.71
Bread	-0.67	NA	-0.15	-0.12	0.71
Fruits and Vegetables	-0.44	NA	-0.15	-0.12	0.71
Dairy Products	-1.74	NA	-0.15	-0.12	0.71
Mixed Organics	NA	NA	-0.14	-0.14	0.29

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

18.3 Raw Materials Acquisition and Manufacturing

For food waste, the GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and food production processes, (2) GHG emissions from energy used to transport materials, (3) non-energy GHG emissions resulting from production processes, and (4) non-energy GHG emissions resulting from refrigerated transportation and storage. Process non-energy GHG emissions occur during the manufacture and application of agricultural fertilizers, from the management of livestock manure, and from enteric fermentation resulting from livestock. Transportation and storage non-energy emissions result from the fugitive emission of refrigerants.

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average truck, rail, water, and other-modes transportation emissions required to transport food products from the production or processing facility to the retail/distribution point. Transportation emissions for the retail point to the consumer are not included. The energy and GHG emissions from retail transportation for each food waste type are presented in Section 18.4.1 describing the source reduction methodology for each food waste type.

EPA excluded emissions from food product packaging production, processing, and disposal from the food RMAM estimates because (1) food wastes and packaging wastes are frequently managed using different waste management pathways and (2) emission factors for many common packaging materials are already separately available in WARM.

The net emissions factors for source reduction of food waste include RMAM "upstream emissions" and are shown in the section on source reduction.

18.3.1 Beef

The emission factor for beef includes the energy and emissions associated with producing beef for retail sale, including the upstream impacts of producing livestock feed, cattle raising, enteric fermentation from cattle, and processing of the beef to prepare it for retail sale. In addition, the emission factor includes the energy and GHG emissions associated with the transport of beef products from production to retail sale. According to the USDA ERS loss-adjusted food availability data, beef constituted approximately 9 percent of food waste in 2010, as shown in Exhibit 18-7. Unlike some other food waste categories in WARM, the beef emission factor is a category solely represented by beef rather than a mix of individual food components, as shown in Exhibit 18-11.

Exhibit 18-11: Beef in the U.S. Food Waste Stream in 2010

Material Modeled in WARM	Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Beef	12,777	100%	100%

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of beef, several key assumptions were made:

- Due to the large variety of potential products and coproducts from beef cattle (e.g., different beef cuts, inedible portions of the cattle, further-processed beef products) EPA has not separately modeled the impacts associated with the varied end-products derived from one animal. Instead, the EPA used LCI data in this analysis to estimate the energy and GHG emissions from a functional unit of one short ton of boneless, edible beef (Battagliese et al. 2013).
- EPA used LCI data for the production of conventional beef and did not model the production of organic beef or veal. The LCI data for the beef RMAM included on-farm data for a U.S. research farm combined with post-farm data aggregated across the U.S. beef industry. The on-farm data is assumed to be representative of farm production of cattle throughout the entire United States (Battagliese et al. 2013).
- EPA estimated energy use and GHG emissions for upstream grain production for cattle feed using data from Battagliese et al. (2013) rather than the grain production emission factor in WARM (See Section 18.3.3). This approach was used because LCI data did not allow for disaggregation of energy and emissions from feed production from the other RMAM inputs for beef.

18.3.2 Poultry

RMAM data for poultry include the upstream impacts of producing broiler chicken (i.e., domesticated chickens raised specifically for meat production) which represents 85.6 percent of poultry products in the U.S. waste stream according to the USDA ERS loss-adjusted food availability data from 2010, as shown in Exhibit 18-12. Turkey, the other component of poultry waste in the ERS loss-adjusted food availability data, was not included due to limitations acquiring RMAM data for its production and because it comprises a small share of the overall waste stream.

The poultry RMAM data includes the upstream energy and GHG emissions of all poultry production processes prior to retail storage and consumer use. For poultry, this includes three upstream stages: production of poultry feed, poultry production on a broiler farm (including energy use and emissions for milling feed and housing poultry), and poultry processing. Each stage accounts for transportation processes, from bringing feed ingredients to the broiler farm up to and including transportation of final broiler poultry products to retail. Transportation includes energy use and emissions from refrigeration.

Exhibit 18-12: Poultry in the U.S. Food Waste Stream in 2010

Material		Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	Chicken	15,134	85.6%	100%
Other Types	Turkey	2,545	14.4%	NA
All Poultry	*Total*	*17,680*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of poultry, several key assumptions were made:

- Due to the large variety of potential products and coproducts from broiler poultry (e.g., different poultry cuts, inedible portions of the chicken, further-processed poultry products) EPA has not separately modeled the impacts associated with the varied end-products derived from one animal. Instead, EPA used LCI data in this analysis to estimate the energy and GHG emissions from a functional unit of one short ton of processed broiler poultry.
- The mix of poultry feed inputs in the LCI data used by EPA included 2.5 percent poultry fat and 2.5 percent poultry by-product meal. Because WARM assumes that the functional unit consists of processed broiler poultry, EPA has not allocated upstream production emissions to poultry fat and by-product meal. This differs from the approach in the primary sources of LCI data used by EPA (Pelletier 2008, Pelletier 2010) but it allows a more consistent methodology with other food factors in WARM and most closely represents the poultry waste managed by WARM users.
- EPA used LCI data for the production of conventional poultry and did not model the production of organic poultry. The LCI data for the emission factor are representative of current, national average practices in the United States. The sources for the LCI data used by EPA (Pelletier 2008, Pelletier 2010) represent U.S. average figures using information from the U.S. poultry industry, academic studies, and peer-reviewed literature.

18.3.3 Grains and Bread

The emission factor for grains includes the upstream impacts of producing wheat flour, corn, and rice, which together constitute over 96 percent of grains in the U.S. waste stream. The USDA Economic Research Service (ERS) loss-adjusted food availability data from 2010 was used to determine the relative shares of various fruits and vegetables within the U.S. waste stream, as shown in Exhibit 18-13. Furthermore, the bread emission factor supplements the grain emission factor by including the additional energy used to manufacture wheat flour into bread, which is the predominant use for wheat flour (USDA 2012a). The other grain categories in the ERS loss-adjusted food availability data were not included either due to limitations acquiring RMAM data for their production and because they comprised such a small share of the overall waste stream. Furthermore, estimates of end-product manufacturing energy for corn and rice were not made due to lack of data availability.

Exhibit 18-13: Relative Shares of Grains in the U.S. Food Waste Stream in 2010

Material		**Loss Rate (Millions of pounds per year)**	**Percent of Category**	**Weighted Percentage in WARM**
Modeled in WARM	Wheat Flour	12,309	65.6%	68.3%
	Corn	3,025	16.1%	16.8%
	Rice	2,689	14.3%	14.9%
	Total Modeled in WARM	*18,023*	*96.1%*	*100%*
Other Types	Oats	609	3.2%	NA
	Other grains	130	0.7%	
All Grains	*Total*	*18,761*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of grains and bread, several key assumptions were made:

- EPA assumed that all grains modeled would be farmed in the United States using conventional (i.e., non-organic) farming practices. Production of winter wheat in Kansas, corn in Iowa and Illinois, and rice in Arkansas was assumed to be representative of national production due to those states' large share of domestic production for each respective grain.
- The LCI data for the production of grains were insufficient to characterize the full scope of energy and emissions associated with the production and processing of grains into a finished form. For this reason, the crop production data for all three grain products was supplemented with additional processing data for grain drying from the Ecoinvent database (Nemecek and Kagi, 2007). As the majority of wheat products use wheat flour, the wheat LCI data was further supplemented with the energy demand associated with wheat milling (Espinoza-Orias 2011).
- The grains emission factor includes milling of wheat into flour but assumes that wheat flour, corn, and rice can be purchased as dried grains without further processing or cooking. The bread emission factor assumes baking of wheat flour into bread. The emission factor for grains may understate the upstream emissions associated with corn and rice products that have undergone further processing.

18.3.4 Fruits and Vegetables

The broad category of fruits and vegetables includes a wide variety of cultivars produced worldwide, all with widely varying inputs, processing stages, and transportation distances. The fruit and vegetable energy and emission factors consist of a weighted average mix of materials that reflects the relative contribution of different fruits and vegetables to the total U.S. waste stream. The USDA Economic Research Service (ERS) loss-adjusted food availability data from 2010 was used to determine the relative shares of various fruits and vegetables within the U.S. waste stream, as shown below in Exhibit 18-14. The ERS loss-adjusted food availability data include several more food categories than were included in the final emission factor; however, these were not included either due to limitations acquiring RMAM data for their production, or because they comprised such a small share of the overall waste stream. The remaining fruits and vegetables included within the emission factor together comprise 59.6 percent of the fruits and vegetables discarded within the United States in 2010, totaling nearly 68 million pounds annually.

Exhibit 18-14: Relative Shares of Fruits and Vegetables in the U.S. Food Waste Stream in 2010

Material		Loss Rate (Millions of pounds per year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	Potatoes	18,294	16.4%	27.5%
	Tomatoes	18,650	16.1%	27.0%
	Citrus	14,200	12.5%	21.0%
	Melons	6,313	5.6%	9.3%
	Apples	5,575	4.9%	8.2%
	Bananas	4,705	4.1%	6.9%
	Total Modeled in WARM	*67,737*	*59.6%*	*100%*
Other Types	Other vegetables	16,815	14.8%	NA
	Other non-citrus fruit	10,428	9.2%	
	Corn	5,723	5.0%	
	Lettuce, spinach, and other greens	5,219	4.6%	
	Onions	4,116	3.6%	
	Legumes	2,005	1.8%	
	Berries	1,667	1.5%	
All Fruits and Vegetables	*Total*	*113,734*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of fruits and vegetables, several key assumptions were made:

- EPA assumed that all of the fruits and vegetables modeled would be farmed in the United States, with the exception of bananas, using conventional (i.e., non-organic) farming practices. Foreign-grown bananas were included within this assessment because they are one of the largest sources of fruit and vegetable waste within the U.S. waste stream. They were assumed to be produced in Central America using conventional farming practices due to the lack of suitable climate for their cultivation on a large scale within the United States.
- The differences in production impacts across different breeds of fruits and vegetables were not considered in the analysis. For example, energy and emissions associated with the production of Fuji apples were assumed to be representative of all apple production in the United States. Likewise, RMAM data for the farming of oranges was assumed to be representative of all citrus production due to lack of data for production of other citrus fruits and food consumption data showing that oranges comprise 65 percent of citrus fruits consumed in the United States in 2012 (Boriss, 2013).
- Because all of the components included in the fruits and vegetable factors can be consumed as fresh fruits and vegetables and due to the lack of data on fruit and vegetable processing, EPA has assumed that all fruits and vegetables enter the waste stream as fresh fruits and vegetables. Processed fruits and vegetables are likely to have a longer shelf life and therefore may comprise a smaller share of the food waste stream than fresh fruits and vegetables. As a result, the source reduction factors for fruits and vegetables exclude any potential impacts from freezing, canning, pickling, or other processing steps. However, the fruits and vegetable factors should be considered an acceptable proxy for processed fruits and vegetable products.

18.3.5 Dairy Products

The production of dairy products includes the production of upstream animal feed for livestock, livestock handling, and the processing of milk into other dairy products. Dairy products within the U.S. waste stream include multiple varieties of milk, cheese, yogurt and frozen products. The weighted emission factor for dairy products in WARM includes 97 percent of the dairy products in the waste stream, as illustrated in Exhibit 18-15. The remaining products were not included due to both data limitations and because they constituted such a small share of dairy food waste.

Exhibit 18-15: Relative Shares of Dairy Products in the U.S. Food Waste Stream in 2010

Material		Per Capita Loss Rate (Lbs/Year)	Percent of Category	Weighted Percentage in WARM
Modeled in WARM	1% Milk	6.96	8.8%	9.0%
	2% Milk	17.83	22.5%	23.2%
	Skim Milk	7.93	10.0%	10.3%
	Whole Milk	13.69	17.3%	17.8%
	Ice Cream and Frozen Dairy	7.18	9.1%	9.3%
	Non-Fat and Dry Milk	1.55	2.0%	2.0%
	Generic Milk	8.45	10.7%	11.0%
	Cheddar	4.73	6.0%	6.1%
	Mozzarella	4.53	5.7%	5.9%
	Yogurt	4.12	5.2%	5.4%
	Total Modeled in WARM	*76.97*	*97.3%*	*100%*
Other Types	Evaporated Condensed Milk	1.77	2.3%	NA
	Eggnog	0.41	0.5%	
All Dairy	*Total*	*79.1*	*100%*	

Source: USDA 2012b.

In order to develop national average estimates of the RMAM GHG emissions associated with production of dairy products, several key assumptions were made:

- EPA used a regional average of milk production from five regions to model "generic milk" as a stand-in for specialty products such as chocolate milk and buttermilk. Similarly, unflavored "ice cream" is assumed to be representative of a variety of flavors in the marketplace.
- EPA used fruit yogurt as a proxy for general yogurt production, as it was the only variant of yogurt available within the dairy products production dataset, whereas ice cream served as a proxy for all frozen dairy products.
- "Cheddar" and "mozzarella" cheeses were assumed to be representative of the entire cheese production process due to their high share of the waste stream.
- GHG emissions for the production of grains used as cattle feed are based on data specific to dairy production and therefore do not use the same data sources used to develop the grains and bread emission factors in WARM.

18.4 Materials Management Methodologies

Source reduction, landfilling, composting, and combustion are four management options used to manage food waste.

18.4.1 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 food waste has negative

RMAM 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 18-16 presents the inputs to the source reduction emission factor for production of each food waste type included in WARM. Beef has the lowest net emission factor, implying greatest emissions savings due to source reduction, owing to the large amount of emissions released during RMAM of beef.

Exhibit 18-16: Source Reduction Emission Factors for Food Waste ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon 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
Food Waste	-3.66	-3.66	NA	NA	-3.66	-3.66
Food Waste (non-meat)	-0.76	-0.76	NA	NA	-0.76	-0.76
Food Waste (meat only)	-15.10	-15.10	NA	NA	-15.10	-15.10
Beef	-30.05	-30.05	NA	NA	-30.05	-30.05
Poultry	-2.47	-2.47	NA	NA	-2.47	-2.47
Grains	-0.62	-0.62	NA	NA	-0.62	-0.62
Bread	-0.67	-0.67	NA	NA	-0.67	-0.67
Fruits and Vegetables	-0.44	-0.44	NA	NA	-0.44	-0.44
Dairy Products	-1.74	-1.74	NA	NA	-1.74	-1.74

NA = Not applicable.

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

All food waste materials are assumed to be produced using 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 food waste, there are no post-consumer emissions because production of the material is avoided in the first place, and the avoided food never becomes post-consumer. Forest carbon storage is not applicable to food waste, and thus does not contribute to the source reduction emission factor.

18.4.1.1 Developing the Emission Factor for Source Reduction of Beef

To produce beef, energy is directly used for livestock management, beef processing, and retail transport. Additionally, during the RMAM phase of the product life-cycle, upstream energy is used to produce cattle feed and other raw material inputs. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in CO_2 emissions, with small amounts of N_2O also emitted. Producing beef also results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. These process non-energy emissions primarily come from enteric fermentation by cattle, as well as the upstream impacts of fertilizer production and application to produce the grains fed to cattle. Exhibit 18-17 shows the results for each component and the total GHG emission factors for source reduction of beef.

Exhibit 18-17: Raw Material Acquisition and Manufacturing Emission Factor for Production of Beef ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Beef	3.85	0.12	26.09	30.05

Beef production. The data for beef production used for developing the beef emission factor was provided by the National Cattlemen's Beef Association (NCBA), an industry group. The data used in WARM were derived from the same data used to produce a 2013 study prepared for NCBA by BASF Corporation, “More Sustainable Beef Optimization Project: Phase 1 Final Report” (Battagliese et al. 2013). The study provides a cradle-to-grave assessment of beef production in 2007 and 2011 and measures the environmental impacts and consumer benefits of beef products in multiple categories, including GHG emissions.

To align the data in Battagliese et al. (2013) with the scope of the source reduction emission factors in WARM, EPA separated the cumulative upstream energy demand and process non-energy emissions from beef production from energy and emissions that are outside the scope of source reduction emission factors in WARM (i.e., retail storage, consumer transport, and retail packaging). The sorted data set included the upstream cumulative energy demand by energy source and the aggregated process non-energy emissions sorted by gas. In the study, some impacts of beef production were allocated to by-products on an economic basis based on their value relative to the beef produced in the value chain. The by-products allocated economically include products from both feed and beef production, such as dried distillers’ grains, beef tallow, and offal.

EPA calculated the emissions associated with beef production in two separate stages: first, process energy emissions were calculated by determining the cumulative energy demand for producing one short ton of beef. Secondly, process non-energy emissions from producing one short ton of beef were estimated separately and added to the process energy emissions. Initially, the energy (in units of million Btu) for beef production was sorted between renewable bio-energy embedded in crops and demand for energy from fossil fuel combustion and the electricity grid. GHG emissions from bio-energy are treated as biogenic emissions that do not contribute to the GHG emission factor. The energy and electricity demand estimated in the data from the Battagliese et al. (2013) report factored in both efficiency losses in the grid and upstream conversion losses from energy extraction. The process energy used to produce beef and the resulting emissions are shown in Exhibit 18-18. The beef source reduction factor is meant to model all beef waste that occurs during consumers use, including losses during preparation and inedible portions.

Exhibit 18-18: Process Energy GHG Emissions Calculations for Production of Beef

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Beef	62.25	3.85

The process non-energy emissions from beef production are dominated by CH_4 and N_2O emissions primarily resulting from enteric fermentation and fertilizer use for feed production, respectively. Methane comprises approximately 63 percent of non-energy GHG emissions from beef production, whereas N_2O comprises 37 percent. Collectively, the process non-energy emissions exceed the process energy emissions associated with beef production. Exhibit 18-19 shows the components for estimating process non-energy GHG emissions for beef.

Exhibit 18-19: Process Non-Energy GHG Emissions Calculations for Production of Beef

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Beef	<0.01	0.66	–	–	0.03	26.09

– = Zero emissions.

Retail Transport. The retail transport data for beef products was taken from the same dataset as the upstream production cumulative energy demand and process non-energy emissions (Battagliese et al. 2013). The energy demand from transportation, which was not disaggregated from the mix of fuels used for other process emissions, was assumed to be derived primarily from diesel fuel consumption during retail transport. This energy demand was scaled by a carbon coefficient for diesel combustion to estimate the retail transportation GHG emissions.

18.4.1.2 Developing the Emission Factor for Source Reduction of Poultry

To produce poultry, energy is directly used on-site at poultry farms, for poultry processing, and for retail transport. During the RMAM phase of the products' life-cycle, upstream energy is used to produce poultry feed. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or via on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, poultry production results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. These process non-energy emissions primarily come from on-farm gaseous emissions by poultry, as well as the upstream impacts of fertilizer production and application in growing poultry feed inputs.

To represent poultry source reduction in WARM, EPA used a functional unit of one short ton of processed broiler poultry.[84] Processed broiler poultry refers to the broiler after it has gone through initial processing to remove trimmings[85] from the bird, leaving the bones and meat that are transported to retail and purchased by consumers. Exhibit 18-20 shows the results for each component and the total GHG emission factors for source reduction of poultry.

Exhibit 18-20: Raw Material Acquisition and Manufacturing Emission Factor for Production of Poultry ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Poultry	1.34	0.27	0.87	2.47

EPA developed the energy and emission factors suitable for inclusion in WARM using the LCI data available from Pelletier (2008, 2010). First, energy and non-energy input assumptions, material processing assumptions, and LCI data were extracted for each source of energy use and GHG emissions. These sources were then assessed to identify gaps within Pelletier (2008, 2010) that were either outside of the scope of the studies but within the scope of WARM, or where assumptions and results were not

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[84] Alternative functional units considered by EPA included one short ton of live weight broiler poultry (before processing) and one short ton of boneless broiler poultry meat. The functional unit of one short ton of processed boiler poultry was used because it is consistent with other food factors in WARM and most closely represents the waste generated from end-use of poultry products.

[85] Trimmings consist of poultry processing wastes, such as offal, blood, and feathers. When these waste products are separated from the broiler, they are processed into poultry fat and poultry by-product meal (BPM) that is used for animal feed, as described in Pelletier (2008, 2010).

provided in enough detail to be sufficiently modeled in WARM without supplementary data. EPA separated the raw data from broiler poultry production into three stages: production of poultry feed, poultry production on a broiler farm, and poultry processing. Inputs at each stage were separated into categories for energy-related inputs (i.e., fuel and electricity) and non-energy related inputs (e.g., materials). Process conversion assumptions—such as the share of each type of feed going into an average metric ton of poultry feed, or the conversion rate to turn poultry feed into live weight broiler poultry—were extracted from the scientific literature and used to develop unit process descriptions at each stage (Pelletier 2008, 2010).

Where data were not available in Pelletier (2008, 2010) to ensure consistency with WARM's life-cycle boundaries, EPA supplemented the LCI data from Pelletier (2008, 2010) with the following data sources:

- Corn production energy use and emissions from existing corn energy and emission factors in WARM, developed from data available in the U.S. Department of Agriculture (USDA) LCA Digital Commons database.[86]
- Fertilizer production energy use and emissions for corn, soy, and synthetic fertilizer offset by poultry litter (Ecoinvent Centre 2007).
- Transportation modes and distances of material inputs for soy production (Ecoinvent Centre 2007).
- Lime and salt production energy use, GHG emissions, and the transportation modes and distances of inputs raw material inputs (Ecoinvent Centre 2007).
- Transportation modes and distances to processing and retail from the Bureau of Transportation Statistics (BTS) Commodity Flow Survey (BTS 2013).
- The share of live-weight broiler poultry that is diverted to waste products (Ockerman 2000).
- Fuel carbon coefficients from the U.S. Greenhouse Gas Inventory (EPA 2014).

EPA used the LCI data obtained from the LCA Digital Commons database, the Swiss Ecoinvent version 2 database, and the BTS Commodity Flow Survey to estimate energy demand and GHG emissions associated with poultry production.

In order to convert embedded emissions from poultry feed into live weight broiler poultry, EPA used a conversion factor of 1.9 kilogram of poultry feed per kilogram of live weight broiler produced (Pelletier 2008). Exhibit 18-21 shows the mix of poultry feed inputs as modeled in WARM based on assumptions in Pelletier (2008, 2010).

Exhibit 18-21: Mix of Poultry Feed Inputs Assumed for Source Reduction Factor (%)

Corn	Soy	Fishmeal	Chicken Fat	Chicken By-Product Meal	Salt and Limestone
70%	20%	2.5%	2.5%	2.5%	2.5%

Corn was assumed to make up 70 percent of poultry feed. Since corn production is already included in WARM as part of the source reduction factor for grains, EPA used process energy emissions

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[86] Where possible, EPA has also been consistent with other food factors in WARM. For instance, corn is assumed to make up a 70 percent of poultry feed. Since EPA had already estimated upstream production emissions for corn during the development of the grain source reduction factor in WARM, the corn LCI data used in the grains factor was incorporated into the poultry factor.

assumptions from on-farm corn production for consistency. See Section 18.4.1.3 for a detailed description on development of emissions estimates for corn production. Soy production was assumed to make up 20 percent of poultry feed. EPA calculated process energy emissions from soy production based on the fuel input mix provided in Pelletier (2010), including petrol, diesel, liquid petroleum gas (LPG), and grid electricity. To estimate the energy emissions associated with producing fertilizers used to produce soy, EPA calculated the cumulative energy demand required to produce the mix of fertilizers needed to grow one kilogram of soybeans based on data available in the Ecoinvent database (Ecoinvent Centre 2007). EPA then determined the share that each fuel type contributed to total energy demand. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM to determine the total process energy emissions associated with the production of fertilizers used in soy production.

Poultry feed was assumed to consist of 2.5 percent fishmeal and 2.5 percent salt and limestone (Pelletier 2010). Total energy use and greenhouse gas emissions per kilogram of fishmeal were obtained from Pelletier (2010). To estimate a fuel breakdown for energy use, EPA assumed that the mix of fuel inputs into fishmeal was the same as for the other broiler poultry feed inputs due to the similar feed ingredients used in producing both fishmeal and poultry—including poultry waste by-product feed, fishmeal, corn, and soy (Pelletier 2010). For salt and limestone, energy use and GHG emissions are based on data sets from the Ecoinvent version 2 database (Ecoinvent Centre 2007). Although the datasets are representative of European production, EPA used data sets that had been converted using U.S. electricity grid mix assumptions that provide a more representative accounting of energy use and GHG emissions in the United States.

Poultry feed was assumed to consist of 2.5 percent poultry fat and 2.5 percent poultry by-product meal (BPM) (Pelletier 2010). EPA chose not to allocate energy use or GHG emissions to the poultry fat or BPM removed at the processing stage. In doing so, EPA's approach allocates all energy use and emissions from producing live weight broiler poultry to poultry meat and bone products. EPA chose this approach because it reflects the type of poultry products likely to enter the municipal solid waste stream[87], the remaining trimmings are a waste product that would not have been produced otherwise, and because poultry fat and BPM is recirculated back into poultry feed as a closed loop. Waste products account for 28 percent of live-weight broiler poultry, while the remaining share is poultry meat and bone (Ockerman 2000). Since EPA's approach did not allocate any emissions to poultry fat or BPM, emissions from the production of these inputs were already included in the source reduction factor and only the additional energy from processing poultry fat and BPM into poultry feed was added to the source reduction factor.

Some energy and GHG emissions are avoided when poultry litter is applied as a fertilizer, offsetting the use of synthetic fertilizers. Pelletier (2008, 2010) provided estimates of the amount of synthetic fertilizers that are avoided through application of poultry litter.[88] Using a similar approach as used for fertilizers for soy production, EPA determined the cumulative energy demand and mix of fuels for the production of synthetic fertilizers avoided by application of poultry litter using data available in the Ecoinvent database (Ecoinvent Centre 2007). Avoided emissions were calculated as described for soy

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[87] Compared to other meat products, poultry bones are more likely to be included in products available to consumers and therefore enter the municipal solid waste stream. Therefore, poultry bones are included in the functional unit used in WARM.

[88] Avoided synthetic fertilizers are provided in kilograms of active ingredients nitrogen (30 kg), phosphorous (30 kg), and potassium (20 kg) avoided per metric ton of poultry litter.

fertilizers by applying fuel-specific carbon coefficients. The total process energy used to produce poultry and the resulting emissions are shown in Exhibit 18-22.

Exhibit 18-22: Process Energy GHG Emissions Calculations for Production of Poultry

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Poultry	22.80	1.34

Process non-energy emissions were estimated by EPA for production and application of fertilizers used in poultry feed production, emissions from poultry litter application as a fertilizer, and emissions avoided by replacing synthetic fertilizers with poultry litter. Non-energy emissions from poultry production are generated from fertilizer production—which includes a variety of chemical processes that release non-fossil fuel carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere—and N_2O emissions from the application of synthetic fertilizer and poultry litter to soils. To capture these emissions, EPA isolated the portion of energy-related GHG emissions and subtracted this from total GHG emissions from fertilizer production, leaving only process non-energy emissions.

To estimate emissions from the application of fertilizer, to agricultural soils, EPA followed IPCC (2006b) guidelines using the active ingredients given from Pelletier (2008). EPA used process non-energy emissions assumptions from on-farm corn production for consistency; see Section 18.4.1.3 for a detailed description on development of emissions estimates for corn production. To estimate process non-energy emissions from soy production, EPA calculated the emissions from the application of the nitrogen-based fertilizer to agricultural soils using IPCC 2006 guidelines (IPCC 2006b). To estimate process non-energy emissions from the application of poultry litter and the avoided non-energy emissions from the resulting displaced fertilizer, EPA's methodology followed IPCC (2006b) guidelines, and applied assumptions on the nitrogen content and the percent of nitrogen emitted from fertilizer application obtained from Pelletier (2008).

Exhibit 18-23: Process Non-Energy Emissions Calculations for Production of Poultry

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Poultry	0.05	<0.01	–	–	<0.01	0.86

– = Zero emissions.

Retail Transport. For this analysis, distribution of poultry products to their final point of sale was assumed to have two components: the energy and GHG emissions associated with diesel consumed during vehicle operation and the GHG impact of fugitive refrigerants emitted from refrigerated vehicles. Fugitive emissions of refrigerants consisted of a mix of 1,1,1,2-Tetrafluoroethane (R-134a), Chlorodifluoromethane (HCFC-22), Monochloropentafluoroethane (R-155), and 1,1-Difluoroethane (HFC-152a). Due to lack of data for poultry-specific transportation, the fugitive emissions associated with refrigerated vehicle transport were assumed to be the same as for refrigerated dairy delivery via a medium-sized truck (Thoma et al. 2010). In the Thoma et al. 2010 study, estimates of fugitive emissions of refrigerants during the transport phase were estimated via a sales-based approach, which equated purchases of refrigerants for the truck fleet to fugitive refrigerants released via leakage.

EPA estimated the retail transport ton-miles per shipment of poultry based on the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). The process energy and non-energy emissions for the transportation of poultry to retail are shown in Exhibit 18-24 and Exhibit 18-25, respectively.

Exhibit 18-24: Process Energy GHG Emissions Calculations for Transportation of Poultry

Material/Product	Transportation Energy per Short Ton (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Poultry	3.68	0.26

Exhibit 18-25: Non-Energy Emissions Calculations for Transportation of Poultry

Material/Product	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Poultry	0.01	–	–	–	0.00	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

18.4.1.3 Developing the Emission Factor for Source Reduction of Grains and Bread

To produce both grains and bread, energy is used during the RMAM phase of the products' life cycles. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, producing grains results in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. The production of winter wheat, corn and rice all require different material and energy inputs, and a weighted average of the three grain types was used to create a single emission factor for grains. The upstream energy and emissions for wheat flour were combined with the energy used to prepare bread to develop a second emission factor for bread. Exhibit 18-26 shows the results for each component and the total GHG emission factors for source reduction of both grains and wheat-based bread.

Exhibit 18-26: Raw Material Acquisition and Manufacturing Emission Factor for Production of Grains and Bread ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Grains	0.31	0.02	0.28	0.62
Bread	0.35	0.01	0.30	0.67

To calculate the production emissions, EPA obtained life-cycle inventory (LCI) data for the three grain products—wheat, corn, and rice—available in the USDA National Agricultural Library's LCA Digital Commons database. The Digital Commons database is intended to provide LCI data for use in life-cycle assessment (LCA) of food, biofuels, and a variety of other biological products. Primary unit process input and output data have been developed by researchers at the University of Washington Design for Environment Laboratory under the direction of Dr. Joyce Cooper using USDA National Agricultural Statistics Service and ERS datasets. Data on bread production was derived from Espinoza-Orias et al. 2011, which contained data characterizing the energy use associated with producing both white bread and wholemeal bread.

The LCI data from the Digital Commons datasets only provide material inputs, outputs and, processes in units of magnitude per unit of agricultural product produced without any estimates of the energy or GHG impacts associated with production. For example, the LCI data include estimates of the amount of fertilizers needed for grain production but do not include data on the energy needed for fertilizer production or the direct GHG emissions from fertilizer application. In order to translate these values into the actual energy demand and emissions associated with agricultural production, EPA identified matching unit processes and corresponding LCI data for those materials and processes within the life-cycle software, SimaPro. The unit processes within the database are taken from the Swiss Ecoinvent version 2 database and the U.S. LCI Database.

Grains. Several steps were needed to develop energy and emission factors suitable for inclusion in WARM using the LCI data available from the Digital Commons and other secondary sources. Translating the upstream LCI data provided by Digital Commons into the SimaPro format required linking materials and processes in the LCI dataset to existing Ecoinvent or U.S. LCI Database upstream processes within the software, albeit at the risk of increasing uncertainty. In the process of matching material and process flows from the Digital Commons LCI files to unit processes in SimaPro, the magnitude of each process or material contribution (e.g., the amount of combine harvesting needed to produce 1 short ton of wheat) from the LCI dataset was preserved. At the end of this stage, each year of grain data included a unit process output (1 short ton of grains) and a series of linked material inputs and processes, each with their respective GHG emissions and energy demands contributing to the total impact of producing that unit of grain.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of each grain. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for each dataset within SimaPro through an energy demand impact assessment method in the software. This method calculated the total life-cycle energy in million Btu required to produce one unit of grain and then separated the total into several categories, including: petroleum, nuclear power, biomass, natural gas, coal, and renewables. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM for all materials to determine the total energy-derived emissions associated with the production of one unit of grain. For wheat, additional energy demand from milling was included due to the fact that over 90 percent of wheat grain used for food is converted to flour prior to use (USDA 2012a). The estimate for milling energy expenditure was taken from Espinoza-Orias 2011 and was assumed to be taken from the national average electricity grid. The process energy used to produce the each individual grain product, the weighted average of grains and the resulting emissions are shown in Exhibit 18-27.

Exhibit 18-27: Process Energy GHG Emissions Calculations for Production of Grains

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Wheat Flour	4.02	0.23
Corn	6.98	0.41
Rice	9.66	0.58
Grains	5.35	0.31

The non-energy emissions came from two components of the grains' life cycle: fertilizer production and fertilizer application. Fertilizer production includes a variety of chemical processes that release non-fossil fuel CO_2, CH_4, and N_2O into the atmosphere. To capture these emissions, EPA ran an impact assessment method within SimaPro on the grains' upstream processes that only considered non-fossil emissions of these gases to isolate the process emissions from fertilizer production.

To estimate the GHG emissions associated with fertilizer application, EPA assessed the total amount of nitrogen fertilizer applied to each grain, and then used stoichiometry to identify the share of nitrogen applied in each dataset. From there, EPA utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching (IPCC 2006b). The IPCC Tier 1 approach was chosen to maintain consistency with other agricultural LCAs and the International EPD System's Product Category Rules (PCR) for arable crops (International EPD System 2013). Exhibit 18-28 shows the components for estimating process non-energy GHG emissions for each type of grain and the weighted average.

Exhibit 18-28: Process Non-Energy Emissions Calculations for Production of Grains

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Wheat Flour	0.04	<0.01	–	–	<0.01	0.30
Corn	0.03	<0.01	–	–	<0.01	0.18
Rice	0.04	<0.01	–	–	<0.01	0.31
Grains	0.04	<0.01	–	–	<0.01	0.28

– = Zero emissions.

The Digital Commons LCI data assumes that the production of each of the three grains included in WARM leads to the production of one or more co-products. These co-products include corn silage, corn stover, wheat straw, and rice straw. In keeping with ISO 14044 standards, EPA allocated impacts to co-products in proportion to the economic value of the products. Using data from the USDA ERS Commodity Costs and Returns database, EPA determined the economic value per acre of production for corn, corn silage, rice, wheat, and wheat straw for each of the LCI data years (USDA 2013). This provided enough data to determine economic allocation percentages for wheat and wheat straw. Supplementary data from a 2009 study by van der Voet et al. provided prices for corn stover, allowing EPA to estimate the allocation percentages for corn, corn silage, and corn stover. However, EPA was unable to find a reliable source for the economic value of rice straw. An anecdotal article cited rice straw's value at approximately $10 to $20 per acre, which would translate to allocation of 1 to 3 percent of rice production energy and emissions to rice straw (Smith 2004).

Bread. Bread production was estimated by taking an estimate of bread production energy intensity from Espinoza-Orias et al. 2011, which contained LCI data characterizing the energy use associated with producing bread. For the purposes of this analysis, white bread was chosen as it is more common than wheat bread. The study found that wheat milling and baking, respectively, had energy demands of 0.059 kWh and 0.600 kWh per loaf of bread, which was assumed to be 0.8 kg. This equated to 2.55 million Btu of cumulative energy demand to prepare one ton of bread, of which the entirety was assumed to be taken from the national average electricity grid. To estimate the total farm-to-retail energy associated with bread, EPA summed the bread production energy emissions with those for wheat flour, but did not include corn or rice. Corn and rice were excluded from this process because the energy use data for milling and baking were based on wheat bread production and because wheat-based bread is the predominant bread category in the United States (USDA 2012a). The process energy used to produce bread and the resulting emissions are shown in Exhibit 18-29.

Exhibit 18-29: Process Energy GHG Emissions Calculations for Production of Bread

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Wheat Flour	4.02	0.23
Bread Baking	2.32	0.12
Bread	6.34	0.35

Retail Transport: Retail transport energy and emissions for both bread and grains were estimated with the Bureau of Transportation Statistics 2012 Commodity Flow Survey, consistent with other materials in WARM, and are equal across the three types of grains. The average miles traveled to retail per shipment are derived from the study and converted into transportation energy, which then is used to estimate GHG emissions from retail transport. The calculations for estimating the transportation energy emission factor for grains and bread are shown in Exhibit 18-30.

Exhibit 18-30: Transportation Energy Emissions Calculations for Production of Bread and Grains

Material/Product	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emission Factors ($MTCO_2e$ per Short Ton of Product)
Grains	265	0.26	0.02
Bread	169	0.17	0.01

Source: BTS 2013.

18.4.1.4 Developing the Emission Factor for Source Reduction of Fruits and Vegetables

To produce fruit and vegetable products, energy is used both in the acquisition of raw materials and in the food production process itself. In general, the majority of energy used for these activities is derived from fossil fuels. Combustion of fossil fuels results in emissions of CO_2. In addition, producing and transporting fruits and vegetables also results in process non-energy emissions of CH_4, N_2O, and refrigerants, as described in detail below. Hence, the RMAM component of the fruits and vegetables source reduction emission factor consists of process energy, non-process energy emissions in the acquisition of raw materials, non-process energy emissions in the transport of fruits and vegetables to retail, and non-energy emissions during transport.

Exhibit 18-31 shows the results for each component and the total GHG emission factors for source reduction of fruits and vegetables. The process energy used to produce the each individual fruit and vegetable, the weighted average for the fruits and vegetables category, and the resulting emissions are shown in Exhibit 18-32. Finally, Exhibit 18-33 shows the components for estimating process non-energy GHG emissions for each type of grain and the weighted average. The methodology used to calculated these emissions estimates is described below.

Exhibit 18-31: Raw Material Acquisition and Manufacturing Emission Factor for Production of Fruits and Vegetables ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Fruits and Vegetables	0.20	0.17	0.07	0.44

Exhibit 18-32: Process Energy GHG Emissions Calculations for Production of Fruits and Vegetables

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Potatoes	1.73	0.10
Tomatoes	3.77	0.25
Citrus	4.60	0.31
Melons	1.80	0.12
Apples	4.58	0.30
Bananas	2.45	0.14
Fruits and Vegetables (weighted average)	*3.17*	*0.20*

Exhibit 18-33: Process Non-Energy Emissions Calculations for Production of Fruits and Vegetables

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Potatoes	0.01	–	–	–	<0.00	0.05
Tomatoes	<0.00	<0.00	–	–	<0.00	0.07
Citrus	0.01	<0.00	–	–	<0.00	0.05
Melons	<0.00	<0.00	–	–	<0.00	0.04
Apples	–	<0.00	–	–	<0.00	0.01
Bananas	0.03	<0.00	–	–	<0.00	0.10
Fruits and Vegetables (weighted average)	*0.01*	*<0.00*	–	–	*<0.00*	*0.06*

– = Zero emissions.

Data used to develop the source reduction emission factor for fresh fruits and vegetables in WARM came primarily from three sources. Data for the production of apples, melons, tomatoes, and oranges came from the University of California Cooperative Extension's (UCCE) sample cost production studies (Fake et al. 2009, O'Connell et al 2009, Stoddard et al. 2007, Wunderlich et al. 2007). These studies are intended as hypothetical guides for farmers to produce crops, and include yield projections and sample requirements for fuel, fertilizers, irrigation, and plant protection products.[89] Data for the production of bananas was acquired from a 2010 life-cycle assessment (LCA) conducted by Soil and More International, on request of the Dole Food Company (Luske 2010). The banana LCA study characterizes the cradle-to-retail GHG emissions associated with banana production in Costa Rica and retail in Western Europe. In developing the source reduction emission factor, EPA used supplementary data to model international shipping and retail transport to the United States. Lastly, the data for potato production was acquired from the Ecoinvent 2.0 database, available within the SimaPro LCA Software.

The primary fruit and vegetable production datasets were supplemented with data from a variety of sources. Retail transport for domestically-produced fruits and vegetables was informed by the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). Loss rates for the transport of fresh fruits and vegetables from production to retail were derived from USDA Economic Research Service (ERS) loss-adjusted food availability data (USDA 2012b). In order to evaluate the impacts from retail transport of bananas produced in Central America to the United States, Luske 2010 was supplemented by disaggregated data for the ocean transport of bananas to various ports in the United States (Bernatz 2009). The cumulative energy demand and non-energy GHG emissions from upstream materials and processes, such as harvesting and fertilizer production, were informed by unit processes from the Ecoinvent 2.0 database, available within SimaPro.

Apples, Oranges, Melons, and Tomatoes. Production of apples, oranges, melons, and tomatoes were all characterized in the UCCE's Cost and Return datasets in terms of expected yields and recommended inputs. In order to translate the material and process inputs estimated by the UCCE, EPA extracted the expected yields and material and process inputs from each study and normalized them by the expected yield of the plot of land to provide inputs in a functional unit per unit of fruits and vegetables (e.g., short tons of urea fertilizer per short ton of apples produced). Next, EPA linked each input to a unit process from either the Ecoinvent 2.0 or the U.S. LCI database within SimaPro. For example, each liter of diesel or short ton of fertilizer required per acre of apple cultivation was

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[89] Practices described in the production studies are based on real-world production practices considered typical for the crop and area, but may not apply to every situation. The sample cost of production studies for a variety of commodities are available from the University of California-Davis, at: http://coststudies.ucdavis.edu/.

translated into liters of diesel or short tons of fertilizer per short ton of fruits and vegetables in the U.S. LCI database. At the end of this stage, each fruit or vegetable dataset within SimaPro included a unit process output (1 short ton of a given fruit or vegetable) and a series of material inputs and processes, each linked to its GHG emissions and energy demands, which collectively contribute to the total impact of producing that unit of fruit or vegetable.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of each type of fruit or vegetable. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for each of the assembled datasets within SimaPro through an energy demand impact assessment method in the software. This method calculated the total life-cycle energy in mega joules (MJ) required to produce one unit of fruit or vegetable and then determined the share of each fuel type contributed to total energy demand, including: petroleum, nuclear power, biomass, natural gas, coal, and renewables. Each energy source's contribution to the total energy demand was then multiplied by the fuel-specific carbon coefficients used in WARM for all materials to determine the total energy-derived emissions associated with the production of one unit of fruit or vegetable.

The non-energy emissions came from two components of the fruit and vegetable life cycle: fertilizer production and fertilizer application. Fertilizer production includes a variety of chemical processes that release non-fossil fuel carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) into the atmosphere. To capture these emissions, EPA ran an impact assessment method within SimaPro on the fruits and vegetables' upstream processes that only considered non-fossil emissions of these gases to isolate the process emissions from fertilizer production.

To estimate the GHG emissions associated with fertilizer application, EPA assessed the total amount of nitrogen fertilizer applied to each crop, and then used stoichiometry to identify the share of nitrogen applied in each dataset. From there, EPA utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching (IPCC 2006b). The IPCC Tier 1 approach was chosen to maintain consistency with other agricultural LCAs and the International EPD System's Product Category Rules (PCR) for arable crops (International EPD System 2012).

Refrigerated road transport is also assumed for apples, oranges, melons, and tomatoes transported to retail in the United States (see "Retail Transport" sub-section below).

Bananas. The source reduction emission factor for bananas was developed using a similar process to the emission factors developed from the UCCE's datasets, utilizing a 2010 LCA of banana production in Costa Rica (Luske 2010). EPA compiled the material and process inputs for banana production and normalized them by the expected yield of bananas to provide inputs in a functional unit per unit of fruit (e.g., short tons of urea fertilizer per short ton of bananas). The normalized inputs were then translated into unit processes within SimaPro for cumulative energy demand and non-energy emissions analysis. Fertilizer emissions were estimated using the IPCC Tier 1 approach using the fertilizer inputs provided by Luske 2010. See the above sub-section (Apples, Oranges, Melons, and Tomatoes) for more information on this process.

Unlike the other components of the fruit and vegetable energy and emission factors, bananas are shipped internationally in specially-made, refrigerated cargo containers to prevent over-ripening prior to sale. The average transportation distance to the United States was multiplied by a separate factor for emissions per ton-kilometer of refrigerated ocean cargo transport (BSR 2012). Additionally, due to the role of refrigeration in the ocean transport of bananas, EPA incorporated the estimate of fugitive refrigerant emissions during processing and transport in Luske 2010, summarized in Exhibit 18-34. In addition to refrigerated ocean transport, refrigerated road transport is also assumed for bananas transported domestically after they are imported into the United States (see “Retail Transport” sub-section below).

Exhibit 18-34: Fugitive Refrigerant Emissions for International Transport of Bananas

Refrigerant	Percent of Total	Global Warming Potential (GWP)[a]	Emissions ($MTCO_2e$/Short Ton of Bananas)
Pentafluoroethane (HFC-125a)	44%	2,800	7.81E-03
1,1,1-Trifluoroethane (HFC-143a)	52%	3,800	9.23E-03
1,1,1,2-Tetrafluoroethane (HFC-134a)	4%	1,300	7.10E-04
Total	100%	3,260	1.77E-02

Source: Luske 2010.

[a] GWP values are based on the IPCC Second Assessment Report (IPCC SAR).

Potatoes. Unlike the emission factors for bananas and the fruits and vegetables characterized by the UCCE, a unit process for potatoes was already available within the SimaPro life-cycle software as part of the Ecoinvent 2.0 database. The unit process included a co-product of potato leaves; however, in the dataset, it was allocated at 0.0 percent due to its low economic value. Consequently, it was not included in this analysis.

As described in the “Apples, Oranges, Melons and Tomatoes” sub-section above, EPA conducted a cumulative energy demand and non-energy emissions assessment in order to export the data in a format suitable for import into WARM.

As with the other components of the fruits and vegetables source reduction emission factors, EPA estimated the GHG emissions associated with fertilizer application. EPA extracted the amounts of nitrogen fertilizer and liming materials applied to the potato crops from the Ecoinvent unit process data and utilized the IPCC Tier 1 method for managed soils to calculate the total amount of N_2O and CO_2 released from fertilizer application, run-off, volatilization, and leaching.

Retail Transport. For this analysis, distribution of fruits and vegetables to their final point of sale was assumed to have two components: the energy and GHG emissions associated with fossil fuel combustion from vehicle operation and the GHG impact of fugitive refrigerants emitted from refrigerated vehicles. The GHG emissions from vehicle operation were a product of diesel fuel combustion. Fugitive emissions of refrigerants consisted of a mix of 1,1,1,2-Tetrafluoroethane (R-134a), Chlorodifluoromethane (HCFC-22), Monochloropentafluoroethane (R-155), and 1,1-Difluoroethane (HFC-152a). Due to lack of data for fruit and vegetable-specific transportation, the fugitive emissions associated with refrigerated vehicle transport were assumed to be the same as for refrigerated dairy delivery via a medium-sized truck (Thoma et al. 2010). In the Thoma et al. 2010 study, estimates of fugitive emissions of refrigerants during the transport phase were estimated via a sales-based approach, which equated purchases of refrigerants for the truck fleet to fugitive refrigerants released via leakage.

Retail transport ton-miles per shipment for all fruits and vegetables were informed by the Bureau of Transportation Statistics (BTS) 2012 Commodity Flow Survey (BTS 2013). Bananas were assumed to have land-based domestic transport in addition to refrigerated ocean transport, as described in the “Bananas” sub-section above. The process energy and non-energy emissions for the transportation of fruits and vegetables to retail are shown in Exhibit 18-35 and Exhibit 18-36, respectively.

Exhibit 18-35: Process Energy GHG Emissions Calculations for Transportation of Fruits and Vegetables

Material/Product	Transportation Energy per Short Ton (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Fruits and Vegetables	2.28	0.17

Exhibit 18-36: Non-Energy Emissions Calculations for Transportation of Fruits and Vegetables

Material/Product	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Fruits and Vegetables	0.01	–	–	–	–	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

Retail transport of perishables such as fruits and vegetables also results in losses due to spoilage and physical damage to the produce that would render it unfit for sale. Loss rates for the transport of fresh fruits and vegetables from production to retail were derived from USDA Economic Research Service (ERS) loss-adjusted food availability data (USDA 2012b). Loss rates for each fruit and vegetable in the analysis were compiled from USDA (2012b) and then re-weighted based on each product's share of the waste stream. An overview of the individual and weighted loss rates for fruit and vegetable transport to retail is presented in Exhibit 18-37. The loss rates were specific to losses incurred strictly during the transport of fresh fruits and vegetables instead of a weighted mix of fresh and processed fruits and vegetables in order to maintain consistency with the scope and methodology used to develop the food waste source reduction emission factors in WARM. The calculated weighted loss rate of 7.1 percent (shown in the final row in Exhibit 18-37) was applied to both production and transportation emissions of all fruits and vegetables modeled in WARM, indicating that for every 1,000 short tons of fruits and vegetables sold at retail, 1,076 short tons had left the production site (indicating a loss of 7.1 percent of the original amount). This factor increased GHG emissions from production and transport by approximately 7.6 percent.

Exhibit 18-37: Loss Rates for Transport of Fruits and Vegetables from Production to Retail

Fruit and Vegetable Category	Total Losses (Millions of Pounds)	Percent of Category	Individual Loss Rate	Weighted Loss Rate
Potatoes	18,650	27.5%	4.0%	1.1%
Tomatoes	18,294	27.0%	15.0%	4.1%
Citrus	14,200	21.0%	3.7%	0.8%
Melons	6,313	9.3%	9.2%	0.9%
Apples	5,575	8.2%	4.0%	0.3%
Bananas	4,705	6.9%	0.0%	0.0%
Fruits and Vegetables (weighted average)	67,737	100%	NA	7.1%

Source: USDA 2012b.

18.4.1.5 Developing the Emission Factor for Source Reduction of Dairy Products

To produce dairy products, energy is used during the acquisition of raw materials and manufacturing (RMAM) phase of the products' life cycle. In general, the majority of the energy for the production of these materials is derived from fossil fuels, either through the electricity grid or during on-site combustion of fuel during the farming process. Combustion of fossil fuels results primarily in emissions of CO_2, as well as small amounts of N_2O. Additionally, dairy production results in in process non-energy emissions of CO_2, CH_4 and N_2O, as described below. Dairy products have a high share of non-energy process emissions of CH_4 from enteric fermentation by dairy cattle. Refrigerated transport of dairy products to retail also results in small amounts of high-global warming potential (GWP) refrigerant emissions. The broad category of dairy foods includes a wide variety of products with differing inputs and processing stages. While dairy products can have differing upstream energy and emissions impacts, the emission factor described in this section considers a weighted average of dairy products commonly found in U.S. municipal waste. Exhibit 18-38 shows the results for each component and the total GHG emission factors for source reduction of dairy products.

Exhibit 18-38: Raw Material Acquisition and Manufacturing Emission Factor for Production of Dairy Products ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e = b + c + d) Net Emissions
Dairy Products	0.80	0.05	0.89	1.74

The LCI data for dairy production used for developing the dairy products emission factor was provided by the Innovation Center for U.S. Dairy, an industry group. The Innovation Center conducted its own LCA for dairy production (Thoma et al. 2010). The Innovation Center's LCA's scope is larger than the scope used to develop the WARM energy and emission factors, covering the cradle-to-grave life-cycle of dairy products including retail storage, consumer use, and disposal. Dairy production is linked to several other systems that produce products outside the scope of this specific LCA, including feed co-products (e.g., dried distillers' grains) and beef. In the data set from the Innovation Center, impacts for most co-products are allocated economically. However, causal allocation is used for both beef based on feed nutrient content and for corn silage based on crop nitrogen requirements determined from reported yield.[90] Causal mass balance is used for different fat-content milks during production (Thoma et al. 2010). Because the Innovation Center's data set already allocated impacts to co-products, EPA did not further modify the data to account for impacts from products outside the scope used in WARM.

Dairy Products. To align the dairy production LCI data with WARM, the LCI data had to be made consistent with the scope of the food waste factors in WARM. This involved removing portions of the unit processes in SimaPro that were outside the scope of the analysis, such as retail storage, consumer transport, packaging, and consumer use (e.g., cooking and consumer food loss). Through this process, EPA created a series of unit processes for specific dairy products (e.g., skim milk, ice cream) that only included the material inputs and process flows prior to retail stocking and sales. For consistency with other energy and emission factors in WARM, EPA also used LCI data for product transportation from production to retail, as described below.

The emissions were calculated in two separate stages: first, energy-derived emissions were calculated by determining the cumulative energy demand for producing one short ton of the weighted average dairy total. Secondly, non-energy emissions were estimated and added to the fossil fuel-derived emissions.

To estimate the energy-derived emissions, EPA calculated the cumulative energy demand for the weighted dairy average using the cumulative energy demand impact assessment method in SimaPro. This method resulted in an estimate of the total life-cycle energy in million Btu required to produce one short ton of weighted average dairy products. EPA then separated the total energy consumption into the fuel categories used for generating the energy, including petroleum, nuclear power, biomass, natural gas, coal, and renewables. EPA then multiplied each energy source's

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[90] Within the framework of the ISO 14040 standard for life-cycle assessment, causal allocation refers to the allocation of environmental impacts based on the physical relationships between materials and their environmental burdens. In this instance, it refers to isolating the energy flows to the cattle system that go towards milk production from those directed towards meat production.

contribution to the total energy demand by the fuel-specific carbon coefficients used in WARM for all materials to determine the total energy-derived emissions associated with the production of one short ton of dairy product. The process energy used to produce dairy products and the resulting emissions are shown in Exhibit 18-39.

Exhibit 18-39: Process Energy GHG Emissions Calculations for Production of Dairy Products

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Dairy Products	13.61	0.80

The bulk of the non-energy production emissions came from three components of the dairy life cycle: enteric fermentation, fertilizer production, and fertilizer application. To capture these emissions, EPA ran an impact assessment method within SimaPro on the upstream dairy production processes that only considered non-fossil emissions of these gases in order to avoid double-counting process emissions from the energy-derived emissions, which are separately calculated within WARM. Exhibit 18-40 shows the components for estimating process non-energy GHG emissions for dairy products.

Exhibit 18-40: Process Non-Energy Emissions Calculations for Production of Dairy Products

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Dairy Products	0.04	0.03	–	–	<0.01	0.88

Retail Transport: The Innovation Center dataset includes complete LCI data on the retail transportation process for dairy products including energy and emissions from onboard refrigeration equipment to prevent spoilage. Because these data were available in the Innovation Center dataset and because refrigeration is an essential part of the transport of these milk-based products, EPA used these data to develop the retail transport energy and emissions estimates for WARM. This approach differs from the methodology used for estimating retail transport for other materials currently in WARM, which rely on average commodity retail transportation distances provided by the U.S. Census Bureau data and, for materials other than fruits and vegetables, do not involve refrigerated transport. EPA estimated the energy-derived emissions from transport by calculating the cumulative energy demand within the software. Non-energy emissions, which were in the form of fugitive refrigerants, were evaluated with the non-fossil-derived GHG emissions impact assessment method within the software. The process energy and non-energy emissions for the transportation of dairy products to retail are shown in Exhibit 18-39 and Exhibit 18-42, respectively.

Exhibit 18-41: Process Energy GHG Emissions Calculations for Transportation of Dairy Products

Material/Product	Process Energy per Short Ton (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Dairy Products	0.65	0.05

Exhibit 18-42: Non-Energy Emissions Calculations for Transportation of Dairy Products

Material/Product	CO_2 Emissions (MT/Short Ton)[a]	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Dairy Products	0.01	–	–	–	–	0.01

– = Zero emissions.

[a] The estimate of non-energy CO_2 emissions includes a mixture of various refrigerants, predominantly HFC 143a, HFC 134a, HFC-125, and HCFC-22, released during refrigerated transport.

18.4.2 Recycling

Recycling, as modeled in WARM (i.e., producing new products using end-of-life materials), does not commonly occur with the food waste types modeled in WARM. Therefore, WARM does not consider GHG emissions or storage associated with the traditional recycling pathway for food waste. However, food waste can be converted to compost, a useful soil amendment, as described in section 18.4.3.

18.4.3 Composting

18.4.3.1 Developing the Emissions Factor for the Composting of Food Waste

Composting food waste results in increased carbon storage when compost is applied to soils. The net composting emission factor is calculated as the sum of emissions from transportation, processing of compost, the carbon storage resulting from compost application, and the fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[91] WARM currently assumes that carbon dioxide (CO_2) emissions that occur as a result of the composting process are biogenic and are not counted (for further explanation, see the text box on biogenic carbon in the Introduction and Background chapter). Exhibit 18-43 details these components for food waste and mixed organics. For additional information on composting in WARM, see the Composting chapter. The three emission sources and one emission sink resulting from the composting of organics are:

- *Nonbiogenic CO_2 emissions from collection and transportation*: Transportation of yard trimmings and food scraps to the central composting site results in nonbiogenic CO_2 emissions.[92] In addition, during the composting process the compost is mechanically turned, and the operation of this equipment also results in nonbiogenic CO_2 emissions.
- *Carbon Storage*: When compost is applied to the soil, some of the carbon contained in the compost does not decompose for many years and therefore acts as a carbon sink.
- *Fugitive CH_4 and N_2O emissions*: microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH_4 and N_2O gas, a net contributor to the GHG emissions associated with the composting pathway.

Exhibit 18-43: Components of the Composting Net Emission Factor for Food Waste and Mixed Organics

Composting of Post-Consumer Material (GHG Emissions in $MTCO_2e$/Short Ton)						
Material Type	**Raw Material Acquisition and Manufacturing (Current Mix of Inputs)**	**Transportation to Composting**	**Compost CO_2**	**Compost CH_4 and N_2O**	**Soil Carbon Storage**	**Net Emissions (Post-Consumer)**
Food Waste	NA	0.04	–	0.05	-0.24	-0.15
Mixed Organics	NA	0.04	–	0.07	-0.24	-0.14

NA = Not applicable.
[a] Yard trimmings are a 50%, 25%, 25% weighted average of grass, leaves, and branches, based on U.S. generation data from EPA (2014b).

Transportation energy emissions occur when fossil fuels are used 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 these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 18-44.

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[91] These fugitive emission sources were added in June 2014 to WARM Version 13.

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

Exhibit 18-44: 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 ($MTCO_2e$)
All Material Types	0.36	0.22	0.58	0.04

[a] Based on estimates found on Table I-17 on page I-32 of FAL 1994.

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)[93] and carbon stored in non-reactive humus compounds (the "increased humus formation" effect)[94]. 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 18-45.

Exhibit 18-45: Soil Carbon Effects as Modeled in Century Scenarios ($MTCO_2e$/Short Ton of Organics)

	Soil Carbon Restoration				
Scenario	Unweighted	Proportion of C that is Not Passive	Weighted estimate	Increased Humus Formation	Net Carbon Flux[a]
Annual application of 32 tons of compost per acre	-0.04	48%	-0.07	-0.17	-0.20

[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 $MTCO_2e$.

The nonbiogenic CO_2 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. As Exhibit 18-43 illustrates, WARM estimates that the net composting GHG factor for all organics types is the same for all sources of compost.

18.4.4 Combustion

18.4.4.1 Developing the Emissions Factor for the Combustion of Food Waste

Combusting food waste results in a net emissions offset (negative emissions) due to the avoided utility emissions associated with energy recovery from waste combustion. The combustion net emission factor is calculated as the sum of emissions from transportation of waste to the combustion facility, nitrous oxide (N_2O) emissions from combustion, and the avoided CO_2 emissions from energy recovery in a waste-to-energy (WTE) plant. Although combustion also releases the carbon contained in food waste in the form of CO_2, these emissions are considered biogenic and are not included in the WARM net emission factor. Exhibit 18-46 presents these components of the net combustion emission factor for food waste and mixed organics. WARM assumes the same emission factors for all food waste types. For

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[93] 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.

[94] 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 CO_2. For more information, see the Composting chapter.

additional information on combustion in WARM, see the Combustion chapter. The two emissions sources and one emissions offset that result from the combusting of food waste are:

- *CO_2 emissions from transportation of waste.* Transporting waste to the combustion facility and transporting ash from the combustion facility to a landfill both result in transportation CO_2 emissions.
- *Nitrous oxide emissions from combustion.* Waste combustion results in measurable emissions of nitrous oxide (N_2O), a GHG with a high global warming potential (EPA, 2014a).
- *Avoided utility CO_2 emissions*. Combustion of MSW with energy recovery in a WTE plant also results in *avoided* CO_2 emissions at utilities.

Exhibit 18-46: Components of the Combustion Net Emission Factor for Food Waste and Mixed Organics ($MTCO_2e$/Short Ton)

	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)
Food Waste	NA	0.03	–	0.04	-0.18	–	-0.12
Mixed Organics	NA	0.03	–	0.04	-0.20	–	-0.14

NA = Not applicable

For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate of 60 lbs CO_2 per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2e$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW and the resulting ash. WARM assumes that transportation of food waste uses the same amount of energy as transportation of mixed MSW.

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (IPCC, 2006a). The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. WARM averages the midpoints of each range and converts the units to $MTCO_2e$ of N_2O per ton of MSW. Because the IPCC did not report N_2O values for combustion of individual components of MSW, WARM uses the same value for food waste and mixed organics.

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 MSW combustion would be in the form of electricity, as shown in Exhibit 18-47. 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 CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 18-47: Utility GHG Emissions Offset from Combustion of Food Waste

(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)
Food Waste	4.7	17.8%	0.22	0.18

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from combustion N_2O and transportation CO_2. These emissions were then added to the avoided utility emissions in order to calculate the net GHG emission factor, shown in Exhibit 18-46. WARM estimates that combustion of food wastes results in a net emission reduction.

18.4.5 Landfilling

18.4.5.1 Developing the Emissions Factor for the Landfilling of Food Waste

Landfilling food waste can result in either net carbon storage or net carbon emissions, depending on the specific properties of the waste material. 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 landfilling, and the carbon storage resulting from undecomposed carbon remaining in landfills. Exhibit 18-48 presents these components of the landfilling emission factor for food waste and mixed organics. WARM assumes the same emission factors for all food waste types. For additional information on landfilling in WARM, see the Landfilling chapter. The two emissions sources and one emissions sink that result from the landfilling of food waste are:

- *Transportation of food waste*. Transportation of food waste to landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- *Methane emissions from landfilling*. When food waste is landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2, collectively referred to as landfill gas (LFG). Only the CH_4 portion of LFG is counted in WARM, because the CO_2 portion is considered of biogenic origin and therefore is assumed to be offset by CO_2 captured by regrowth of the plant sources of the material.
- *Landfill carbon storage.* Because food waste is not completely decomposed by anaerobic bacteria, some of the carbon in these materials remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation.

Exhibit 18-48: Landfilling Emission Factors for Food Waste and Mixed Organics ($MTCO_2e$/Short Ton)

Material Type	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)
Food Waste	–	0.04	0.79	-0.04	-0.07	0.71
Mixed Organics	–	0.04	0.57	-0.03	-0.30	0.29

Note: The emission factors for landfill CH_4 presented in this table assume that the methane management practices and decay rates at the landfill are an average of national practices.

Negative values denote GHG emission reductions or carbon storage.

NA = Not applicable; upstream raw material acquisition and manufacturing GHG emissions are not included in landfilling since the life-cycle boundaries in WARM start at the point of waste generation and landfilling does not affect upstream GHG emissions.

Transportation energy emissions occur when fossil fuels are used to collect and transport food waste to a landfill, and then to operate the landfill equipment. To calculate these emissions, WARM relies on assumptions from FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2e$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW. WARM assumes that transportation of food waste uses the same amount of energy as transportation of mixed MSW.

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. There are three categories of landfills modeled in WARM: (1) landfills that do not recover LFG, (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. The Excel version of WARM allows users to select component-specific decay rates based on different assumed moisture contents of the landfill and landfill gas collection efficiencies for a series of landfill management scenarios. The tables in this section show values using the national average moisture conditions, based on the national average precipitation at landfills in the United States and for landfill gas collect efficiency from "typical" landfill operations in the United States. The decay rate and management scenario assumed influences the landfill gas collection efficiency. For further explanation, see the Landfilling chapter.

Exhibit 18-49 depicts the emission factors for each LFG collection type based on the national average landfill moisture scenario and "typical" landfill management operations. Overall, landfills that do not collect LFG produce the most CH_4 emissions. Food waste readily degrades in landfills, and consequently emits the most CH_4 of all organic materials in landfills. The emissions generated per short ton of material drop by over half for food waste if the landfill recovers and flares CH_4 emissions. These emissions are even lower in landfills where LFG is recovered for electricity generation because LFG recovery offsets emissions from avoided electricity generation.[95]

Exhibit 18-49: Landfill CH_4 Emissions for Three Different Methane Collection Systems, National Average Landfill Moisture Conditions, Typical Landfill Management Operations, and National Average Grid Mix ($MTCO_2e$/Wet Short Ton)

Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation
Food Waste	1.57	0.68	0.46

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

A portion of the carbon contained in food waste does not decompose after disposal and remains stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the carbon in the organic material would be released as CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic carbon sink. The carbon storage associated with each material type depends on the initial carbon content, the extent to which that carbon decomposes into CH_4 in landfills, and temperature and moisture conditions in the landfill. The background and details of the research underlying the landfill carbon storage factors are detailed in the Landfilling chapter. Exhibit 18-50 shows the carbon storage factor calculations for landfilled food waste.

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[95] These values include a utility offset credit for electricity generation that is avoided by capturing and recovering energy from landfill gas to produce electricity. 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.

Exhibit 18-50: Calculation of the Carbon Storage Factor for Landfilled Food Waste

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (grams of Carbon Stored/dry gram of Material)[a]	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Storage to Wet Weight (grams of Carbon/wet gram of Material) (d = b × c)	(e) Amount of Carbon Stored ($MTCO_2e$ per Wet Short Ton)
Food Waste	0.08	0.27	0.02	0.07

[a] Based on estimates developed by James W. Levis, Morton Barlaz, Joseph F. DeCarolis, and S. Ranji Ranjithan at North Carolina State University; see Levis et al. 2013.

The landfill CH_4 and transportation emissions sources are added to the landfill carbon sink in order to calculate the net GHG landfilling emission factors for food waste, shown in the final three columns of Exhibit 18-51 for landfills equipped with different LFG collection systems. The final net emission factors indicate that food waste results in net emissions, due to relatively high CH_4 emissions and low carbon storage in landfills.

Exhibit 18-51: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2e$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation	Net Landfill Carbon Storage	GHG Emissions From Transportation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Food Waste	1.57	0.68	0.46	-0.07	0.04	1.54	0.64	0.43

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

18.5 Limitations

The results of the analysis presented in this chapter are limited by the reliability of the various data elements used. This section details limitations, caveats and areas of current and future research.

18.5.1 Source Reduction

EPA will conduct follow-on research to continue to refine and improve the accuracy of the food waste emission factors.

- The food waste factors assume conventional production practices and therefore do not capture any potential differences in life-cycle impacts from organic production practices.
- The LCI data used to model beef production is based on on-farm data from the largest research farm in the U.S. combined with post-farm data for the entire U.S. beef industry (Battagliese et al. 2013). The study authors intend to expand the next phase of the research effort to reflect regional differences in beef production throughout the United States, though the overall impact of these regional differences on the final findings is uncertain.
- For poultry production, GHG emissions have been allocated to both poultry meat and bones. EPA has chosen this allocation method to be consistent with other WARM food waste factors and to represent the waste materials that users of WARM are most likely to generate. However, there are other allocation methods not represented here, including allocating emissions only to

boneless poultry meat or to the entire live weight mass of the broiler, resulting in emissions also being allocated to poultry fat and BPM products that are reprocessed into poultry feed.

- EPA's peer review process for the poultry source reduction factors brought to EPA's attention the growing use of distiller's grains as a potential input to poultry feed. Distiller's grains have not been included at this point because these were not included as a feed input in the underlying LCI data used to develop the poultry source reduction. EPA will evaluate information on the use of distiller's grains as it becomes available in future updates to the poultry factors.
- For grain production, upstream energy demand and emissions associated with fertilizer production for nitrogen-based fertilizers are determined from a unit process for a weighted production mix of nitrogen fertilizers used in the United States. In the future, EPA may break this out into impacts by each specific type of nitrogen fertilizer and incorporate more recent LCI data for fertilizer production.
- Fertilizer-related soil emissions were estimated for poultry, grains, fruits and vegetables using the IPCC Tier 1 Method. In the future, EPA will investigate how use of the IPCC Tier 1 method may differ from the current methodology for estimating emissions from soils from fertilizer use in the U.S. EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks report.
- Impacts from co-products of fruit and vegetable products were not included in this analysis due to data limitations. For apples, oranges, melons, and tomatoes, the primary RMAM datasets did not include any information about co-products. However, differences between the amount of fruits and vegetables harvested in these scenarios and the final amount available for sale indicates that a portion of the production was unsalable. Due to a lack of data on the pathways for these fruits and vegetables and their assumed value, EPA determined that the impacts from any possible co-products are outside the scope of this effort.
- Luske 2010 determined that approximately 10 percent (by mass) of the bananas produced within the scope of its assessment were unsuitable for international sale and sold to a separate distributor for a much lower price for local distribution. Relative to the price of the bananas destined for international sale, these bananas had approximately 0.3 percent of the value of the entire yield. Because of the low value and lack of distribution to the United States, EPA deemed that impacts from this co-product were outside of the scope of analysis.
- Though Luske 2010 reported its own estimate for the life-cycle emissions for banana production, EPA supplemented the data and applied a different methodology to maintain consistency with the other fruits and vegetables within the weighted emission factor and with the scope of WARM. First, to narrow the scope of the data to cradle-to-retail, EPA did not assess the impacts of retail storage at the destination country. Second, to make the dataset more relevant to bananas sold within the United States, EPA did not utilize the ocean transport data for bananas shipped to Belgium and Germany from the study. Instead, EPA assumed an average transportation distance from Central American banana plantations to U.S. ports, acquired from a separate study on fruit transportation distances (Bernatz 2009). On average, the port-to-port shipment distance to the United States from Guatemala and Costa Rica, the two largest suppliers of bananas, was approximately 3,094 kilometers per shipment.
- Food products that are discarded at any point from primary production through retail transport could generate GHG impacts through decomposition during landfilling or composting. However, this potential source of GHG emissions is not included in the WARM fruits and vegetables source reduction emission factor for various reasons. First, the fruits and vegetables that are lost or

otherwise discarded at the point of production may simply be left on the field and are accounted for in the soil emissions calculations described above. Secondly, USDA (2012b) does not distinguish between the food loss rates at primary production versus those during transportation, and therefore it is unclear what share of the food waste loss occurs during retail transport itself. In its 2010 tomato packaging sustainable materials management study, EPA also found that information on losses at farm and in distribution was limited and in some cases conflicting (EPA 2010). EPA assumes that the share of food waste loss during retail transport is small and that the corresponding GHG impact of its disposal would not have a large impact on the final emission factor.

- Due to lack of available data, emissions from the release of fugitive refrigerants during refrigerated transportation of poultry and fruits and vegetables were estimated based on data developed specific to dairy products (Thoma et al. 2010). However, the emissions burden from fugitive refrigerants likely varies across the different food types modeled in WARM. EPA will evaluate incorporating refrigerated transport data and assumptions specific to different food types modeled in future updates, if available.

18.5.1.1 Composting

- Due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (cropland soil). EPA analyzed two types of compost feedstocks—yard trimmings and food scraps—although sewage sludge, animal manure and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils growing corn, despite widespread use of compost in specialty crops, land reclamation, silviculture, horticulture and landscaping.
- This analysis did not consider the full range of soil conservation and management practices that could be used in combination with application of compost, and the impacts of those practices on carbon storage. Research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no-till, residue management, crop rotation, wintering and summer fallow elimination.
- In addition to the carbon storage benefits of adding compost to agricultural soils, composting may lead to improved soil quality, improved plant productivity, improved soil water retention and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.
- This analysis did not consider the differences in compost emissions resulting from composting different food waste types. A future improvement may involve research into developing food type-specific composting factors for WARM.

18.5.1.2 Landfilling

- WARM currently assumes that 82 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems (EPA, 2014a). The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate, so the application of landfill gas collection systems at landfills will have an effect on lowering the emission factors presented here over time. WARM is updated annually to account for changes in the percent of MSW landfill CH_4 that is collected at U.S. landfills.
- This analysis did not consider the differences in landfill emissions resulting from landfilling different food waste types. A future improvement may involve research into developing food type-specific landfilling factors for WARM.

18.5.1.3 Combustion

- Opportunities exist for the combustion system efficiency of WTE plants to improve over time. As efficiency improves, more electricity can be generated per ton of waste combusted (assuming no change in utility emissions per kWh), resulting in a larger utility offset, and the net GHG emissions benefit from combustion of MSW will increase.
- The reported ranges for N_2O emissions from combustion of organics were broad. In some cases, the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. In the absence of better data on the composition and N_2O emissions from food waste combustion on a national scale in the United States , the average value used for food waste should be interpreted as an approximate value.
- This analysis used the non-baseload mix of electricity generation facilities as the proxy for calculating the GHG emissions intensity of electricity production that is displaced at the margin from energy recovery at WTE plants and LFG collection systems. Actual avoided utility GHG emissions will depend on the specific mix of power plants that adjust to an increase in the supply of electricity, and could be larger or smaller than estimated in these results.
- This analysis did not consider the differences in combustion emissions resulting from combusting different food waste types. A future improvement may involve research into developing food type-specific combustion factors for WARM.

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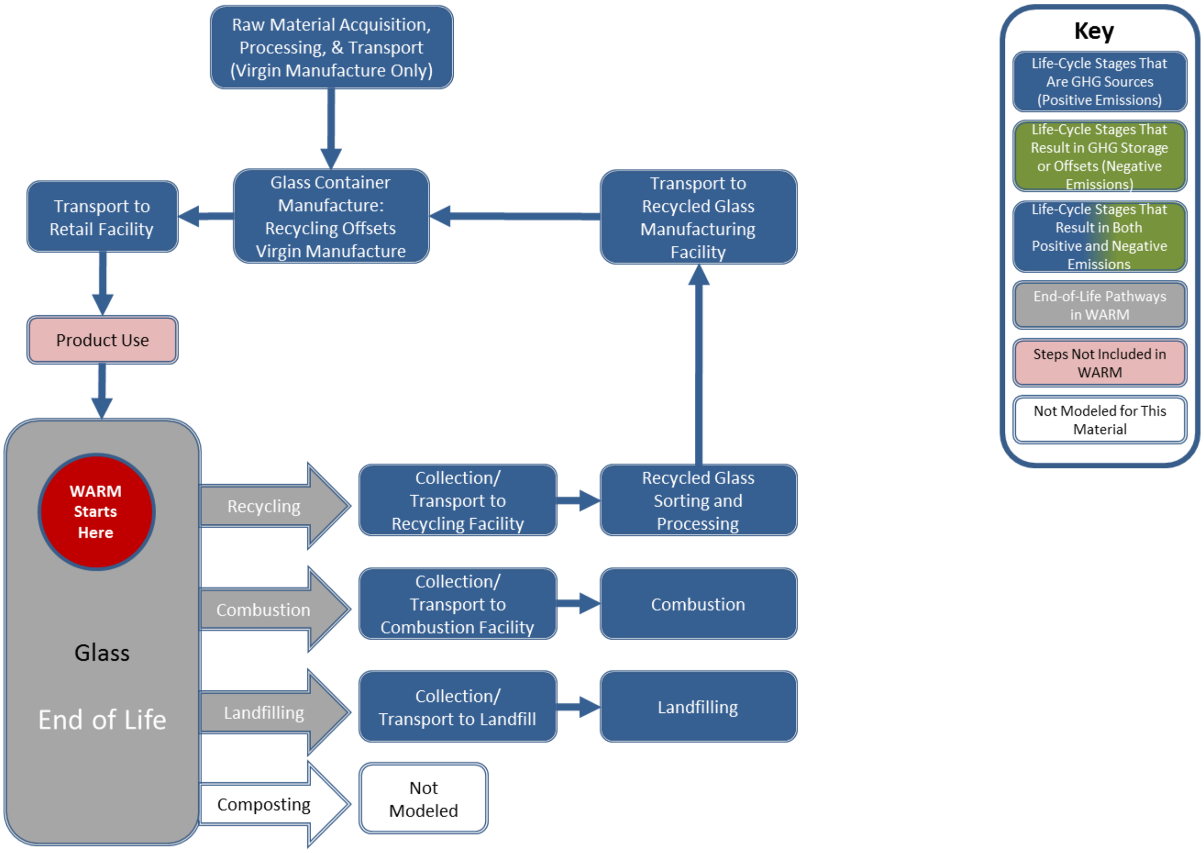
19 GLASS

19.1 Introduction to WARM and Glass

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate 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 the following four materials management alternatives: source reduction, recycling, landfilling, and combustion. Exhibit 19-1 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 Introduction & 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 19-1: 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. Recent figures on glass container generation and recovery are shown in Exhibit 19-2.

Exhibit 19-2: U.S. Glass Container Generation and Recovery in 2012

Type of Product	Generation (Short Tons)	Recovery (Short Tons)	Total MSW Generation (Short Tons)	Glass as % of Total MSW
Glass Bottles and Jars	11,570,000	3,200,000	250,890,000	4.6%

Source: EPA (2014).

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).

19.2 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.[96] 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 19-3.

Exhibit 19-3: Process and Transportation Energy for Manufacture of Glass Using Virgin and Recycled Inputs

Material/ Product	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 19-4 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 CH_4 emissions when landfilled. Therefore, the emissions associated with landfilling glass include only transportation- and landfill-equipment-related emissions. Glass cannot be composted and therefore this pathway is not considered in WARM.

Exhibit 19-4: 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** • Transport of raw materials and products • Virgin manufacture process energy • Virgin manufacture process non-energy	NA	NA

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[96] 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** • 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 recycling center • Sorting and processing energy
Composting	Not applicable since glass cannot be composted		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Energy required for combustion
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 19-4 and calculates net GHG emissions per short ton of glass generated for each materials management alternative as shown in Exhibit 19-5. For additional discussion on the detailed methodology used to develop these emission factors, see sections 19.3 and 19.4 .

Exhibit 19-5: Net Emissions for Glass under Each Materials Management Option (MTCO$_2$e/Short Ton)

Material/ Product	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
Glass	-0.52	-0.28	NA	0.05	0.04

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.

19.3 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 19-6. 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 19-6; 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 19-6: Typical Composition of Modern Container Glass

Chemical	Purpose	Source	% Composition
Silica (SiO_2)	Former	Sand	72% to 73.5%
Soda (Na_2O)	Flux	Soda ash (Na_2CO_3) from trona ore	12% to 14%
Potash (K_2O)	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_2O_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 CO_2 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 19-7, 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 19-7: Retail Transportation Energy Use and GHG Emissions

Material/Product	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions ($MTCO_2e$ per Short Ton of Product)
Glass	356	0.35	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.

19.4 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 19-8 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 19-8: 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 19-9.

Exhibit 19-9: 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 19-9. 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.

19.4.1 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 19-10 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.[97]

Exhibit 19-10: Source Reduction Emission Factors for Glass ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Glass	-0.52	-0.60	NA	NA	-0.52	-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

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[97] The "100 percent virgin" inputs emission factor assumes a minimum recycled content of 5 percent, since glass is rarely manufactured from entirely virgin inputs.

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.

19.4.1.1 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 CO_2. In addition, manufacturing glass also results in process non-energy CO_2 emissions from the heating of carbonates (soda ash and limestone). Hence, the RMAM component consists of process energy, non-process energy and transport emissions in the acquisition and manufacturing of raw materials, as shown in Exhibit 19-11.

Exhibit 19-11: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Glass ($MTCO_2e$/Short Ton)

(a) Material/Product	(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 CO_2 and CH_4, from all fuel types used in glass production. The process energy used to produce glass and the resulting emissions are shown in Exhibit 19-12.

Exhibit 19-12: Process Energy GHG Emissions Calculations for Virgin Production of Glass

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/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 19-13.

Exhibit 19-13: Transportation Energy Emissions Calculations for Virgin Production of Glass

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/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 19-7.

Non-energy GHG emissions occur during manufacturing but are not related to consuming fuel for energy. For glass, non-energy CO_2 emissions (based on data from ICF (1994)) are emitted in the virgin glass manufacturing process during the melting and refining stages from the heating of carbonates (soda ash and limestone). Exhibit 19-14 shows the components for estimating process non-energy GHG emissions for glass.

Exhibit 19-14: Process Non-Energy Emissions Calculations for Virgin Production of Glass

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)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Glass	0.16	–	–	–	–	0.16

– = Zero emissions.

19.4.2 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, 2014). 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 19-15. For more information, please refer to the Recycling chapter.

Exhibit 19-15: Recycling Emission Factor for Glass ($MTCO_2e$/Short Ton)

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

19.4.2.1 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 19-12, Exhibit 19-13, and Exhibit 19-14, 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 19-16 and Exhibit 19-17. 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 19-16: Process Energy GHG Emissions Calculations for Recycled Production of Glass

Product/Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Glass	4.32	0.23

Exhibit 19-17: Transportation Energy GHG Emissions Calculations for Recycled Production of Glass

Product/Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/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 19-7.

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 19-18.

Exhibit 19-18: Differences in Emissions between Recycled and Virgin Glass 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
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 19-18 by 97.6 percent, the amount of material retained after losses (i.e., 100 percent input – 2.4 percent lost = 97.6 percent retained).

19.4.3 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.

19.4.4 Combustion

WARM estimates (1) gross emissions of CO_2 and N_2O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) CO_2 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

19-19 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 19-19: Components of the Combustion Net Emission Factor for Glass ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_20 from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Glass	–	0.03	–	–	0.02	–	0.05

– = Zero emissions.

19.4.4.1 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 0.03 $MTCO_2e$ for one short ton of glass (FAL, 1994).

CO_2 from Combustion and N_2O from Combustion: Glass does not contain any C or N, so the emission factors for CO_2 and N_2O from combustion are estimated to equal zero.[98]

Avoided Utility Emissions: Most waste-to-energy (WTE) plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with MSW combustion would be in the form of electricity, and thus estimated the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant. 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 $MTCO_2e$ of avoided utility CO_2, 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.

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

19.4.5 Landfilling

WARM considers the CH_4 emissions, transportation-related CO_2 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 CH_4 or sequester any carbon when landfilled. The only emissions associated with landfilling glass are those from transporting glass to the landfills and moving waste

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

around in the landfills. Transportation of waste materials results in anthropogenic CO_2 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 19-20 provides the net emission factor for landfilling glass.

Exhibit 19-20: Landfilling Emission Factor for Glass ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

19.5 Limitations

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

19.6 References

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20 METALS

20.1 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 20-1 through Exhibit 20-3 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 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 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 20-1: Life Cycle of Aluminum Ingot and Cans in WARM

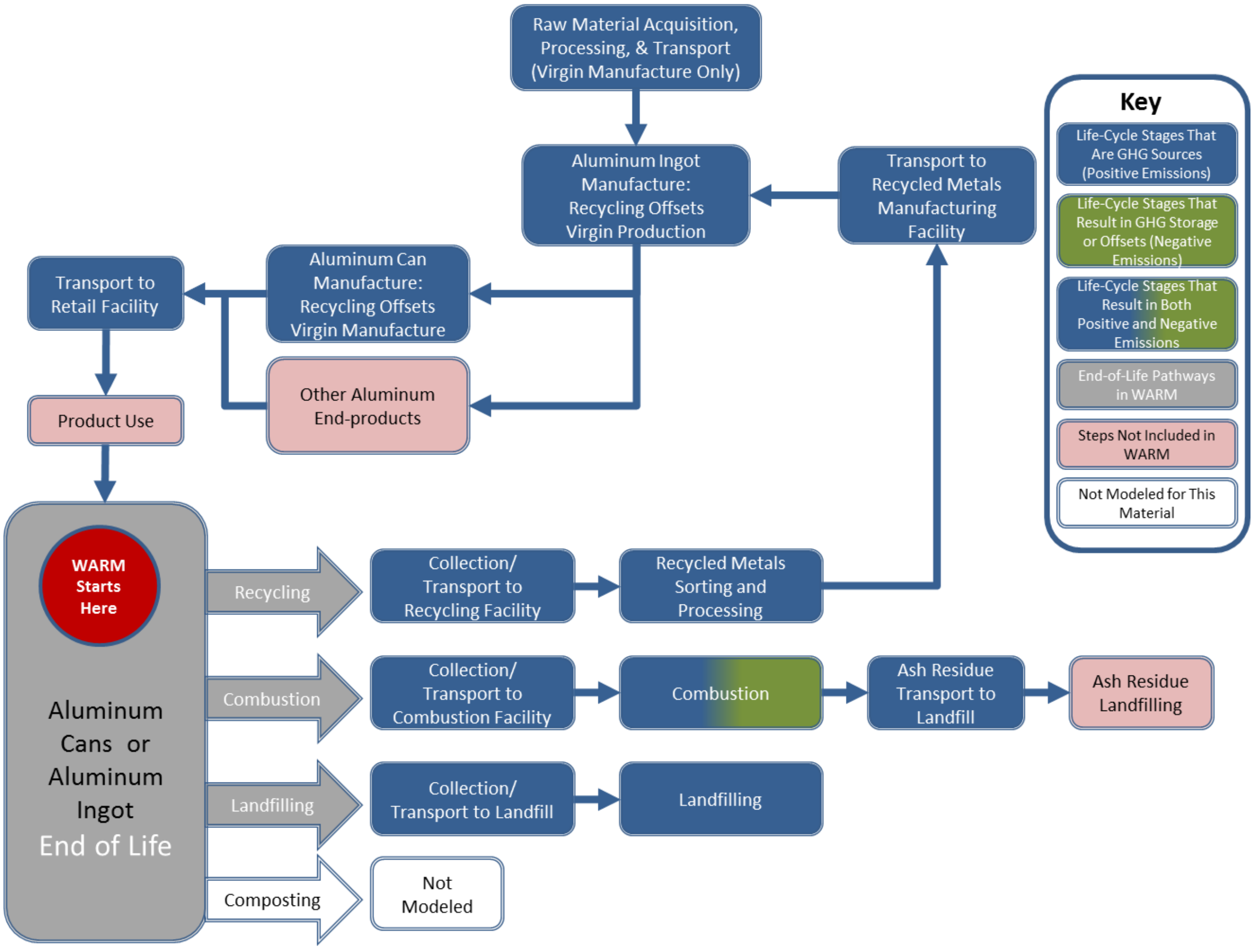


Exhibit 20-2: Life Cycle of Steel Cans in WARM

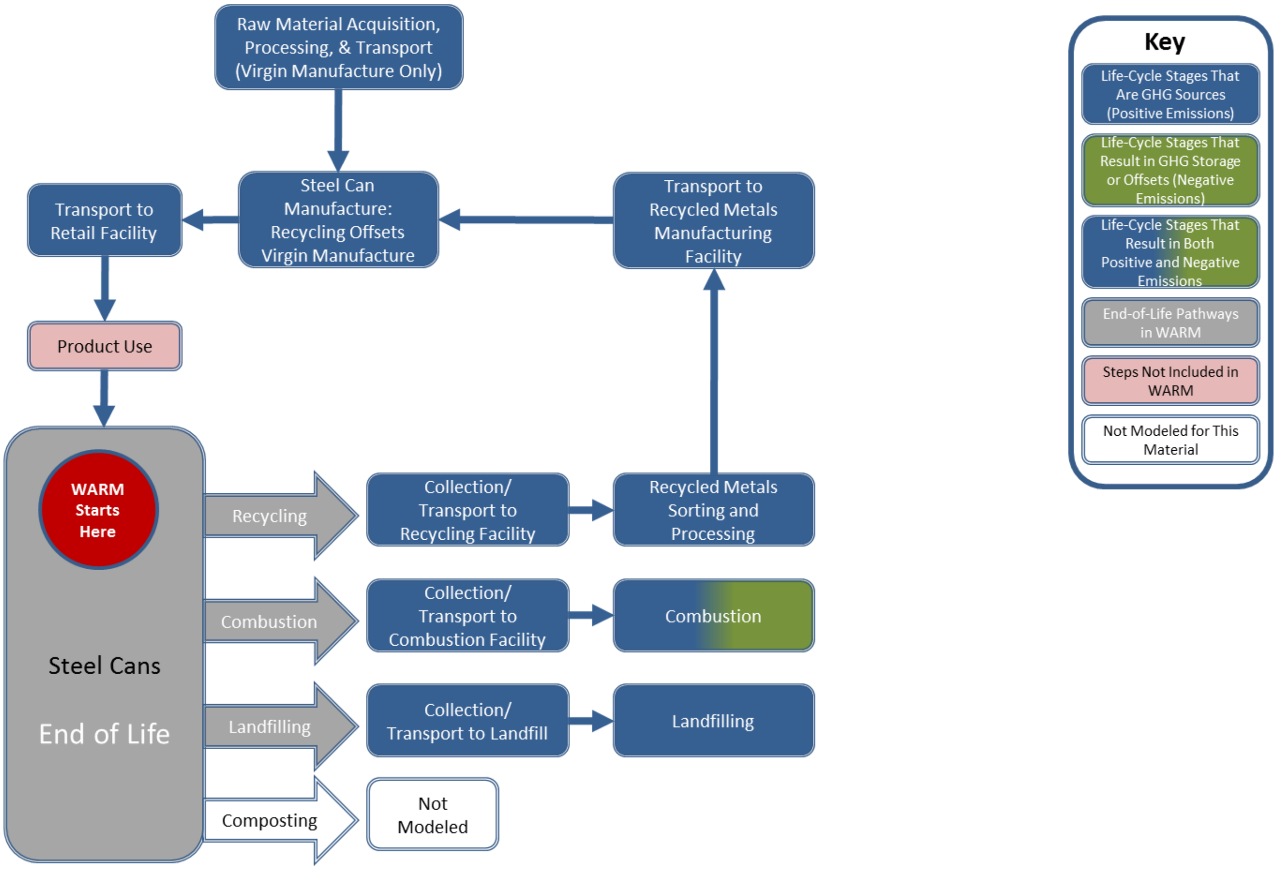
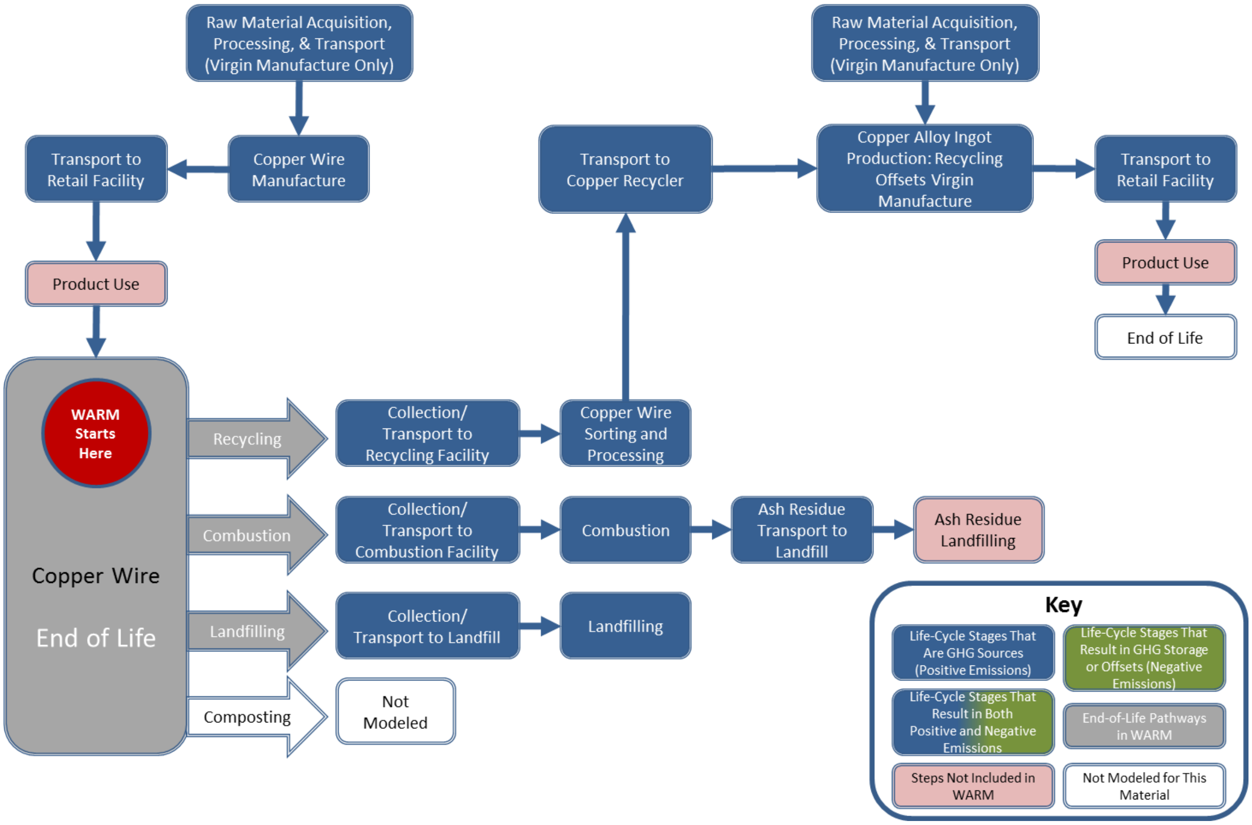


Exhibit 20-3: Life Cycle of Copper Wire in WARM



The metals category in WARM comprises copper wire, steel cans, and aluminum cans and ingot.[99] 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 (2014) report, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012*, 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 20-4**. 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 from research on personal computers and their raw material inputs as explained in the Personal Computers chapter.

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[99] 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.

Exhibit 20-4: Relative Prevalence of Metals in the Waste Stream in 2010

(a) Material/Product	(b) Generation (Short Tons)	(c) % of Total Container Metal Generation	(d) Recovery (Short Tons)	(e) % of Total Metals Recovery	(f) Recovery Rate
Aluminum Cans	1,420,000	43%	710,000	35%	50%
Aluminum Ingot	NA	NA	NA	NA	NA
Steel Cans	1,850,000	57%	1,310,000	65%	71%
Copper Wire	NA	NA	NA	NA	NA

Source: EPA (2014).
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 wires[100], 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).

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 20-4).

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

20.2 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.[101] 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 20.3. 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 20-5.

Exhibit 20-5: Life-Cycle Energy Associated with Manufacture (with 100% Virgin and 100% Recycled Inputs)

Material/Product	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 20-8.

As Exhibit 20-6 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.[102] Metals do not contain carbon and do not generate CH_4 emissions when landfilled. Therefore, the emissions associated with landfilling metals include only transportation- and landfill-equipment-related emissions. Metals cannot be composted and therefore this pathway is not considered in WARM.

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[101] 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.

[102] 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 20-6: 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** • 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** • 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 recycling center A. Sorting and processing energy
Composting	Not applicable since metals cannot be composted		
Combustion	NA	NA	**Emissions** B. Transport to WTE facility • Energy required for combustion **Offsets** C. Steel recovery and recycling
Landfilling	NA	NA	**Emissions** • Transport to landfill D. Landfilling machinery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 20-6 and calculates net GHG emissions per short ton of metal generated for each materials management alternative as shown in Exhibit 20-7. For additional discussion on the detailed methodology used to develop these emission factors, see sections 20.3 and 20.4.

Exhibit 20-7: Net Emissions for Metals under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Aluminum Cans	-4.92	-9.11	NA	0.05	0.04
Aluminum Ingot	-7.47	-7.19	NA	0.05	0.04
Steel Cans	-3.06	-1.81	NA	-1.55	0.04
Copper Wire	-7.03	-4.72	NA	0.05	0.04
Mixed Metals	-3.71	-4.38	NA	-0.99	0.04

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

20.3 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 $CaCO_3$), and the manufacture of lime results in CO_2 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 20-8. 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 20-8: Retail Transportation Energy Use and GHG Emissions

Material/Product	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	0.326	0.024
Aluminum Ingot	331	0.326	0.024
Steel Cans	331	0.326	0.024
Copper Wire	331	0.326	0.024

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.

20.3.1 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—Al_2O_3— 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.[103] 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

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[103] PE Americas, 2010 assumes 85 percent of aluminum production is from prebake and the remaining 15% is from Söderbeg 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 clocks 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.[104] 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).

20.3.2 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

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[104] 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 CO_2.

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.[105]

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.

20.3.3 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 CO_2 (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.

20.4 Materials Management

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 20-6 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 20-9 shows the range of recycled content used for manufacturing steel, and value for "virgin" steel used in WARM.

Exhibit 20-9: Typical Recycled Content Values in the Marketplace

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

Source: FAL (2003a)

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[105] 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.

The current mix of recycled and virgin inputs used for manufacturing each metal is provided in Exhibit 20-10. 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 20-10. 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 20-10: Current Mix of Inputs for Metals Manufacturing

Material/Product	% 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.

20.4.1 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 20-11 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 20-11: Source Reduction Emission Factors for Metals ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon 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	-4.92	-11.09	NA	NA	-4.92	-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	-7.03	-7.10	NA	NA	-7.03	-7.10
Mixed metals	-3.71	-6.28	NA	NA	-3.71	-6.28

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.

20.4.1.1 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 CO_2. In addition, manufacturing metals also results in process non-energy CO_2 emissions from the use of limestone fluxes. Hence, the RMAM component consists of process energy, non-process energy and transport emissions in the acquisition and manufacturing of raw materials. Exhibit 20-12 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 20.4.2, Recycling.

Exhibit 20-12: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Metals ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Aluminum Cans	7.28	0.09	3.72	11.09
Aluminum Ingot	4.23	0.07	3.18	7.47
Steel Cans	2.43	0.36	0.87	3.67
Copper Wire	7.04	0.06	0.00	7.10

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 CO_2 and CH_4, from all fuel types used in metals production. The process energy used to produce metals and the resulting emissions are shown in Exhibit 20-13.

Exhibit 20-13: Process Energy GHG Emissions Calculations for Virgin Production of Metals

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Aluminum Cans	184.74	7.28
Aluminum Ingot	115.16	4.23
Steel Cans	31.58	2.43
Copper Wire	122.52	7.04

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 2010). 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 20-14.

Exhibit 20-14: Transportation Energy Emissions Calculations for Virgin Production of Metals

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Aluminum Cans	0.91	0.07

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions (MTCO$_2$e/Short Ton)
Aluminum Ingot	0.56	0.04
Steel Cans	4.60	0.34
Copper Wire	0.46	0.03

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 20-8.

Non-energy GHG emissions occur during manufacturing but are not related to the consumption of fuel for energy. For metals, non-energy CO$_2$ emissions are emitted in the virgin metals manufacturing process. Exhibit 20-15 shows the components for estimating process non-energy GHG emissions for each category of metals.

Exhibit 20-15: Process Non-Energy Emissions Calculations for Virgin Production of Metals

Material/Product	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.

20.4.2 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 20-9), 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”[106] and 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,[107] 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).[108]

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 20-16. 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 20-16: Copper Wire Scrap Mix Used to Create Copper Ingot

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

Source: USGS (2004b).

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[106] 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.

[107] Based on conversations with Marshall Wang, Senior Sustainability Specialist, Aluminum Association.

This section describes the development of the recycling emission factors for metals, which are shown in the final column of Exhibit 20-17. 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.

Exhibit 20-17: Recycling Emission Factor for Metals ($MTCO_2e$/Short Ton)

Material/Product	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	–	–	-4.67	-0.06	–	–	-4.72
Mixed Metals	–	–	-3.03	-0.04	-1.31	–	-4.38

– = Zero emissions.

[a] Includes emissions from the initial production of the material being managed, except for food waste, yard waste and mixed MSW.

20.4.2.1 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 20-13, Exhibit 20-14, and Exhibit 20-15 in the source reduction section for aluminum and steel and in Exhibit 20-18 and Exhibit 20-19 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 20-18: Process Energy GHG Emissions Calculations for Virgin Production of Copper Ingot

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Copper Ingot	109.23	6.24

Exhibit 20-19: Transportation Energy Emissions Calculations for Virgin Production of Copper Ingot

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Copper Ingot	3.06	0.21

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 20-16. 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 20-20, Exhibit 20-21, and Exhibit 20-22 present the results for recycled or secondary product process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

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

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Aluminum Cans	36.24	1.93
Aluminum Ingot	4.50	0.24
Steel Cans	11.78	0.63
Copper No. 1 Scrap	7.89	0.44
Copper No. 2 Scrap	22.40	1.40

Exhibit 20-21: Transportation Energy GHG Emissions Calculations for Recycled Production of Metals

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/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 20-22: Process Non-Energy Emissions Calculations for Recycled Production of Metals

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
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 20-23.

Exhibit 20-23: Differences in Emissions between Recycled and Virgin Metals 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
Aluminum Cans	7.28	0.09	3.72	1.93	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	0.36	0.87	0.63	0.32	0.87	-1.81	-0.04	–
Copper Wire	7.04	0.06	0.00	5.60	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 20-24 are the product of the recovery and manufacturing retention rates.

Exhibit 20-24: Material Loss (Retention) Rates for Recycled Metals

Material/Product	% 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 20-23 by the retention rates in the last column of Exhibit 20-24.

20.4.3 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.

20.4.4 Combustion

This study's general approach was to estimate (1) gross emissions of CO_2 and N_2O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill), (2) CO_2 emissions avoided due to displaced electric utility generation, and (3) CO_2 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 20-25 provides the emission factors related to combusting of metals.

Exhibit 20-25: Components of the Combustion Net Emission Factor for Metals ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_20 from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Aluminum Cans	–	0.03	–	–	0.03	–	0.05
Aluminum Ingot	–	0.03	–	–	0.03	–	0.05
Steel Cans	–	0.03	–	–	0.02	-1.60	-1.55
Copper Wire	–	0.03	–	–	0.02	–	0.05
Mixed Metals	–	0.03	–	–	0.02	-1.04	-0.99

– = Zero emissions.

20.4.4.1 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 CO_2 and N_2O emissions from combustion do not occur.[109] 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 CO_2 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 $MTCO_2e$ of avoided utility CO_2.

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).[110] 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 20-26.

Exhibit 20-26: Avoided CO_2 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 ($MTCO_2e$/Ton)	Avoided CO_2 Emissions per Ton of Waste Combusted ($MTCO_2e$/Ton)
Steel Cans	0.88	1.81	1.60

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[109] At the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because 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 N_2O emissions.

[110] 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.

20.4.5 Landfilling

Because metals do not contain biogenic carbon, they do not generate CH_4 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 CO_2 emissions, due to the combustion of fossil fuels in the vehicles used. For further information please refer to the chapter on Landfilling. Exhibit 20-27 provides the net emission factor for landfilling of metals.

Exhibit 20-27: Landfilling Emission Factors for Metals ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Aluminum Cans	–	0.04	–	–	–	0.04
Aluminum Ingot	–	0.04	–	–	–	0.04
Steel Cans	–	0.04	–	–	–	0.04
Copper Wire	–	0.04	–	–	–	0.04
Mixed Metals	–	0.04	–	–	–	0.04

20.5 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 materials[111]), 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 to zero). EPA did not credit increased recycling of nonferrous materials, because of a lack of information

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[111] 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

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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21 PAPER PRODUCTS

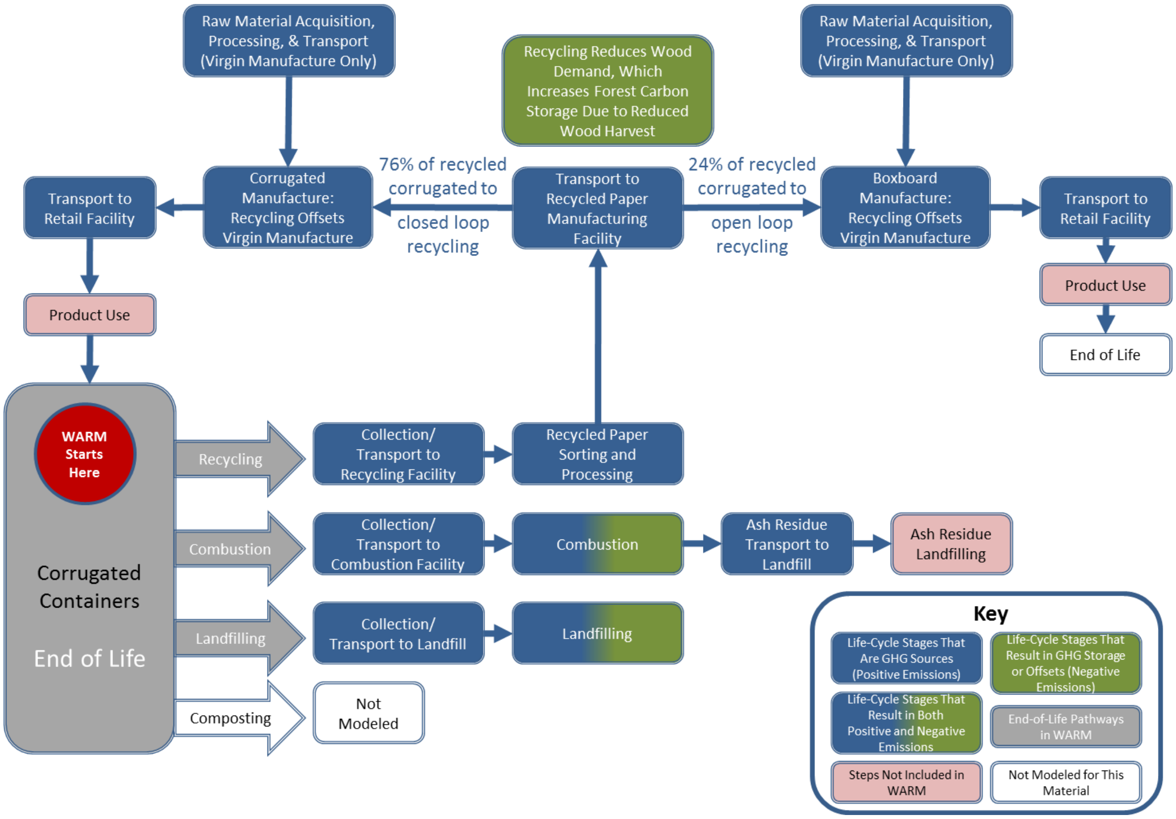
21.1 Introduction to WARM and Paper Products

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 Introduction & 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.

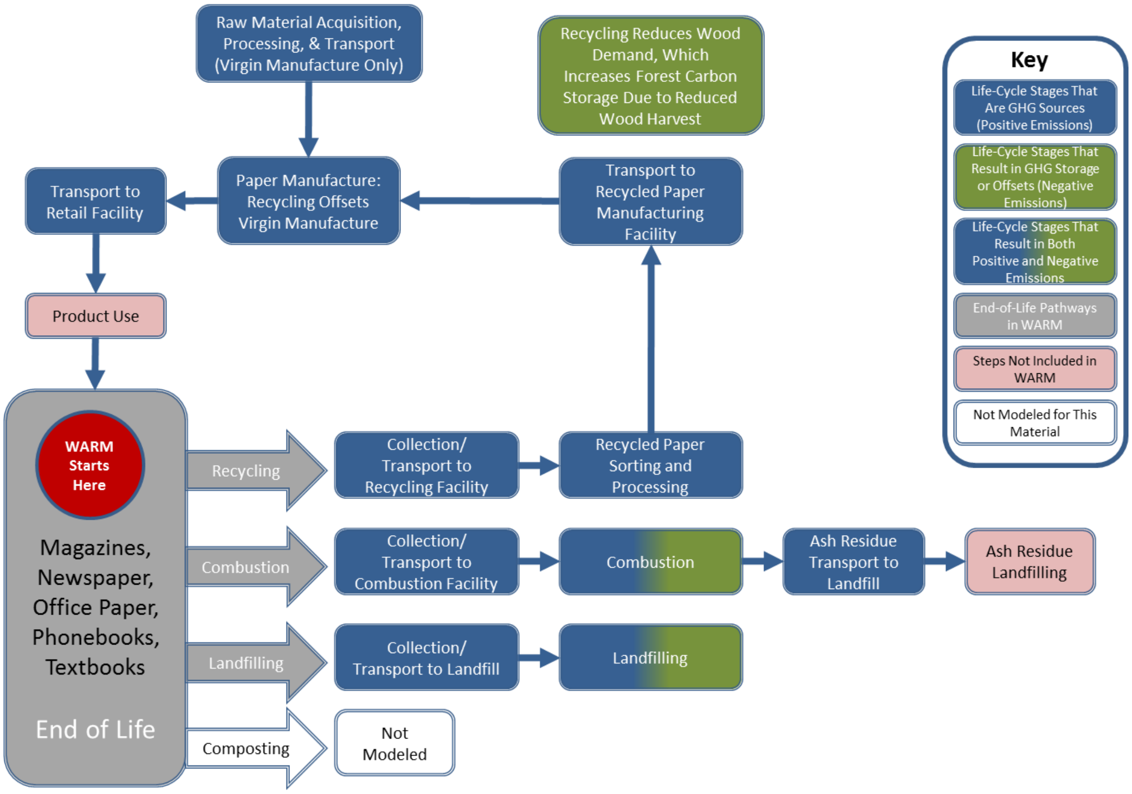
Corrugated containers are boxes made from containerboard (liner and corrugating medium) used in packaging applications (EPA, 2006). Exhibit 21-1 shows the general outline of materials management pathways for corrugated containers in WARM.

Exhibit 21-1: 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 21-2 shows the general outline of materials management pathways for magazines/third-class mail, newspaper, office paper, phone books and textbooks in WARM.

Exhibit 21-2: 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 21-3 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 21.4.2).

Exhibit 21-3: 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.[112] Exhibit 21-4 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 21-4: 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 21-5 shows the general outline of materials management pathways for the three definitions of mixed paper in WARM.

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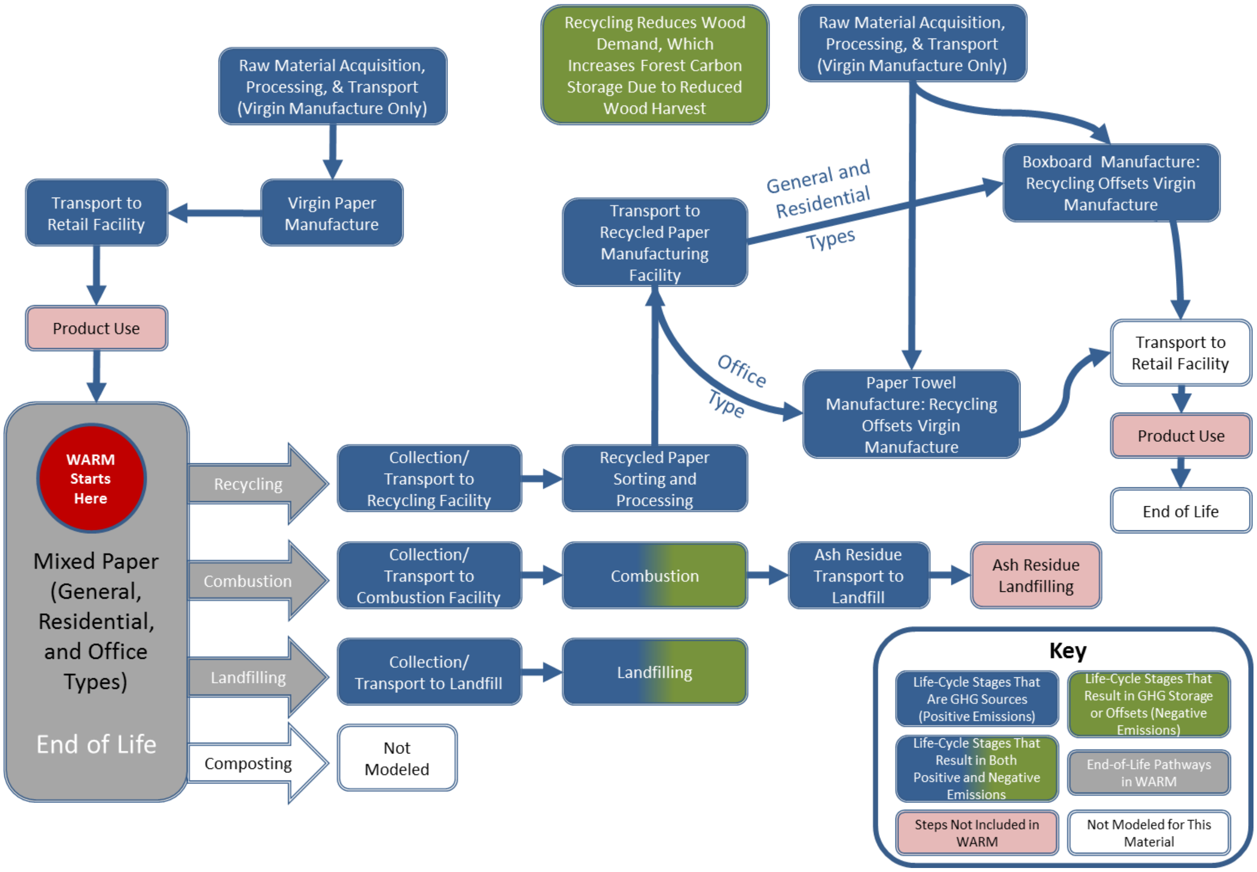
[112] The corrugated containers category was used to proxy tissue paper and towels, paper plates and cups, other non-packaging paper and corrugated boxes. The magazines/third-class mail category was used to proxy magazines and standard mail. Newspaper was used to proxy newsprint, groundwood inserts and 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 21-5: Life-Cycle of Mixed Paper in WARM



According to EPA's report, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012* (EPA, 2014a), paper products accounted for 27.4 percent of total municipal solid waste (MSW) generation in 2010. Recent figures on paper and paperboard generation and recovery are shown in Exhibit 21-6.

Exhibit 21-6: U.S. Paper and Paperboard Generation and Recovery in 2012

Material/Product	Generation (Short Tons)	Recovery (Short Tons)	Total MSW Generation (Short Tons)	Paper as % of Total MSW
Paper and Paperboard	68,620,000	44,360,000	250,890,000	27.4%

Source: EPA (2014a).

21.2 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. WARM models the source reduction of mixed paper as a weighted average of its components (see Exhibit 21-3), but users may also choose to model the source reduction of each type of paper individually.[113] Exhibit 21-7 illustrates the GHG sources and offsets that are relevant to paper products in this analysis.

Exhibit 21-7: 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** • Transport of raw materials and intermediate products • Virgin process energy and non-energy • Transport of paper products to point of sale	**Offsets** • Increase in forest carbon storage	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled process energy and non-energy **Offsets** • Transport of raw materials and intermediate products • Virgin process energy and non-energy • Transport of paper products to point of sale	**Offsets** • Increase in forest carbon storage	**Emissions** • Collection of paper products and transportation to recycling center
Composting	Not Modeled in WARM		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related N_2O **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery **Offsets** • Carbon storage in landfill • Energy recovery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 21-7 and calculates net GHG emissions per short ton of inputs, shown in Exhibit 21-8 for the four materials management pathways.

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[113] 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.

For more detailed methodology on emission factors, please see sections 21.4.1, 21.4.2, 21.4.3, 21.4.4, and 21.4.5.

Exhibit 21-8: Net Emissions for Paper Products under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Corrugated Containers	-5.59	-3.12	NA	-0.48	0.45
Magazines/Third-Class Mail	-8.60	-3.07	NA	-0.35	0.67
Newspaper	-4.77	-2.75	NA	-0.55	-0.73
Office Paper	-7.97	-2.86	NA	-0.47	1.52
Phone Books	-6.22	-2.64	NA	-0.55	-0.73
Textbooks	-9.07	-3.11	NA	-0.47	1.52
Mixed Paper (general)	-6.75	-3.53	NA	-0.49	0.40
Mixed Paper (primarily residential)	-6.65	-3.53	NA	-0.48	0.35
Mixed Paper (primarily from offices)	-7.96	-3.59	NA	-0.44	0.69

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

21.3 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 ($CaCO_3$) into lime (CaO), which results in CO_2 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,[114] 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 reams[115] (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

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

[115] 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.

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 21-9. 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, 1998a).

Exhibit 21-9: Retail Transportation Energy Use and GHG Emissions for Paper Products

Material/Product	Average Miles per Shipment	Transportation Energy per Short Ton of Product (Million Btu)	Transportation Emission Factors ($MTCO_2e$/ Short Ton)
Corrugated Containers	675	0.67	0.05
Magazines/Third-Class Mail	257	0.25	0.02
Newspaper	257	0.25	0.02
Office Paper	257	0.25	0.02
Phone Books	546	0.54	0.04
Textbooks	546	0.54	0.04

21.4 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 21-8, 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 21-10 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 21-10: Typical Paper Products Recycled Content Values in the Marketplace

Material/Product	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 21-11. 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 21-11 (FAL, 2003a).

Exhibit 21-11: Current Mix of Inputs for Paper Products Manufacturing

Material/Product	% 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%

Material/Product	% of Current Production from Recycled Inputs	% of Current Production from "Virgin" Inputs
Mixed Paper (general)	23%	77%
Mixed Paper (primarily residential)	25%	75%
Mixed Paper (primarily from offices)	10%	90%

21.4.1 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 21-12 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 CO_2 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 21-12: Source Reduction Emission Factors for Paper Products ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Corrugated Containers	-0.87	-0.84	-4.73	-7.26	-5.59	-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.

21.4.1.1 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 21-13 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 (21.4.2).

Exhibit 21-13: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Paper Products ($MTCO_2e$/Short Ton)

(a) Material/Product	(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	1.96	0.05	–	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 21.4.

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 (2014b). 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 21-14.

Exhibit 21-14: Process Energy GHG Emissions Calculations for Virgin Production of Paper Products

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Corrugated Containers	25.13	0.69
Magazines/Third-Class Mail	32.99	1.62
Newspaper	39.92	1.96
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, 2014b). Transportation energy also includes "retail transportation," as described in section 21.3. The transportation energy used to produce paper products and the resulting emissions are shown in Exhibit 21-15.

Exhibit 21-15: Transportation Energy Emissions Calculations for Virgin Production of Paper Products

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/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 21-9.

Non-energy GHG emissions occur during manufacturing, but are not related to consuming fuel for energy. For corrugated containers and newspaper, non-energy CO_2 emissions are based on data from RTI (2004). For office paper, non-energy CO_2 emissions are based on the original analysis supporting the first edition of this report (ICF, 1994). Exhibit 21-16 shows the components for estimating process non-energy GHG emissions for paper products.

Exhibit 21-16: Process Non-Energy Emissions Calculations for Virgin Production of Paper Products

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
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 21-17. 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 21-17: Forest Carbon Storage from Source Reduction of Paper Products

(a) Material/Product	(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 ($MTCO_2e$/Short Ton) ($e = c \times d \times 0.907$)	(f) Percent Virgin Inputs in the Current Mix of Inputs	(g) Net Change in C Storage per Unit of Increased Source Reduction, Current Mix ($MTCO_2e$/Short Ton) ($g = e \times f$)
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.

21.4.2 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 21-2.

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 21-5.

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 21-1.

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 21-18, is discussed further below. For more information on recycling in general, see the Recycling chapter.

Exhibit 21-18: Recycling Emission Factor for Paper Products ($MTCO_2e$/Short Ton)

Material/Product	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.

21.4.2.1 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 21-14, Exhibit 21-15, and Exhibit 21-16.

Step 2. *Calculate GHG emissions for recycled production of paper products.* Exhibit 21-19, Exhibit 21-20, and Exhibit 21-21 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 21.4.1.1.

Exhibit 21-19: Process Energy GHG Emissions Calculations for Recycled Production of Paper Products

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/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 21-20: Transportation Energy GHG Emissions Calculations for Recycled Production of Paper Products

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/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 21-9

Exhibit 21-21: Process Non-Energy Emissions Calculations for Recycled Production of Paper Products

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/ Short Ton)
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 21-22.

Exhibit 21-22: Differences in Emissions between Recycled and Virgin Paper Products Manufacture ($MTCO_2e$/Short Ton)

Material/Product	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
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:

Net Retention Rate for Paper Products = Recovery Stage Retention Rate × Manufacturing Stage Retention Rate

Exhibit 21-23 shows the retention rate calculations for each of the paper products.

Exhibit 21-23: Paper Products Retention Rate Calculation

Material/Product	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 21-24. 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 21-24: 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 ($MTCO_2e$/Short Ton)	(e) Net Change in C Storage per Unit of Increased Paper Product Recycling ($MTCO_2e$/Short Ton) ($e = b \times c \times 0.907 + d$)
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 21-18.

21.4.3 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.

21.4.4 Combustion

Combusting paper products results in emissions of both carbon dioxide (CO_2) and nitrous oxide (N_2O). Because carbon in paper products is considered to be biogenic,[116] CO_2 emissions from combustion are not considered in WARM. The N_2O 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, consequently reducing the power sector's consumption of fossil fuels. WARM takes this into account by

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[116] WARM assumes that biogenic CO_2emissions are balanced by CO_2 captured by re-growth of the plant sources of the material. Consequently, these emissions are excluded from net GHG emission factors in WARM.

calculating an avoided utility emission offset.[117] Exhibit 21-25 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 21-25: Components of the Combustion Net Emission Factor for Paper Products ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion[a]	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Corrugated Containers	–	0.03	–	0.04	-0.55	–	-0.48
Magazines/ Third-Class Mail	–	0.03	–	0.04	-0.41	–	-0.35
Newspaper	–	0.03	–	0.04	-0.62	–	-0.55
Office Paper	–	0.03	–	0.04	-0.53	–	-0.47
Phone Books	–	0.03	–	0.04	-0.62	–	-0.55
Textbooks	–	0.03	–	0.04	-0.53	–	-0.47
Mixed Paper (general)	–	0.03	–	0.04	-0.55	–	-0.49
Mixed Paper (primarily residential)	–	0.03	–	0.04	-0.55	–	-0.48
Mixed Paper (primarily from offices)	–	0.03	–	0.04	-0.51	–	-0.44

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
– = Zero emissions.
[a] CO_2 emissions from combustion of paper products are assumed to be biogenic and are excluded from net emissions.

Exhibit 21-26 provides the calculation for the avoided utility emissions. EPA uses three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in paper products to delivered electricity,[118] and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants. For more information on combustion in general, see the Combustion chapter.

Exhibit 21-26: Utility GHG Emissions Offset from Combustion of Paper Products

(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) ($e = b \times c \times d$)
Corrugated Containers	14.1	17.8%	0.22	0.55
Magazines/Third-Class Mail	10.5	17.8%	0.22	0.41
Newspaper	15.9	17.8%	0.22	0.62

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[117] 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.

[118] 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/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)
Office Paper	13.6	17.8%	0.22	0.53
Phone Books	15.9	17.8%	0.22	0.62
Textbooks	13.6	17.8%	0.22	0.53

21.4.5 Landfilling

When paper products are landfilled, anaerobic bacteria slowly degrade the materials, producing CH_4 and CO_2 over time. Because paper is derived from sustainably harvested sources of wood in the United States, CO_2 emissions are not counted, as they are biogenic and would be produced through natural decomposition in forests. CH_4 emissions, however, are included in WARM's emission factors, since the CH_4 is emitted as a result of placing the paper in a landfill, making the CH_4 a human-caused (i.e., anthropogenic) source of GHG emissions. In addition to CO_2 and CH_4 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 CO_2 emissions due to the combustion of fossil fuels in vehicles and landfilling equipment. Exhibit 21-27 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 CH_4 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 21-27: Landfilling Emission Factors for Paper Products ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Corrugated Containers	–	0.04	1.19	-0.07	-0.72	0.45
Magazines/Third-Class Mail	–	0.04	1.14	-0.06	-0.45	0.67
Newspaper	–	0.04	0.46	-0.03	-1.19	-0.73
Office Paper	–	0.04	1.71	-0.11	-0.12	1.52
Phonebooks	–	0.04	0.46	-0.03	-1.19	-0.73
Textbooks	–	0.04	1.71	-0.11	-0.12	1.52
Mixed Paper (general)	–	0.04	1.11	-0.07	-0.69	0.40
Mixed Paper (primarily residential)	–	0.04	1.09	-0.06	-0.72	0.35
Mixed Paper (primarily from offices)	–	0.04	1.22	-0.07	-0.49	0.69

Note: The emission factors for landfill CH_4 presented in this table are based on national-average rates of landfill gas capture and energy recovery. Avoided CO_2 emissions from energy recovery are calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, 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.

21.4.5.1 Developing the Emission Factor for Landfilling of Paper Products

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 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 CH_4 is not captured, is flared without energy recovery, or is combusted onsite for energy recovery.[119, 120] The Landfill CH_4 column of Exhibit 21-27 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, 2010). For further explanation, see the Landfilling chapter.

Exhibit 21-28 depicts the specific emission factors for each landfill gas collection type. Overall, landfills that do not collect LFG produce the most CH_4 emissions.

Exhibit 21-28: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2e$/Short Ton)

(a)	**(b) Net GHG Emissions from CH_4 Generation**			**(c)**	**(d)**	**(e) Net GHG Emissions from Landfilling (e = b + c + d)**		
Material/ Product	**Landfills without LFG Recovery**	**Landfills with LFG Recovery and Flaring**	**Landfills with LFG Recovery and Electricity Generation**	**Net Landfill Carbon Storage**	**GHG Emissions from Transport-ation**	**Landfills without LFG Recovery**	**Landfills with LFG Recovery and Flaring**	**Landfills with LFG Recovery and Electricity Generation**
Corrugated Containers	2.36	1.14	0.75	-0.72	0.04	1.68	0.46	-0.08
Magazines/ Third-Class Mail	2.33	0.99	0.79	-0.45	0.04	1.92	0.58	0.23
Newspaper	0.94	0.43	0.28	-1.19	0.04	-0.21	-0.73	-0.94
Office Paper	3.50	1.61	1.05	-0.12	0.04	3.41	1.53	0.73
Phone Books	0.94	0.43	0.28	-1.19	0.04	-0.21	-0.73	-0.94
Textbooks	3.50	1.61	1.05	-0.12	0.04	3.41	1.53	0.73
Mixed Paper (general)	2.24	1.05	0.70	-0.69	0.04	1.59	0.40	-0.10
Mixed Paper (primarily residential)	2.19	1.03	0.69	-0.72	0.04	1.51	0.35	-0.14

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[119] 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.

[120] For the year 2012, an estimated 38 percent of landfill CH4 was generated at landfills with landfill gas recovery systems and flaring, while 44 percent was generated at landfills with gas collection and energy recovery systems (EPA, 2014b).

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material/ Product	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation	Net Landfill Carbon Storage	GHG Emissions from Transport-ation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Mixed Paper (primarily from offices)	2.48	1.11	0.78	-0.49	0.04	2.03	0.66	0.16

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 21-29 provides the landfill carbon storage calculation used in WARM.

Exhibit 21-29: 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 ($MTCO_2e$ per Wet Ton)
Corrugated Containers	0.26	83%	0.22	0.72
Magazines/Third-Class Mail	0.15	92%	0.13	0.45
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.

21.5 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.

21.6 References

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22 PERSONAL COMPUTERS

22.1 Introduction to WARM and Personal Computers

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

The main components of a PC are the central processing units (CPU) and the monitor. The PC modeled in WARM is based on a typical desktop PC with a cathode ray tube (CRT) monitor. The CPU consists of housing (mostly steel) and internal electronic components, while the monitor's primary components are the CRT, plastic case and circuit boards. The wide range of PC models makes it difficult to specify the exact composition of a typical PC, and PC technology continues to evolve rapidly. For WARM analysis, EPA considers the CPU and CRT monitor, while the peripheral equipment (e.g., keyboards, external cables, printers) are left out of the analysis. Flat-panel monitors are now dominant in today's market, having displaced CRT monitors that were common in the 1990's and early 2000's. Although flat-panel monitors are beginning to enter the MSW stream in larger quantities, CRT monitors are still present and will likely remain a sizable component of end-of-life electronics for a number of years.

Upon disposal, PCs can be recovered for recycling, sent to a landfill or combusted. Exhibit 22-1 shows the general outline of materials management pathways in WARM. Recycling PCs is an open-loop process, meaning that components are recycled into secondary materials such as asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet. PCs are collected curbside and at special events, or individuals can bring them to designated drop-off sites. Once PCs have been collected for recycling, they are sent to Material Recovery Facilities (MRFs) that specialize in separating and recovering materials from electronic products. Building on Exhibit 22-1, a more detailed flow diagram showing the open-loop recycling pathways of PCs is provided in Exhibit 22-2.

Exhibit 22-1: Life Cycle of Personal Computers in WARM

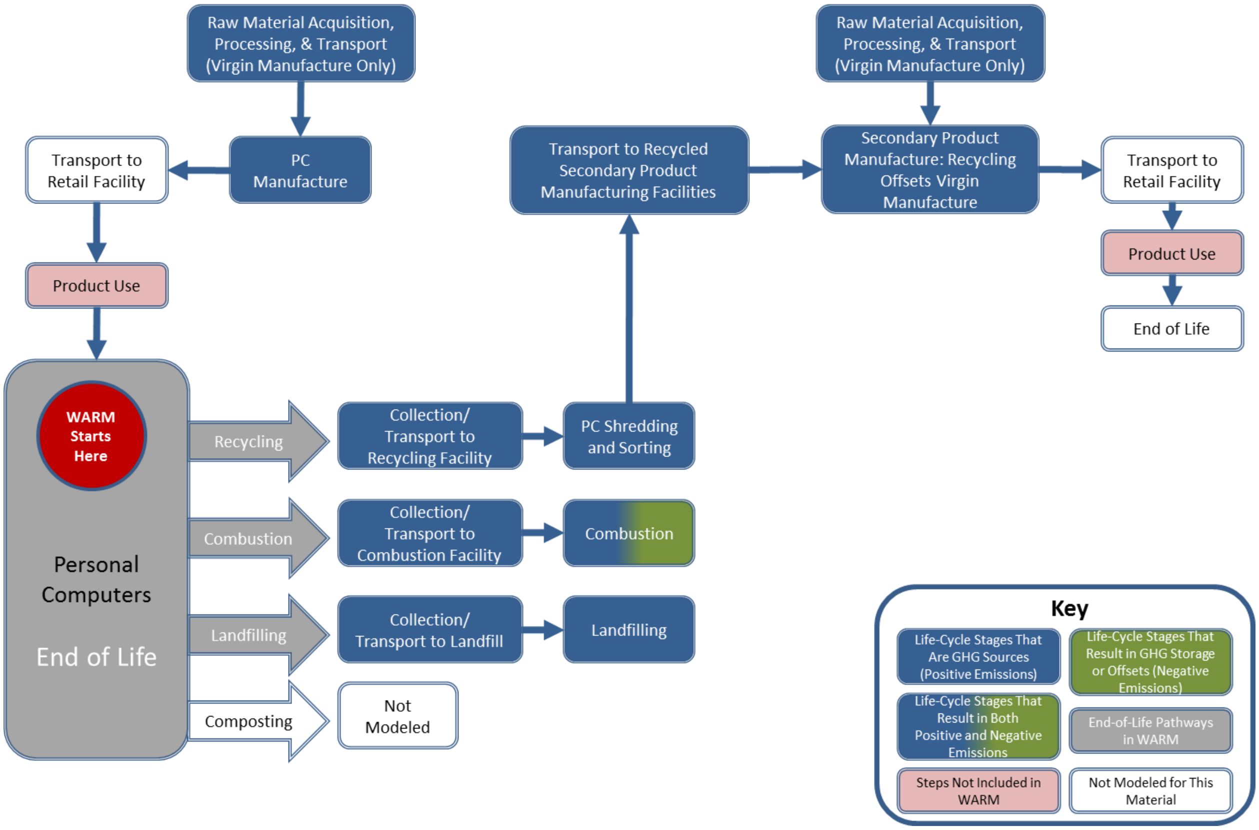
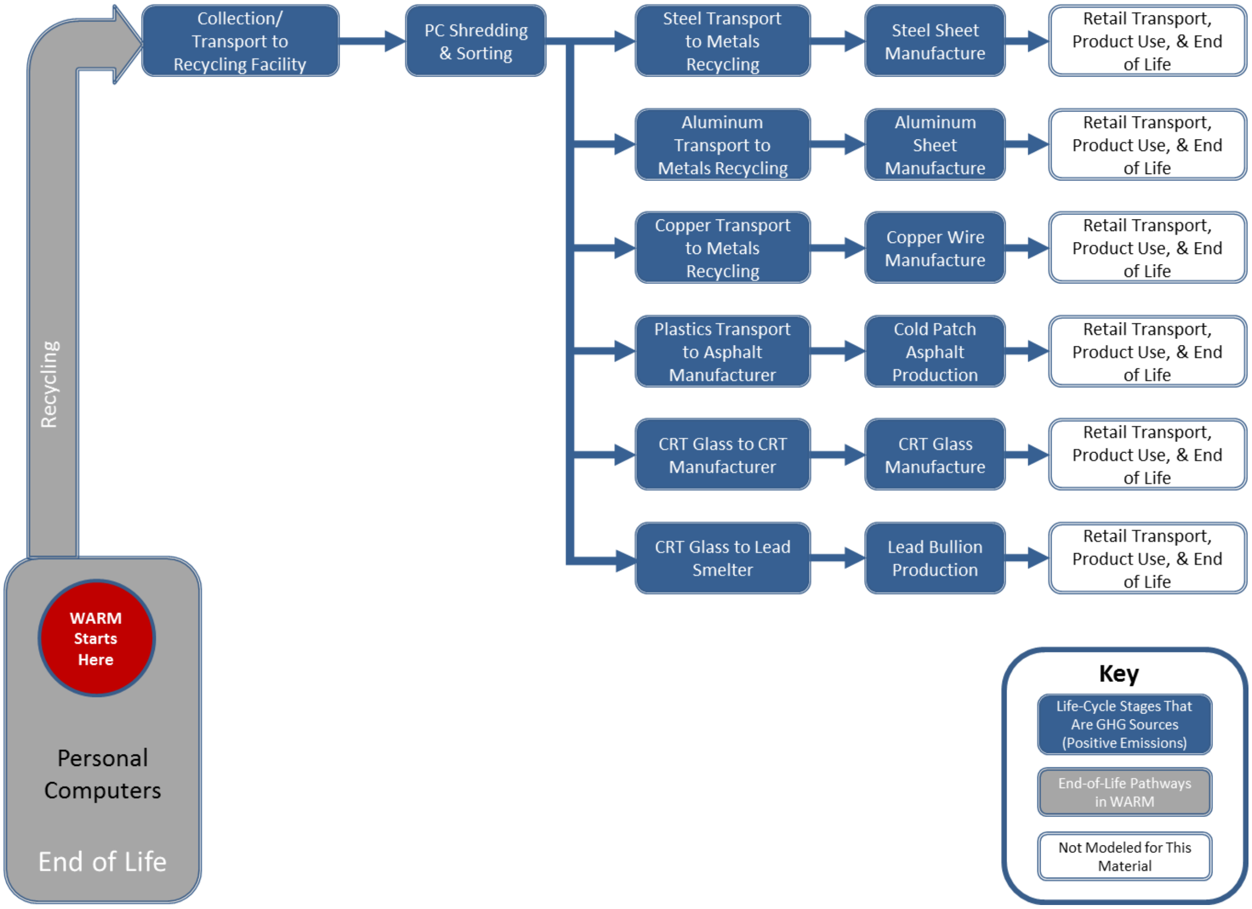


Exhibit 22-2: Detailed Recycling Flows for Personal Computers in WARM



22.2 Life-Cycle Assessment and Emission Factor Results

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

WARM includes source reduction, recycling, landfilling and combustion pathways for materials management of PCs. As Exhibit 22-3 illustrates, most of the GHG emissions from end-of-life management of PCs occur from the waste management of these products, while most of the GHG savings occur from offsetting upstream raw materials acquisition and manufacturing of other secondary materials that are recovered from PCs.

Exhibit 22-3: PC GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for PCs	GHG Sources and Sinks Relevant to PCs		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	Materials Management
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Virgin process non-energy • Transport of PCs to point of sale	NA	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled process energy • Recycled process non-energy **Offsets** • Emissions from producing asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet from virgin material	NA	**Emissions** • Collection of PCs and transportation to recycling center • Demanufacturing PCs
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related CO_2 and N_2O **Offsets** • Avoided utility emissions • Steel recovery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 22-3 and calculates net GHG emissions per short ton of PC inputs as shown in Exhibit 22-4. For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

Exhibit 22-4: Net Emissions for PCs under Each Materials Management Option ($MTCO_2e$/Short Ton)

Product/Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
PCs	-50.80	-2.51	NA	-0.17	0.04

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

22.3 Raw Materials Acquisition and Manufacturing

Exhibit 22-5 provides the assumed material composition of the typical PC used for this analysis.

Exhibit 22-5: Material Composition of a Desktop PC (CPU and CRT Monitor)

Product/Material	Application(s)	% of Total Weight	Weight (lbs.) (Assuming a 70-lb. Computer)
Plastics	Monitor case and other molded parts		
ABS[a]		8.0%	5.6
PPO/HIPS[b]		5.3%	3.7
TBBPA[c] (flame retardant)		5.7%	4.0
Glass	CRT glass/substrate for PWBs[d]	22.0%	15.4

Product/Material	Application(s)	% of Total Weight	Weight (lbs.) (Assuming a 70-lb. Computer)
Lead	CRT glass/electronic connections	8.0%	5.6
Steel	CPU case/CRT shield	28.6%	20.0
Copper	PWB conductor/wiring	6.6%	4.6
Zinc	Galvanization of CPU case	3.0%	2.1
Aluminum	Structural components/ PWB conductor	9.5%	6.7
Other	Metals and plastics for disk drives, fasteners and power supplies	3.3%	2.3
Total		**100.0%**	**70.0 lbs**

Source: FAL (2002).

[a] Acrylonitrile butadiene styrene.

[b] Polyphenylene oxide/High-impact polystyrene.

[c] Tetrabromobisphenol A.

[d] Printed wiring boards.

The quantity of components and the complexity of their manufacturing processes require that the analysis focus only on the key materials and processes. In particular, the life-cycle assessment (LCA) of PC production includes the following steps:

Chip manufacture (including wafer production, fabrication and packaging). A chip (or integrated circuit) is a compact device made of a semi-conducting material such as silicon. Although chip manufacture requires thousands of steps, the primary steps are wafer production, wafer fabrication and chip packaging.

Printed wiring board production. Printed wiring boards (PWBs) are part of the circuitry in electronic products.

CRT production. Computer monitors and televisions are the two largest applications for CRTs. A CRT is made of many materials and sub-assemblies, including a glass funnel, glass neck, faceplate (screen), electron gun, shadow mask, phosphors and PWBs.

Monitor housing production. The monitor case is made of one or more types of plastic resin including acrylonitrile-butadiene-styrene (ABS), polyphenylene ether alloys (referred to as PPE or PPO), and high impact polystyrene (HIPS). Monitor production also involves incorporation of flame retardants into the monitor housing.

CPU housing production. CPU cases are made of plastic panels and face plates and steel for structural stability. Much of the steel used in CPU cases is scrap steel; the rest is manufactured from virgin inputs.

PC assembly. PCs are assembled manually; the main energy requirement is the operation of conveyor belts for the assembly line.

22.4 Materials Management Methodologies

This analysis considers source reduction, recycling, landfilling, and combustion pathways for materials management of PCs. It is important to note that PCs are not recycled into new PCs, however; they are recycled in an open loop. The LCA of their disposal must take into account the variety of second-generation products from recycling PCs. Information on PC recycling and the resulting second-generation products is sparse; however, EPA has modeled pathways for which consistent LCA data are available for recycled PC components. The second-generation products considered in this analysis are: non-leaded CRT glass into glass cullet, recovered lead into lead bullion, steel into scrap steel, copper into scrap copper, aluminum into scrap aluminum, and plastic into ground plastic as an input to asphalt manufacturing.

The data source used to develop these emissions factors is a 2002 report published by Franklin Associates, Limited (FAL) on energy and GHG emission factors for the manufacture and end-of-life management of PCs. These data are based on a number of industry and academic data sources dating from the 1990's and 2000's. The data sources for ABS resin production and silicon wafer production rely on older sources; the ABS resin data are taken from confidential industry data sources in the 1970's and the silicon wafer production data are based on photovoltaic-grade silicon production in the 1980's (FAL, 2002).

Source reduction leads to the largest reduction in GHG emissions for PCs, since manufacturing PCs and their components is especially energy intensive. Recycling PCs leads to greater reductions than combustion and landfilling, since it also reduces similarly energy-intensive product manufacturing. Combustion still has a negative net emission factor that is driven by the GHG savings associated with recovered steel, while landfilling has a slightly positive emission factor due to the emissions from landfill operation equipment.

22.4.1 Source Reduction

Source reduction activities reduce the number of PCs that are produced, thereby reducing GHG emissions from PC production. Increasing the lifetime of a PC (e.g., through upgrades in software) or finding alternatives to purchasing new PCs (e.g., using a donated PC) are examples of source reduction. For more information on this practice, see the Source Reduction chapter.

Exhibit 22-6 outlines the GHG emission factor for source reducing PCs. GHG benefits of source reduction are calculated as the avoided emissions from raw materials acquisition and manufacturing (RMAM) of new PCs.

Exhibit 22-6. PC Source Reduction Emission Factor for PCs ($MTCO_2e$/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 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
PCs	-50.80	-50.80	NA	NA	-50.80	-50.80

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

22.4.1.1 Developing the Emission Factor for Source Reduction of PCs

To calculate the avoided GHG emissions for PCs, EPA looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 22-7 shows the results for each component and the total GHG emission factor for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 22-7: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of PCs ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
PCs	50.33	0.37	0.10	50.80

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

First, EPA obtained an estimate of the amount of energy required to produce one short ton of PCs, which is reported as 945 million Btu (FAL, 2002). Next, we determined the fuel mix that comprises this Btu estimate using data from FAL (2002) and then multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. The sum of the resulting GHG emissions by fuel type comprise the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in PC production. The process energy used to produce PCs and the resulting emissions are presented in Exhibit 22-8.

Exhibit 22-8: Process Energy GHG Emissions Calculations for Virgin Production of PCs

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
PCs	945.13	50.3

Transportation energy emissions come from fossil fuels used to transport PC raw materials and intermediate products. The methodology for estimating these emissions is the same as that used for process energy emissions. Based upon an estimated total PC transportation energy in Btu, EPA calculates the total emissions using fuel-specific carbon coefficients. Exhibit 22-9 shows the calculations for estimating 0.37 $MTCO_2e$ per short ton of PCs.

Exhibit 22-9: Transportation Energy Emissions Calculations for Virgin Production of PCs

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
PCs	5.03	0.37

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

Non-energy GHG emissions occur during manufacturing but are not related to combusting fuel for energy. For PCs, non-energy GHGs are emitted in the virgin CRT glass manufacturing process by the production of lime and in the evaporation of solvent vapors from photolithography procedures that are used to apply phosphors onto the screen (FAL, 2002, pp. 8, 10). Production of virgin steel and aluminum generate non-energy process GHG emissions from the use of limestone as a fluxing agent, and from the use of coke as a reducing agent (EPA, 2006, p. 11). Perfluorocarbons (PFCs) are also emitted from the smelting stage of virgin aluminum production. FAL provided data on GHG emissions from non-energy-related processes in units of pounds of native gas (2002). We convert pounds of gas per 1,000 lbs. of PCs to metric tons of gas per short ton of PCs and then multiply that by the ratio of carbon to gas to produce the emission factor in $MTCO_2e$ per short ton of PCs, as detailed in the example below, which shows the calculation of CH_4 process emissions for PCs.

$$1.01 \text{ lbs } CH_4/1{,}000 \text{ lbs PC} \times 2{,}000 \text{ lbs PC}/1 \text{ short ton PC} \times 1 \text{ metric ton } CH_4/2{,}205 \text{ lbs } CH_4 \times 25\ MTCO_2e/\text{metric ton } CH_4 = 0.02\ MTCO_2e/\text{short ton PC}$$

Exhibit 22-10 shows the components for estimating process non-energy GHG emissions for PCs.

Exhibit 22-10: Process Non-Energy Emissions Calculations for Virgin Production of PCs

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)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
PCs	0.08	0.00	–	–	–	0.10

– = Zero emissions.

22.4.2 Recycling

According to EPA (2011), 40 percent of CPUs and 33 percent of computer displays are recycled annually. EPA and other organizations have recently been increasing their focus on improving the recycling of PCs and other electronics because of several factors: (1) rapid sales growth and change are generating a growing stream of obsolete products, (2) manufacturing PCs and other electronics consumes large amounts of energy and materials, (3) electronics contain toxic substances, and (4) convenient and widespread systems for collecting and recycling PCs are not yet fully established. This section describes the development of the emission factor, which is shown in the final column of Exhibit 22-11. For more information on recycling in general, please see the Recycling chapter.

Exhibit 22-11: Recycling Emission Factor for PCs (MTCO$_2$e/Short Ton)

Material/ Product	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)
PCs	–	–	-1.59	-0.04	-0.88	–	-2.51

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

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

WARM models PCs as being recycled in an open loop into the following secondary materials: asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet (Exhibit 22-12). Specifically, recovered plastic can be used as a filler component in the production of cold-patch asphalt for road construction. Steel and aluminum sheet become scrap metal that can be used to produce a wide range of materials, from auto parts to cookware. Recovered CRT glass can be used for the production of new CRTs or processed to recover lead bullion that can be used to produce items such as batteries and X-ray shielding. Recycled copper wire can be used in various electrical applications, depending on its grade.

The recycled input credits shown in Exhibit 22-11 include all of the GHG emissions associated with collecting, transporting, processing, and recycling or remanufacturing PCs into secondary materials. None of the upstream GHG emissions from manufacturing the PC in the first place are included; instead, WARM calculates a “recycled input credit” by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of secondary materials from virgin inputs. Consequently, GHG emissions associated with management (i.e., collection, transportation and processing) of end-of-life PCs are included in the recycling credit calculation. Because PCs do not contain any wood products, there are no recycling benefits associated with forest carbon sequestration. The GHG benefits from the recycled input credits are discussed in greater detail below.

Exhibit 22-12: Fate of Recycled PCs

Primary Material from Recycled PCs	Secondary Product from Recycled PCs	% Composition of Original PC, by Weight
Plastic from CRT monitor and CPU housing	Asphalt	38%
Steel from CPU frame	Steel Sheet	27%
Lead from CRT monitor glass and electronic connections	Lead Bullion	10%
CRT glass from CRT monitor	CRT Glass	2%
Copper from wiring and PWBs	Copper Wire	5%
Aluminum from structural components and PWBs	Aluminum Sheet	18%

Note that the copper industry identifies two types of copper scrap, with No. 1 being cleaner and purer (therefore more desirable) and No. 2 being less pure. USGS (2004) indicates that consumption of purchased copper-base scrap in the United States comprises approximately 93 percent No. 1 scrap and 7 percent No. 2 scrap. WARM uses these percentages to create a weighted average of the two scrap types to represent copper wire manufacture from recycled inputs, as the two types of scrap display different process and transportation energy characteristics.

22.4.2.1 Developing the Emission Factor for Recycling of PCs

EPA calculates the GHG benefits of recycling PCs by comparing the difference between the emissions associated with manufacturing a short ton of each of the secondary products from recycled PCs and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. These results are then weighted by the distribution shown in Exhibit 22-12 to obtain a composite emission factor for recycling one short ton of PCs. 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 six steps, which are described in detail below.

Step 1. *Calculate emissions from virgin production of one short ton of secondary product.* We apply fuel-specific carbon coefficients to the data for virgin RMAM of each secondary product (FAL, 2002). 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 secondary product. The calculations for virgin process, transportation and process non-energy emissions for the secondary products are presented in Exhibit 22-13, Exhibit 22-14, and Exhibit 22-15, respectively.

Exhibit 22-13: Process Energy GHG Emissions Calculations for Virgin Production of PC Secondary Products

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Asphalt	0.50	0.03
Steel Sheet	14.60	0.81
Lead Bullion	19.46	1.04
CRT Glass	9.16	0.52
Copper Wire	122.52	7.04
Aluminum Sheet	213.33	11.38

Exhibit 22-14: Transportation Energy Emissions Calculations for Virgin Production of PC Secondary Products

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Asphalt	0.20	0.01
Steel Sheet	1.41	0.10

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Lead Bullion	0.63	0.05
CRT Glass	0.28	0.02
Copper Wire	0.46	0.03
Aluminum Sheet	7.15	0.52

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

Exhibit 22-15: Process Non-Energy Emissions Calculations for Virgin Production of PC Secondary Products

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)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Asphalt (Cold Patch)	0.00	–	–	–	–	0.00
Steel Sheet	1.43	0.00	–	–	–	1.48
Lead Bullion	0.02	0.00	–	–	–	0.03
CRT Glass	0.16	–	–	–	–	0.16
Copper Wire	0.00	–	–	–	–	0.00
Aluminum Sheet	2.14	–	0.00	0.00	–	3.72

– = Zero emissions.

Step 2. *Calculate GHG emissions for recycled production of one short ton of the secondary product.* EPA then applies the same carbon coefficients to the energy data for the production of the secondary products from recycled PCs, and calculates non-energy process GHGs by converting data found in FAL (2002) to metric tons of gas per short ton of secondary product. Exhibit 22-16, Exhibit 22-17, and Exhibit 22-18 present the results for secondary product process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

Exhibit 22-16: Process Energy GHG Emissions Calculations for Recycled Production of PC Secondary Products

Product/Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Asphalt	5.49	0.29
Steel Sheet	12.53	0.67
Lead Bullion	19.50	1.04
CRT Glass	7.29	0.41
Copper Wire	101.05	5.60
Aluminum Sheet	16.59	0.90
Copper No. 1 Scrap	7.89	0.44
Copper No.2 Scrap	22.40	1.40

Exhibit 22-17: Transportation Energy GHG Emissions Calculations for Recycled Production of PC Secondary Products

Product/Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Asphalt	0.98	0.07
Steel Sheet	0.67	0.05
Lead Bullion	4.01	0.29
CRT Glass	5.28	0.39
Copper Wire	2.17	0.16
Aluminum Sheet	1.01	0.07
Copper No. 1 Scrap	1.85	0.14
Copper No.2 Scrap	2.42	0.18

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

Exhibit 22-18: Process Non-Energy Emissions Calculations for Recycled Production of PC Secondary Products

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)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Asphalt	0.00	–	–	–	–	0.00
Steel Sheet	0.02	–	–	–	–	0.02
Lead Bullion	0.02	–	–	–	–	0.02
CRT Glass	–	–	–	–	–	–
Copper Wire	0.00	–	–	–	–	0.00
Aluminum Sheet	–	–	–	–	–	–

– = 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 22-19.

Exhibit 22-19: Differences in Emissions between Recycled and Virgin PC Secondary Products 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
Asphalt	0.03	0.01	0.00	0.29	0.07	0.00	0.26	0.06	0.00
Steel Sheet	0.81	0.10	1.47	0.67	0.05	0.02	-0.14	-0.05	-1.46
Lead Bullion	1.04	0.05	0.03	1.04	0.29	0.02	0.00	0.24	-0.01
CRT Glass	0.52	0.02	0.16	0.41	0.39	–	-0.11	0.37	-0.16
Copper Wire	7.04	0.03	0.00	5.60	0.16	0.00	-1.44	0.13	–
Aluminum Sheet	11.38	0.52	3.72	0.90	0.07	–	-10.48	-0.45	-3.72

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
Totals may not sum due to independent rounding.

Step 4. *Adjust the emissions differences to account for recycling losses.* In the case of PCs, data indicated an 18 percent recovery-stage loss rate for PCs (i.e., 82 percent of recovered PCs for recycling were actually sent to a recycler; the remainder were landfilled). For the manufacturing stage, data indicated a 35-percent loss rate for asphalt; a 0.5-percent loss rate for lead bullion; and a 1-percent loss rate for copper wire. Zero manufacturing-stage losses were reported for the other secondary products. Because losses occur in both the recovery and manufacturing stages, the net retention rate was calculated as the product of the recovery and manufacturing retention rates, as shown below, using asphalt as an example:

Net Retention Rate for Asphalt = Recovery Stage Retention Rate × Manufacturing Stage Retention Rate

= 82.2% × 65.2% = 53.6%

Exhibit 22-20 shows how the retention rates are calculated. The differences in emissions from process energy, transportation energy and non-energy processing are then adjusted to account for the loss rates by multiplying the final three columns of Exhibit 22-19 by the retention rates in column (d) of Exhibit 22-20.

Exhibit 22-20: Calculation of Adjusted GHG Savings for PCs Recycled into Secondary Products

(a) Product/ Material	(b) Recovered Materials Retained per Short Ton PCs Collected (%)	(c) Short Tons Product Produced per Short Ton Recycled Inputs (%)	(d) Short Tons Product Made per Short Ton PCs Collected (%) (= b × c)
Asphalt	82.2%	65.2%	53.6%
Steel Sheet	82.2%	100.0%	82.2%
Lead Bullion	82.2%	99.5%	81.8%
CRT Glass	82.2%	100.0%	82.2%
Copper Wire	82.2%	99.0%	81.4%
Aluminum Sheet	82.2%	100.0%	82.2%

Step 5. *Weight the results by the percentage of recycled PCs that the secondary product makes up.* Using the percentages provided in Exhibit 22-12, EPA weights the individual GHG differences from Step 4 for each of the secondary products. In the case of asphalt, the MTCO$_2$e/Short Ton estimates from Step 3, as modified by the loss rates in Step 4, were weighted by the percentage of recycled PCs converted to asphalt (38 percent), as shown below:

Process Energy: 0.14 MTCO$_2$e/short ton$_{\text{unweighted}}$ x 38 % = 0.05 MTCO$_2$e/short ton
Transportation Energy: 0.03 MTCO$_2$e/short ton$_{\text{unweighted}}$ x 38 % = 0.01 MTCO$_2$e/short ton
Process Non-energy: 0.00 MTCO$_2$e/short ton$_{\text{unweighted}}$ x 38 % = 0.00 MTCO$_2$e/short ton

Each product’s process energy, transportation energy and process non-energy emissions are weighted by the percentages in Exhibit 22-12 and then they are summed as shown in the final column of Exhibit 22-21.

Exhibit 22-21: Personal Computer Recycling Emission Factors (MTCO$_2$e/Short Ton)

	Recycled Input Credit for Recycling One Short Ton of PCs			
Product/Material	Weighted Process Energy (MTCO$_2$e/Short Ton of Each Material)	Weighted Transport Energy (MTCO$_2$e/Short Ton of Each Material)	Weighted Process Non-Energy (MTCO$_2$e/Short Ton of Each Material)	Total (MTCO$_2$e/Short Ton of PCs Recycled)
Asphalt	0.05	0.01	0.00	0.07
Steel Sheet	-0.03	-0.01	-0.32	-0.36
Lead Bullion	0.00	0.02	-0.00	0.02
CRT Glass	-0.00	0.01	-0.00	0.00
Copper Wire	-0.06	0.01	0.00	-0.05
Aluminum Sheet	-1.58	-0.07	-0.56	-2.21
PC total	**NA**	**NA**	**NA**	**-2.54**

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.
Totals may not sum due to independent rounding.

Step 6. *Factor in process emissions from demanufacturing PCs.* EPA assumes that PCs are shredded to extract the materials that are recycled into secondary products. The act of shredding computers consumes electricity, and the GHG emissions associated with this electricity use are allocated to the total emission factor for recycling one short ton of PCs. The final PC recycling emission factor is the sum of the weighted secondary products’ emission factors from Exhibit 22-21 and the process emissions from demanufacturing PCs as shown in Exhibit 22-22.

Exhibit 22-22: Calculation of Recycling Emission Factor for PCs

Product/Material/Stage	Total (GHG Emissions in $MTCO_2e$/Short Ton)
Asphalt	0.07
Steel Sheet	-0.36
Lead Bullion	0.02
CRT Glass	0.00
Copper Wire	-0.05
Aluminum Sheet	-2.21
Demanufacturing Emissions	0.02
PCs (Sum)	**-2.51**

Totals may not sum due to independent rounding.

22.4.2.2 Limitations

Given the complex open-loop recycling process, the international flows of end-of-life electronics, and a lack of consistent and up-to-date information on PC recycling, the recycling factor for PCs is subject to important limitations. A primary data gap is the availability of representative life-cycle inventory (LCI) data for PCs and the materials recovered from them in the open-loop recycling process. For this analysis, we utilize an LCI from 2001 for PCs (FAL, 2002) and assume that these data are representative of the current processes used to collect and recover materials from PCs in the United States. This source was selected because it offered consistent and sufficient LCI data to produce an emission factor; however, but improved LCI data in at least three areas could have important effects on our results:

First, the recycling pathway for plastics recovered from PCs is largely unknown and poorly quantified. In this analysis, we assume that plastics are recycled as filler material in asphalt. This is very likely not representative of the dominant recycling pathway for plastics (Masanet, 2009). In reality, plastics are more likely sent overseas to Asia and recycled into low-grade plastic products (Masanet, 2009; McCarron, 2009; Moore, 2009). This might result in greater energy and GHG emissions savings from plastics recycling, but LCI data were not available for calculating a recycling credit for this pathway.

Second, the recycling pathways for CRT glass recovered from CRT monitors dismantled in the United States are not well quantified. It is uncertain what fraction of CRT glass is currently sent to smelters in North America versus recycled into new CRT glass in Asia, although it is likely that glass-to-glass recycling will diminish as the market for CRT monitors declines due to customers switching to flat-panel models (Gregory et al., 2009). Our analysis also assumes that CRT monitors are dismantled and sorted in the United States. A fraction of recovered CRT monitors, however, are likely exported to developing countries. This practice may increase transportation energy and GHG emissions, and result in different dismantling and recovery processes that could influence the energy and GHG emission implications of recycling PCs. The data were insufficient to quantify the flow of CRT monitors from the United States to other countries for recycling.

Finally, only a few integrated shredders are currently operated in the United States (Masanet, 2009). As a result, the emission factor for demanufacturing PCs may be inaccurate and dismantling PCs by hand may be a more common practice. Dismantling PCs by hand is likely to be less energy- and GHG-intensive than shredding them (Liu et al., 2009).

In addition, the life-cycle data for PCs assumes that the monitor is a CRT monitor. However, in the last several years, the sales and use of CRT monitors have been almost entirely supplanted by flat-panel monitors in the United States. This is a significant limitation of the analysis, as CRT and flat-panel monitors differ considerably in composition and weight.

22.4.3 Composting

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

22.4.4 Combustion

GHG emissions from combusting PCs result from the combustion process as well as from indirect emissions from transporting PCs to the combustor. Combustion also produces energy that can be recovered to offset electricity and GHG emissions that would have otherwise been produced from non-baseload power plants feeding into the national electricity grid. Finally, most waste-to-energy (WTE) plants recycle steel that is left after combustion, which offsets the production of steel from other virgin and recycled inputs. All of these components make up the combustion factor calculated for PCs.

It is likely that very few whole PCs are combusted, since components of PCs can interfere with the combustion process and the combustion of CRT monitors in particular can deposit lead that exceeds permitted levels in the combustion ash. Consequently, some level of disassembly and sorting is likely required to separate combustible plastics from other electronic components (EPA, 2008; FAL, 2002), although this is not included in WARM's combustion modeling approach. WARM accounts for the GHG emission implications of combusting PCs, but material managers should ensure that PCs are appropriately processed and sorted before sending the components to combustors.

For further information, see the Combustion chapter. Because WARM's analysis begins with materials at end of life, emissions from RMAM are zero. Exhibit 22-23 shows the components of the emission factor for combustion of PCs. Further discussion on the development of each piece of the emission factor is provided below.

Exhibit 22-23: Components of the Combustion Net Emission Factor for PCs ($MTCO_2e$/Short Ton)

Material/ Product	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)
PCs	–	0.03	0.38	–	-0.12	-0.46	-0.17

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

22.4.4.1 Developing the Emission Factor for Combustion of PCs

EPA estimates that PCs have a carbon content of 12 percent and that 98 percent of that carbon is converted to CO_2 during combustion. This carbon is contained within the plastics in PCs. The resulting direct CO_2 emissions from combustion of carbon in PCs are presented in Exhibit 22-24.

Exhibit 22-24: PC Combustion CO_2 Emission Factor Calculation ($MTCO_2e$/Short Ton)

Components	% of Total Weight	Carbon Content	Total $MTCO_2e$/Short Ton of PCs	Carbon Converted to CO_2 during Combustion	Combustion CO_2 Emissions ($MTCO_2e$/Short Ton of PCs)
ABS	8%	84%	7%	98%	0.23
PPO/HIPS	6%	85%	5%	98%	0.15
PCs (Sum)	**NA**	**NA**	**12%**	**98%**	**0.38**

NA = Not applicable.
Totals may not sum due to independent rounding.

EPA estimates CO_2 emissions from transporting PCs to the WTE plant and transporting ash from the WTE plant to the landfill using data provided by FAL.

Most utility power plants use fossil fuels to produce electricity, and the electricity produced at a WTE plant reduces the demand for fossil-derived electricity. As a result, the combustion emission factor for PCs includes avoided GHG emissions from utilities. We calculate the avoided utility CO_2 emissions based on the energy content of the plastics within PCs; the combustion efficiency of the WTE plant, including transmission and distribution losses; and the national average carbon-intensity of electricity produced by non-baseload power plants. Exhibit 22-25 shows utility offsets from PC combustion.

Exhibit 22-25: Utility GHG Emissions Offset from Combustion of PCs

(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)
PCs	3.07	17.8%	0.22	0.12

The combustion of PCs at WTE facilities also includes steel recovery and recycling processes. Approximately 90 percent of combustion facilities have ferrous recovery systems. FAL reports that one short ton of PCs contains 286 pounds of steel. Since some of this steel is lost during combustion, we included a ferrous recovery factor of 98 percent. The emission impacts of recycling of this recovered steel are shown in Exhibit 22-26.

Exhibit 22-26: Steel Production GHG Emissions Offset from Steel Recovered from Combustion of PCs

Material	Short Tons of Steel Recovered per Short Ton of Waste Combusted	Avoided CO_2 Emissions per Ton of Steel Recovered ($MTCO_2e$/Short Ton)	Avoided CO_2 Emissions per Ton of Waste Combusted ($MTCO_2e$/Short Ton)
PCs	0.25	1.81	0.46

22.4.5 Landfilling

22.4.5.1 Overview and Developing the Emission Factor for Landfilling of PCs

Roughly 60 percent of PCs entering the municipal solid waste stream are disposed of, and the vast majority of these end up in landfills. In WARM, landfill emissions comprise landfill CH_4 and CO_2 from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since PCs are inorganic and do not contain biogenic carbon, there are zero emissions from landfill CH_4, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling PCs, as shown in Exhibit 22-27. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling PCs represents only the emissions associated with collecting the waste and operating the landfill equipment. EPA estimates these emissions to be 0.04 $MTCO_2e$/short ton of PCs landfilled. For more information, refer to the Landfilling chapter.

Exhibit 22-27: Landfilling Emission Factor for PCs ($MTCO_2e$/Short Ton)

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

NA = Not applicable.
– = Zero emissions.

22.5 Limitations

As outlined in the recycling section (12.4.2), the open-loop recycling process has several limitations, including limited availability of representative LCI data for PCs and the materials recovered from them.

- The recycling pathway for plastics recovered from PCs is largely unknown and poorly quantified. While we assume that plastics are recycled as filler material in asphalt, in reality they are more likely sent overseas to Asia and recycled into low-grade plastic products.
- The recycling pathways for CRT glass recovered from CRT monitors dismantled in the United States are not well quantified, and it is likely that glass-to-glass recycling will diminish as the market for CRT monitors declines due to customers switching to flat-panel models (Gregory et al., 2009).
- Emission factors are based on PCs comprising a CPU and a CRT monitor, but CRT monitors are no longer common in PCs sold in the United States, having been replaced by flat-panel monitors.
- While we assume that CRT monitors are dismantled and sorted in the United States, a fraction of recovered CRT monitors are likely exported to developing countries.
- Only a few integrated shredders are currently operated in the United States, and as a result, the emission factor for demanufacturing PCs may be inaccurate and dismantling PCs by hand may be a more common practice, reducing the associated energy and GHG intensities.

22.6 References

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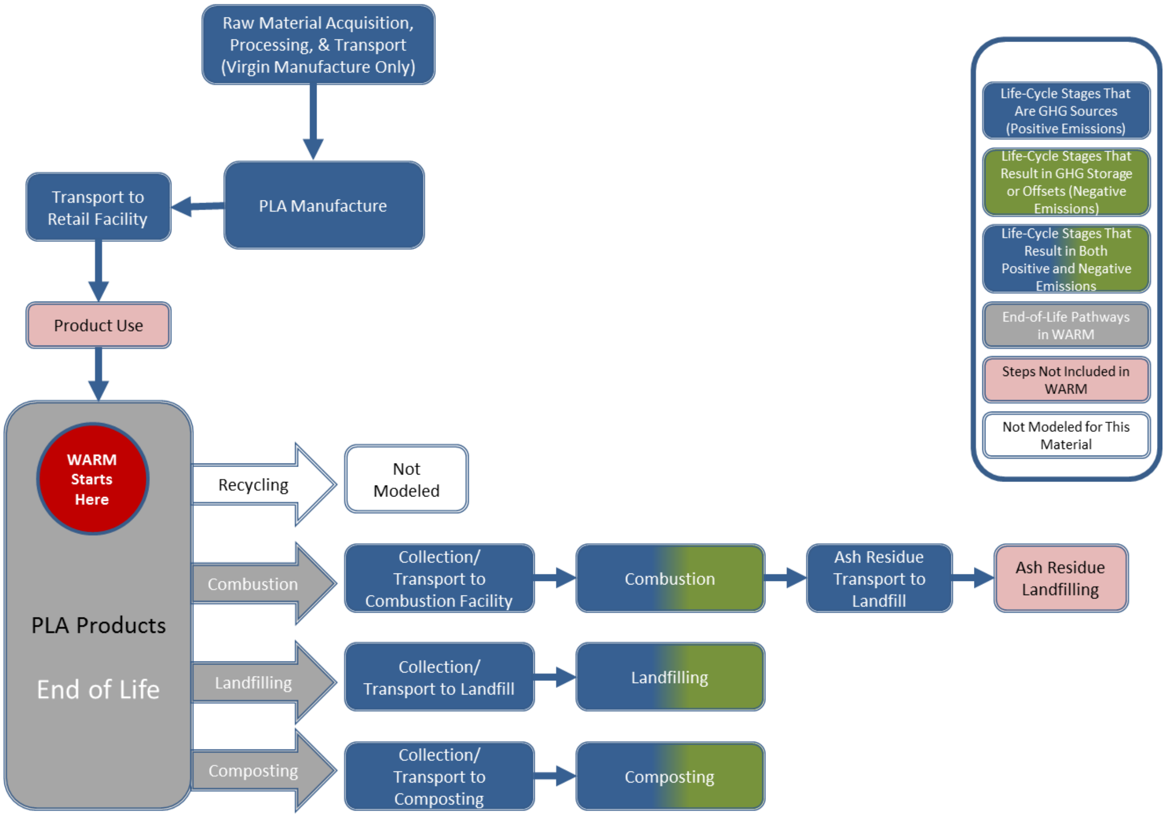
23 POLYLACTIDE (PLA) BIOPOLYMER

23.1 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.[121] The rest of this module provides details on these materials management options as life-cycle pathways for PLA. Exhibit 23-1 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 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 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 23-1: Life Cycle of PLA in WARM



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[121] 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.[122] 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).

23.2 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.[123] 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 20.3. 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 23-2. 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.

Exhibit 23-2: Life-Cycle Energy Associated with Manufacture (with 100% Virgin and 100% Recycled Inputs)

Material/Product	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	29.19	0.15	NA	NA

NA = Not applicable.

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[122] A list of the various PLA grades can be found here: http://www.natureworksllc.com/Technical-Resources.aspx

[123] 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 23-3 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 CH_4 emissions when landfilled because it stores carbon. Therefore, the emissions associated with landfilling PLA include only transportation- and landfill-equipment-related emissions.

Exhibit 23-3: 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** • 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** • Transport to landfill • Landfilling machinery **Offsets** • Landfill carbon storage

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 23-3 and calculates net GHG emissions per short ton of PLA generated for each materials management alternative as shown in Exhibit 23-4. For additional discussion on the detailed methodology used to develop these emission factors, see sections 20.3 and 20.4.

Exhibit 23-4: Net Emissions for PLA under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs*	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
PLA	-2.08	NA	-0.13	-0.62	-1.62

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

23.3 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, CO_2

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 23-5. 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 23-5: Retail Transportation Energy Use and GHG Emissions

Material/Product	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	0.490	0.036

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.

23.4 Materials Management

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 23-3 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.

23.4.1 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 23-6 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 23-6: Source Reduction Emission Factors for PLA (MTCO$_2$e/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs*	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon 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	-2.08	-2.08	NA	NA	-2.08	-2.08

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.

23.4.1.1 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 23-7 shows the results for each component and the total GHG emission factors for source reduction of PLA.

Exhibit 23-7: Raw Material Acquisition and Manufacturing Emission Factor for Source Reduction of Virgin Production of PLA (MTCO$_2$e/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
PLA	1.81	0.05	0.22	2.08

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 CO_2 and CH_4, from all fuel types used in PLA production. The process energy used to produce PLA and the resulting emissions are shown in Exhibit 23-8.

Exhibit 23-8: Process Energy GHG Emissions Calculations for Virgin Production of PLA

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
PLA	29.19	1.81

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 23-9.

Exhibit 23-9: Transportation Energy Emissions Calculations Virgin Production of PLA

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
PLA	0.15	0.01

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 23-5.

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 N_2O emissions associated with offgassing from fertilizer production and application in corn production. Also, non-energy CO_2 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 (N_2O) and 30 percent of the total CO_2 emitted are non-energy emissions, and the CH_4 emissions are mainly energy related.[124] Hence, the appropriate proportion of total CO_2 and all of the N_2O 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 23-10 shows the components for estimating process non-energy GHG emissions for PLA.

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[124] According to responses received from NatureWorks (EPA 2010b) all of the N_2O is released during crop production and is hence considered non-energy process emissions.

Exhibit 23-10: Process Non-Energy Emissions Calculations for Source Reduction of Virgin Production of PLA

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
PLA	0.11	NA*	–	–	0.00	0.22

* CH_4 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.

23.4.2 Recycling

Although the NatureWorks' PLA website[125] 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.

23.4.3 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 CO_2 emissions.[126] In addition, during the composting process the compost is mechanically turned, and the operation of this equipment results in non biogenic CO_2 emissions. Additionally, microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH_4 and N_2O 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 23-11 details these components for PLA.

PLA is biogenic and according to the NatureWorks' PLA website[127], 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 23-11 shows the two emission sources and one emission sink resulting from the composting of organics.

Exhibit 23-11: Components of the Composting Net Emission Factor for Organics

	Composting of Post-Consumer Material (GHG Emissions in $MTCO_2e$/Short Ton)					
Material Type	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Composting	Compost CO_2	Compost CH_4 and N_2O	Soil Carbon Storage	Net Emissions (Post-Consumer)
PLA	NA	0.04	–	0.07	-0.24	-0.13

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[125] http://www.natureworksllc.com/The-Ingeo-Journey/End-of-Life-Options/Recycling.aspx

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

[127] http://www.natureworksllc.com/The-Ingeo-Journey/End-of-Life-Options/Composting.aspx

23.4.3.1 *Emissions from Collection and Transport*

Transportation energy emissions occur when fossil fuels are used 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 these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 23-12.

Exhibit 23-12: 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 ($MTCO_2e$)
PLA	0.36	0.22	0.58	0.04

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

23.4.3.2 *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)[128] and carbon stored in non-reactive humus compounds (the "increased humus formation" effect).[129] 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 23-13.

Exhibit 23-13: Soil Carbon Effects as Modeled in Century Scenarios ($MTCO_2e$/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 $MTCO_2e$.

23.4.3.3 *Net Composting Emission Factor*

The nonbiogenic CO_2 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.

23.4.4 Combustion

This study's general approach was to estimate (1) gross emissions of CO_2 and N_2O from MSW combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill), (2) CO_2 emissions avoided due to displaced electric utility generation, and (3)

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[128] 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.

[129] 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 CO_2. For more information, see the Composting chapter.

CO_2 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 23-14 provides the emission factors related to combusting of PLA.

Exhibit 23-14: Components of the Combustion Net Emission Factor for PLA ($MTCO_2e$/Short Ton)

Material/Product	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)
PLA	–	0.03	–	–	-0.65	–	-0.62

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 N_2O emissions from combustion. There are also no emissions avoided due to steel recovery.

Emissions from Transportation of Waste. For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate of 60 lbs CO_2 per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2e$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW and the resulting ash. 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 23-15. 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 CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 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 website[130], 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 CO_2 emissions of 0.68 $MTCO_2e$/short ton of PLA combusted as shown below.

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[130] http://www.natureworksllc.com/The-Ingeo-Journey/End-of-Life-Options/Incineration.aspx

Exhibit 23-15: Utility GHG Emissions Offset from Combustion of PLA

(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)
PLA	16.74	17.8%	0.22	0.65

Source: NatureWorks, LLC (2010a).

To estimate the gross GHG emissions per ton of PLA combusted, EPA adds transportation CO_2 emissions to the avoided utility emissions in order to calculate the net GHG emission factor. As shown in Exhibit 23-15 WARM estimates that combustion of PLA results in a net emissions reduction.

23.4.5 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) ($C_{13}H_{21}O_4$) 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.[131] This is similar to petroleum-based polyethylene (PE) plastic resin. Therefore, landfill CH_4 emissions in the landfilling pathway are determined to be zero for PLA.[132] Accordingly, there are no avoided CO_2 emissions from landfill gas recovery for energy.

However, we can calculate the amount of biogenic carbon stored in the landfill based on the CO_2 sequestered via photosynthesis in corn production. The “inputs from nature” in the US LCI Database PLA spreadsheet accounts for “CO_2 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 23-16).

Exhibit 23-16: Biogenic Carbon Content of PLA[133]

(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)
1.83	1.66	0.50	50%

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

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[131] http://www.natureworksllc.com/The-Ingeo-Journey/End-of-Life-Options/Landfill.aspx

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

[133] In response to the *Preliminary Review of NatureWorks polylactide biopolymer (PLA) LCI Data* memo (EPA, 2010) prepared by ICF, NatureWorks responded that the “net CO_2 uptake is 1.833 kg CO_2/kg PLA” which implies that Carbon content of PLA is 50% (EPA 2010b).

equipment results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used. For further information please refer to the chapter on Landfilling. Exhibit 23-17 provides the net emission factor for landfilling of PLA.

Exhibit 23-17: Landfilling Emission Factors for PLA ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
PLA	–	0.04	–	–	-1.66	-1.62

23.5 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 23-3. 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.

23.6 References

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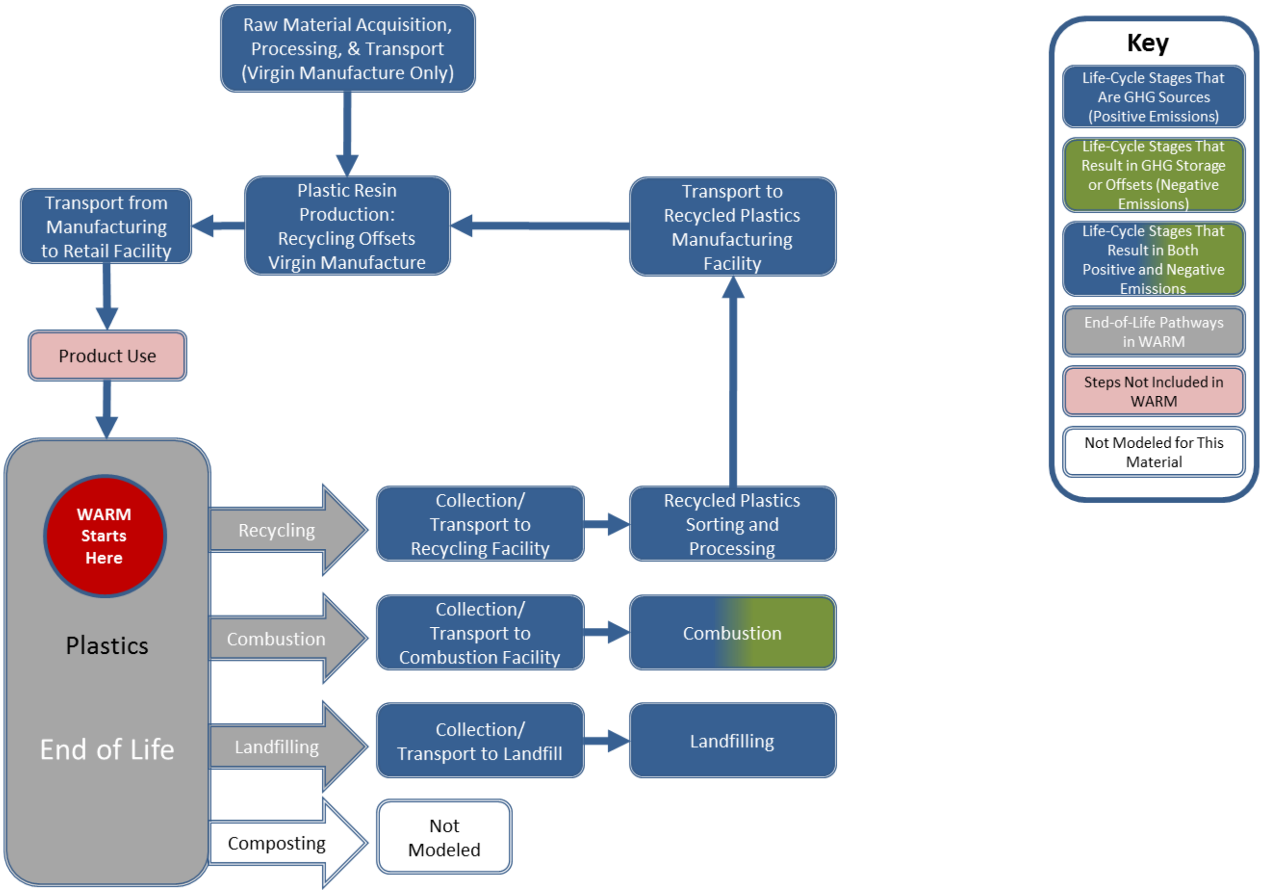
24 PLASTICS

24.1 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 24-1 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 24-1: Life Cycle of Plastics in WARM[134]



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).[134] According to the EPA report, *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures for 2012,* these seven plastics accounted for over eighty-seven percent of the plastic waste generated in

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

2012 (EPA, 2014). 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 column (f) of Exhibit 24-2.[135] Further discussion on the end uses of these plastics is provided below.

Exhibit 24-2: Plastic Waste Generation and Recovery in the United States, 2012

(a) Type of Product	(b) Generation (Short Tons)	(c) % of Total Generation	(d) Recovery (Short Tons)	(e) % of Total Recovery	(f) Recovery Rate (%)
HDPE	5,530,000	17.4%	570,000	20.4%	10.3%
LDPE/LLDPE	7,350,000	23.1%	390,000	13.9%	5.3%
PET	4,520,000	14.2%	880,000	31.4%	19.5%
PP	7,190,000	22.6%	40,000	1.4%	0.6%
PS	2,240,000	7.1%	20,000	0.7%	0.9%
PVC	870,000	2.7%	0	0%	0%
All Plastics	**31,750,000**		**2,800,000**		**8.8%**

Source: EPA (2014).

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

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[135] 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.

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).

24.2 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, 2014). The types of plastics examined here cannot be composted, so composting is not included. As Exhibit 24-3 illustrates, most of the GHG sources relevant to plastics in this analysis are associated with raw materials acquisition and manufacturing (RMAM).

Exhibit 24-3: 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		

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
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.
* 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 24-3 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 24-4 provides the net emission factors for all plastic types under all materials management scenarios.[136] The next sections include more detailed methodology on the derivation of the emission factors.

Exhibit 24-4: 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	-1.47	-0.88	NA	1.27	0.04
LDPE	-1.80	NA	NA	1.27	0.04
PET	-2.21	-1.13	NA	1.24	0.04
LLDPE	-1.58	NA	NA	1.27	0.04
PP	-1.55	NA	NA	1.27	0.04
PS	-2.50	NA	NA	1.64	0.04
PVC	-1.96	NA	NA	0.67	0.04
Mixed Plastics	-1.92	-1.03	NA	1.25	0.04

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

24.3 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.

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[136] 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.

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 for all plastic resins are presented in Exhibit 24-5. 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 24-5: 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)
All Plastics	497	0.49	0.04

RMAM non-process energy data was based on FAL (2011a).[137] 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 24.4.1.

24.4 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

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[137] Non-process energy emissions are equivalent to "process" emissions in FAL (2011a and 2011b). Non-process energy emissions include non-energy CO_2 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.

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 24-6 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 24-6: 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[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.

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 24.4.1, source reduction.

24.4.1 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 24-7. The methodology for calculating the source reduction emission factors is outlined in this section. As mentioned in section 24.1, 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 24-7: Source Reduction Emission Factors for Plastics (MTCO$_2$e/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 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	-2.21	-2.25	NA	NA	-2.21	-2.25
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	-1.96	-1.96	NA	NA	-1.96	-1.96
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 24.3), the RMAM emissions associated with plastics can be broken down into three emission sources: process energy, transportation energy and non-energy processes. Exhibit 24-8 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 24-6. The methodology for estimating emissions from manufacturing plastic from recycled materials is discussed in the next section, Recycling.

Exhibit 24-8: 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	1.19	0.19	0.20	1.57
LDPE	1.40	0.19	0.21	1.80
PET	1.75	0.11	0.39	2.25
LLDPE	1.14	0.19	0.25	1.58
PP	1.17	0.17	0.21	1.55
PS	1.87	0.18	0.45	2.50
PVC	1.69	0.12	0.14	1.96

Exhibit 24-9, Exhibit 24-10, and Exhibit 24-11 provide the calculations for each source of RMAM emissions: process energy, transportation energy and non-energy processes.

Exhibit 24-9: 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	23.73	1.19
LDPE	27.86	1.40
PET	28.43	1.75
LLDPE	23.11	1.14
PP	23.72	1.17
PS	35.98	1.87
PVC	30.43	1.69

Exhibit 24-10: 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	2.74	0.15
LDPE	2.79	0.15
PET	1.00	0.07
LLDPE	2.76	0.15
PP	2.36	0.13
PS	2.32	0.15
PVC	1.45	0.08

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 24-5.
– = Zero emissions.

Exhibit 24-11: 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	0.06	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.

24.4.2 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.[138] 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 24-12. As mentioned in section 24.1, 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 24-12: Recycling Emission Factor for Plastics ($MTCO_2e$/Short Ton)

Product/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	–	–	-0.71	0.00	-0.17	–	-0.88
LDPE	–	–	–	–	–	–	–
PET	–	–	-0.88	0.09	-0.34	–	-1.13
LLDPE	–	–	–	–	–	–	–
PP	–	–	–	–	–	–	–
PS	–	–	–	–	–	–	–
PVC	–	–	–	–	–	–	–
Mixed Plastics	–	–	-0.81	0.06	-0.28	–	-1.03

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

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[138] 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).

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 (FAL, 2011b). Exhibit 24-13 and Exhibit 24-14 provide the calculations for GHG emissions from manufacturing each plastic type from 100 percent recycled materials. Exhibit 24-15 provides the differences between virgin and recycling plastics manufacture that account for the recycled input credits in Exhibit 24-12. Process and transportation energy for recycling HDPE and PET were based on FAL (2011b).

Exhibit 24-13: 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	5.45	0.35
PET	12.26	0.77

Exhibit 24-14: 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	2.08	0.15
PET	2.34	0.17

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 24-5.

Exhibit 24-15: Differences in Emissions between Recycled and Virgin Plastics Manufacture ($MTCO_2e$/Short Ton)

	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)		
Product/ Material	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
HDPE	1.19	0.19	0.20	0.35	0.19	–	-0.83	0.00	-0.20
PET	1.75	0.11	0.39	0.77	0.21	–	-0.98	0.10	-0.39

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

24.4.3 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.

24.4.4 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 24-16 provides the emission factors for combusting each plastic type and their components.

Exhibit 24-16: Components of the Combustion Net Emission Factor for Plastics (MTCO$_2$e/Short Ton)

Product/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	–	0.03	2.79	–	-1.55	–	1.27
LDPE	–	0.03	2.79	–	-1.55	–	1.27
PET	–	0.03	2.04	–	-0.82	–	1.24
LLDPE	–	0.03	2.79	–	-1.55	–	1.27
PS	–	0.03	2.79	–	-1.55	–	1.27
PP	–	0.03	3.01	–	-1.40	–	1.64
PVC	–	0.03	1.25	–	-0.61	–	0.67
Mixed Plastics	–	0.03	2.33	–	-1.11	–	1.25

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 24-17 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 24-17: Plastics CO$_2$ Combustion Emission Factor Calculation

Product/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 24-18 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 24-18: 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	40.0	17.8%	0.22	1.55
LDPE	39.8	17.8%	0.22	1.55
PET	21.2	17.8%	0.22	0.82
LLDPE	39.9	17.8%	0.22	1.55
PP	39.9	17.8%	0.22	1.55
PS	36.0	17.8%	0.22	1.40
PVC	15.8	17.8%	0.22	0.61

24.4.5 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 24-19 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 24-19: 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 Storage	Net Emissions (Post-Consumer)
HDPE	–	0.04	–	–	–	0.04
LDPE	–	0.04	–	–	–	0.04
PET	–	0.04	–	–	–	0.04
LLDPE	–	0.04	–	–	–	0.04
PP	–	0.04	–	–	–	0.04
PS	–	0.04	–	–	–	0.04
PVC	–	0.04	–	–	–	0.04
Mixed Plastics	–	0.04	–	–	–	0.04

– = Zero emissions.

24.5 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 CO_2 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.

24.6 References

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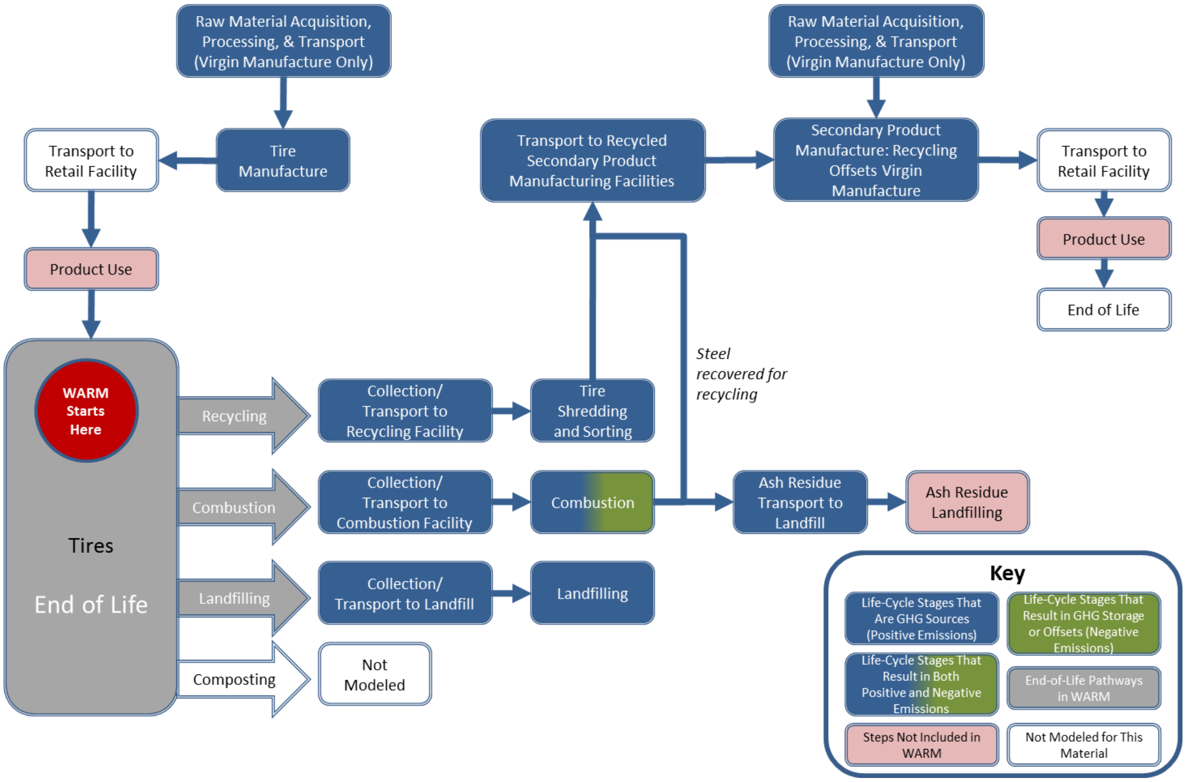
25 TIRES

25.1 Introduction to WARM and Tires

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for passenger vehicle tires beginning at the waste generation reference point.[139] The WARM GHG emission factors are used to compare the net emissions associated with scrap passenger tires in the following four materials management alternatives: source reduction, recycling, landfilling and combustion (with energy recovery). Exhibit 25-1 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 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 25-1: Life Cycle of Tires in WARM



Scrap tires have several end uses in the U.S. market, including as a fuel, in civil engineering, and in various ground rubber applications such as running tracks and molded products. These three end uses of scrap tires are modeled by WARM because they represented more than 90 percent of the scrap tire market in the United States in 2007 (RMA, 2009b). Scrap tires' use as ground rubber and in civil

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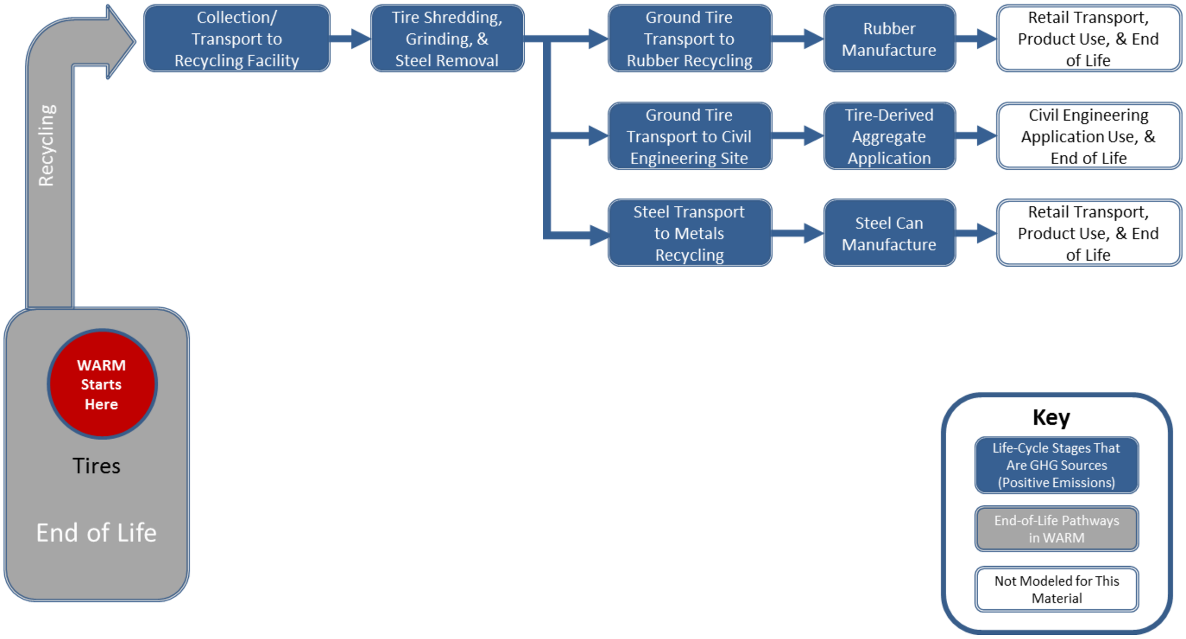
[139] EPA would like to thank Michael Blumenthal of the Rubber Manufacturers' Association and Albert Johnson of CalRecycle for their efforts in improving these estimates.

engineering practices is an open-loop recycling process, meaning that the tires are not recycled back into tires. Building on Exhibit 25-1, a more detailed flow diagram showing the open-loop recycling pathways of PCs is provided in Exhibit 25-2.

Exhibit 25-2: Detailed Recycling Flows for Tires in WARM



25.2 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.[140] Recycling and source reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not consider composting for the tires category. As Exhibit 25-3 illustrates, most of the GHG sources relevant to tires in this analysis are contained in the end-of-life management section of the life-cycle assessment, with the exception of recycling tires and transporting the recycled products.

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

Exhibit 25-3: Tires GHG Sources and Sinks from Relevant Waste Management Pathways

Materials Management Strategies for Tires	GHG Sources and Sinks Relevant to Tires		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Transport of tires to point of sale	NA	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled ground rubber and TDA[a] manufacture process energy **Offsets** • Transport of virgin ground rubber and soil/sand • Virgin ground rubber and soil/sand manufacture process energy	NA	**Emissions** • Collection of scrap tires and transportation to recycling center • Production of ground rubber and rubber for civil engineering applications **Offsets** • Steel recovery from steel-belted radial tires
Composting	Not applicable since tires cannot be composted		
Combustion	NA	NA	**Emissions** • Transport to combustion facilities • Combustion-related CO_2 and N_2O **Offsets** • Avoided utility emissions • Steel recovery
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery

NA = Not applicable.

[a] Tire-derived aggregate (TDA) is used in civil engineering applications.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 25-3 and calculates net GHG emissions per short ton of tire inputs. More detailed methodology on emission factors are provided in the sections below on individual waste management strategies.

Exhibit 25-4: Net Emissions for Tires under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/ Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Tires	-4.28	-0.39	NA	0.52	0.04

25.3 Raw Materials Acquisition and Manufacturing

Exhibit 25-5 provides the characteristics of scrap tires as modeled in WARM. The average scrap tire weight and the amount of steel in an average scrap tire are provided by the Rubber Manufacturers' Association (RMA, 2009a; Blumenthal, 2010). The assumed energy content for scrap tires provided in Exhibit 25-3 is from the California Integrated Waste Management Board (CIWMB, 1992). While this source is fairly old, it is believed to still be accurate today (Blumenthal, 2010). The percent of scrap tire weight that is polyester fiber is from NIST (1997), and the remaining material by weight (i.e., total tire weight minus steel and fiber) is assumed to be rubber.

Exhibit 25-5: Scrap Tire Characteristics

Scrap Tire Weight	22.5 lb.
Energy Content	13,889Btu/lb.
Material Composition (by Weight):	
Rubber	74%
Steel Wire	11%
Polyester Fiber	15%

Tire manufacturing starts out with the extraction of petroleum, which is processed into synthetic rubber, polyester fiber, oils and carbon black; the mining and manufacture of steel, which is made into steel cords; and the mining and processing of silica. These materials are transported to the tire manufacturer, who selects several types of rubber, along with special oils, carbon black, silica and other additives for production. An electrically powered Banbury mixer combines the various raw materials into a homogenized black gummy material. This material is then sent for further machine processing to make the different components of the tire (i.e., sidewalls, treads, etc.), requiring additional energy inputs. The tire is then assembled by adding the inner liner, which is a special rubber, resistant to air and moisture penetration. The polyester and steel are then added to give the tire strength while also providing flexibility. Next, the tire is placed inside a mold and inflated to press it against the mold, creating the tire's tread. Finally, the tire is heated at more than 300 degrees Fahrenheit for 12 to 15 minutes to be cured (RMA, 2010). The entire tire manufacturing process requires approximately 74 million Btu of energy per short ton of tire produced.

In addition to manufacturing, 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 25-6. Transportation emissions from the retail point to the consumer are not included. The number of miles traveled is obtained from the *2012 Commodity Flow Survey* (BTS, 2013) and mode-specific fuel use is from *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 25-6: 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)
Tires	497	0.58	0.04

25.4 Materials Management Methodologies

This analysis considers source reduction, recycling, landfilling and combustion pathways for management of scrap tires. It is important to note that tires modeled in WARM are not recycled into new tires; instead, they are recycled in an open loop. Assessing the impacts of their disposal must take into account the secondary products made from recycled tires. Information on tire recycling and the resulting secondary products is sparse; however, EPA modeled the pathways that the majority (approximately 93 percent in 2007) of recycled tires follows, and for which consistent life-cycle assessment data are available (RMA, 2009b). The secondary products considered in this analysis are shredded tires (also known as tire-derived aggregate or TDA) for civil engineering applications and for ground rubber.

The data source used to develop these emission factors is a 2004 report by Corti and Lombardi that compares four end-of-life pathways for tires. These data were based on research from several studies in the 1990s and 2000s in Europe, but EPA believes there are similar energy requirements for processing scrap tires in the United States.

Source reduction leads to the largest reduction in GHG emissions for tires, since manufacturing tires is energy intensive. Recycling tires leads to greater reductions than do combustion and landfilling, since it reduces similarly energy-intensive secondary product manufacturing. Combustion with energy recovery results in positive net emissions, driven primarily by the combustion of carbon compounds found in the rubber portion of the tires. Landfilling results in minor emissions due to the use of fossil fuels in transporting tires to the landfill and in landfilling equipment.

25.4.1 Source Reduction

Source reduction activities reduce the number of tires manufactured, thereby reducing GHG emissions from tire production. Extending the life of tires by choosing to purchase long-life tires is an example of source reduction. For more background on source reduction, see the Source Reduction chapter.

Exhibit 25-7 outlines the components of the GHG emission factor for source reduction of tires. The GHG benefits of source reduction are from avoided raw materials acquisition and manufacturing (RMAM) emissions.

Exhibit 25-7: Source Reduction Emission Factors for Tires ($MTCO_2e$/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
Tires	-4.28	-4.44	NA	NA	-4.28	-4.44

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

To calculate the avoided GHG emissions for tires, EPA looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and process non-energy GHG emissions. Exhibit 25-8 provides the estimates for each of these three categories for tires made from 100 percent virgin material. In WARM, the user also has the option of selecting source reduction based on the current mix of recycled and virgin material, as shown in Exhibit 25-9. EPA calculates the RMAM emission factors for the current mix of material inputs by weighting the emissions from manufacturing tires from 100 percent virgin material and the emissions from manufacturing tires from 100 percent recycled material by an assumed recycled content. More information on each component making up the final emission factor is provided in Exhibit 25-7. The source reduction emission factor for tires includes only emissions from RMAM, since no forest carbon sequestration is associated with tire manufacture.

Exhibit 25-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Tires ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy[a]	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Tires	4.40	0.04	–	4.44

– = Zero Emissions.
Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 25-6.

Exhibit 25-9: Recycled Content Values in Tire Manufacturing

Product/Material	Recycled Content Minimum (%)	Recycled Content for "Current Mix" in WARM (%)	Recycled Content Maximum (%)
Tires	0%	5%	5%

Data on energy used to manufacture a new passenger tire from Atech Group (2001), passenger tire weights from RMA (2009a), and data on fuel consumption from the Energy Information Administration's (EIA) *2006 Manufacturing Energy Consumption Survey* (EIA, 2009) were used to estimate avoided process energy. By using EIA (2009) data, EPA assumes that tire manufacturing uses the same mix of fossil fuels as does the entire synthetic rubber manufacturing industry as a whole. Exhibit 25-10 provides the process energy requirement and associated emissions for tires.

Exhibit 25-10: Process Energy GHG Emissions Calculations for Virgin Production of Tires

Product/Material	Process Energy per Ton Made from Virgin Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Tires	73.79	4.40

25.4.2 Recycling

WARM models tires as being recycled in an open loop into the following secondary materials: TDA for civil engineering applications and ground rubber (Exhibit 25-11). Eighty-three percent of the scrap tires recovered in 2007 for recycling were used as TDA in civil engineering applications or as ground rubber. Since these pathways account for the majority of recycling processes, the tire recycling emission factor is a weighted average of the life-cycle emissions from ground rubber and TDA end uses. For more information on recycling in general, please see the Recycling chapter.

Exhibit 25-11: Fate of Recycled Tires

Recycled Tire Material	Virgin Product Equivalent	% Composition of Modeled Market
TDA for Civil Engineering Applications	Sand	42%
Ground Rubber	Synthetic Rubber	58%

Preparing tires for these secondary end uses requires shredding the tires and removing any metal components. Further grinding of scrap tire is accomplished through ambient grinding or cryogenic grinding. Ambient grinding, the simplest grinding process, involves using machinery to size the crumb rubber particles. In cryogenic grinding, shredded rubber chips are frozen using liquid nitrogen and ground in a series of milling devices. Freezing causes the rubber to become brittle, which allows it to break down more easily and aids in the creation of smaller-sized particles (Nevada Automotive Test Center, 2004, p. 11; Praxair, 2009). For this analysis, we assume that tires will be converted into ground rubber by ambient grinding because, according to Corti and Lombardi (2004), the ambient grinding process is used to prepare tires for combustion, the largest waste management option used for tires.

The recycled input credits shown in Exhibit 25-12 include all of the GHG emissions associated with collecting, transporting, processing and manufacturing tires into secondary materials, and recovering steel for reuse. None of the upstream GHG emissions from manufacturing the tire in the first place are included; instead, WARM calculates a "recycled input credit" by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of secondary materials from virgin inputs. Consequently, GHG emissions associated with management (i.e., collection, transportation and processing) of scrap tires are included in the recycling credit calculation. Because tires do not contain any wood products, there are no recycling benefits associated with forest carbon sequestration. The GHG benefits from the recycled input credits are discussed further in the next section.

Exhibit 25-12: Recycling Emission Factor for Tires (MTCO$_2$e/Short Ton)

Material/ Product	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)
Tires	–	–	-0.46	0.07	–	–	-0.39

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

25.4.2.1 Developing the Emission Factor for Recycling of Tires

EPA calculates the GHG benefits of recycling tires by calculating the difference between the emissions associated with manufacturing a short ton of each of the secondary products from recycled tires and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. These results are then weighted by their percent contribution to tire recycling to obtain a composite emission factor for recycling one short ton of tires. This recycled input credit is composed of GHG emissions from process energy and transportation energy. EPA does not model any non-energy process emissions for the virgin or recycled production of tires.

Civil engineering applications for scrap tires offset the use of soil or sand, so a recycling credit for this end use can be applied using the difference between extracting and processing sand and creating TDA. Ground rubber applications for scrap tires offset the use of virgin rubber, so a recycling credit for this end use can be applied using the difference between creating ground rubber from synthetic rubber and creating ground tire rubber. Additionally, a recovered steel credit is estimated based on the process energy recycling credit for steel cans (see the Metals chapter for details) and the amount of steel recovered through ambient grinding of tires.

To calculate each component of the recycling emission factor, EPA follows six steps:

Step 1. *Calculate emissions from virgin production of secondary products.* Data on sand from the Athena Institute (Venta and Nesbit, 2000) report, "Life Cycle Analysis of Residential Roofing Products," are used to estimate the GHG emissions associated with sand extraction and processing, which is the virgin alternative to TDA. Because sand is generally produced locally, EPA assumes that its haul distance is approximately 20 miles by truck with no back haul. This information on transportation energy is included in the Athena Institute (Venta and Nesbit, 2000) data. There are no process non-energy emissions from extracting and processing sand for civil engineering applications.

EPA uses data from the International Rubber Research and Development Board, as found in Pimentel et al. (2002), along with EIA (2009) fuel consumption percentages for the synthetic rubber industry, to estimate the GHG emissions associated with synthetic rubber production. Pimentel et al. (2002) include process energy and transportation energy for synthetic rubber manufacture, so no transportation-specific emissions are estimated for synthetic rubber. EPA also assumes that there are no process non-energy emissions from manufacturing synthetic rubber.

The calculations for virgin process and transportation for secondary products are presented in Exhibit 25-13. Note that each product's energy requirements were weighted by their contribution to the recycled tire market modeled in WARM. Also, the transportation energy and emissions are included in the process energy data.

Exhibit 25-13: Process and Transportation Energy GHG Emissions Calculations for Virgin Production of Tire Secondary Products

Material/Product	Process and Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Sand	2.13	0.19
Synthetic Rubber	9.91	0.81
Weighted Sum of Virgin Secondary Materials	**6.67**	**0.55**

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 25-6.

Step 2. *Calculate GHG emissions for recycled production of one short ton of the secondary product.* The recycled secondary product emission factor is based on life-cycle inventory data for the ambient grinding. TDA pieces are on average 2–12 inches, so EPA uses energy data from Corti and Lombardi (2004) on grinding tires to aggregate greater than 16mm in size for the TDA process energy. For ground rubber produced from scrap tires, we use LCI data on the mechanical grinding of scrap tires to less than 2mm in diameter from Corti and Lombardi (2004).

Personal communication with Michael Blumenthal at the Rubber Manufacturers' Association (Blumenthal, 2010) reveals that scrap tires are transported by truck in batches of 1,000–1,200 tires to facilities no greater than 200 miles away to be shredded and ground. To develop this portion of the emission factor, we assume an average of 1,100 tires constituting a batch that is then transported 200 miles by a diesel truck to be shredded or ground. Exhibit 25-14 and Exhibit 25-15 present the results for process-related energy emissions for recycled products and transportation energy emissions, respectively. Again, EPA assumes there are no process non-energy emissions associated with manufacturing.

Exhibit 25-14: Process Energy GHG Emissions Calculations for Recycled Production of Tire Secondary Products

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
TDA	0.47	0.02
Ground Rubber	3.08	0.16
Weighted Sum of Recycled Secondary Materials	**1.99**	**0.11**

Exhibit 25-15: Transportation Energy GHG Emissions Calculations for Recycled Production of Tired Secondary Products

Material/Product	Transportation Energy per Short Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton Product)
TDA	0.75	0.06
Ground Rubber	0.75	0.06
Weighted Sum of Recycled Secondary Materials	**0.75**	**0.06**

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 25-6.

Step 3. *Calculate the difference in emissions between virgin and recycled production.* EPA then subtracts the recycled product emissions (Step 2) from the virgin product emissions (Step 1) to get the GHG savings. These results are shown in Exhibit 25-16.

Exhibit 25-16: Differences in Emissions between Recycled and Virgin Tire Manufacture (MTCO$_2$e/Short Ton)

Material/ Product	Product Manufacture Using 100% Virgin Inputs (MTCO$_2$e/Short Ton)			Product Manufacture Using 100% Recycled Inputs (MTCO$_2$e/Short Ton)			Difference Between 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
Tires	4.40	0.04	–	0.11	0.09	–	-4.29	0.05	–

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.* Corti and Lombardi (2004) report nearly 90 percent recovery of rubber and steel during ambient grinding, while industry assumes 80 percent recovery in the United States (Blumenthal 2010). To adjust the European data reported by Corti and Lombardi to account for differing practices in the United States, EPA scales down the amount of rubber and steel recovered so that the recovery rate for each is 80 percent. The resulting weighted process energy, transportation energy, process non-energy and total emission factors are presented in Exhibit 25-17.

Exhibit 25-17: Tires Recycling Emission Factors Adjusted for Recycling Losses (MTCO$_2$e/Short Ton)

Material/Product	Recycled Input Credit for Recycling One Short Ton of Tires			
	Weighted Process Energy	Weighted Transport Energy	Weighted Process Non-Energy	Total
Tires	-0.36	0.07	–	-0.29

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

Step 5. *Factor in the GHG emission credit from steel recovery.* EPA assumes that 80 percent of the total steel available in scrap tires is recovered at the end of life and is recycled into steel sheet. As a result, an additional recycling input credit from steel recovery is added to the tires recycling process energy emission factor. The recycling input credit for process energy from recycling steel, found in the Metals chapter, is weighted by the relative amount of steel recovered from recycling tires. Exhibit 25-18 shows how the steel recovery credit is calculated and Exhibit 25-19 provides the final calculated recycling emission factor for tires by adding that credit to the tires process energy credit.

Exhibit 25-18: Steel Recovery Emission Factor Calculation (MTCO$_2$e/Short Ton)

Material/Product	Amount of Steel Recovered (MT/Short Ton Product)	Avoided CO$_2$ Emissions per Ton of Steel Recovered (MTCO$_2$e/Short Ton)	Steel Recovery Emissions (MTCO$_2$e/Short Ton Product)
Tires	0.06	1.80	0.10

Exhibit 25-19: Final Tires Recycling Emission Factors (MTCO$_2$e/Short Ton)

Material/Product	Recycled Input Credit for Recycling One Short Ton of Tires			
	Process Energy	Transport Energy	Process Non-Energy	Total
Tires	-0.46	0.07	–	-0.39

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

25.4.3 Composting

Because tires 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.

25.4.4 Combustion

Scrap tires used as fuel made up about 60 percent of the entire scrap tire market in 2007 (RMA, 2009b). About 84 percent of those tires went to pulp and paper mills, cement kilns and utility boilers. WARM models the combustion of tires based on these three facility types. Exhibit 25-20 provides the assumed percent of scrap tires used as fuel that go to each type of facility.

Exhibit 25-20: Percent of Scrap Tires Used as Fuel at the Three Modeled Facility Types

Facility	Share Used as Fuel
Pulp and Paper Mills	51%
Cement Kilns	32%
Utility Boilers	17%

GHG emissions from combusting tires result from the combustion process as well as from indirect emissions from transporting tires to the combustor. Combustion also produces energy that can be recovered to offset electricity and GHG emissions that would have otherwise been produced from non-baseload power plants feeding into the national electricity grid. Finally, many of the facilities where tires are used as fuel recycle steel that is left after combustion, which offsets the production of steel from other virgin and recycled inputs. All of these components make up the combustion factor calculated for tires.

For further information on combustion, see the Combustion chapter. Because WARM's analysis begins with materials at end of life, emissions from RMAM are zero. Exhibit 25-21 shows the components of the emission factor for combustion of tires. Further discussion on the development of each piece of the emission factor is discussed below.

Exhibit 25-21: Components of the Combustion Net Emission Factor for Tires ($MTCO_2e$/Short Ton)

Material/ Product	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)
Tires	–	0.03	2.20	–	-1.57	-0.13	0.52

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

25.4.4.1 Developing the Emission Factor for Combustion of Tires

EPA calculates CO_2 emissions from combusting tires based on the energy content of tires from CIWMB (1992) and the estimated tire carbon coefficient from Atech Group (2001).

Exhibit 25-22: Tires CO_2 Combustion Emission Factor Calculation

Material/Product	Energy Content (Million Btu/Short Ton Product)	$MTCO_2e$ from Combustion per Million Btu	Combustion CO_2 Emissions ($MTCO_2e$/Short Ton Product)
Tires	27.78	0.08	2.20

EPA estimates CO_2 emissions from transporting tires to pulp and paper mills, cement kilns and utility boilers assuming that the distance the tires need to travel is similar to the distance involved in transporting MSW to waste-to-energy facilities, using data provided by FAL (1994).

Most power plants use fossil fuels to produce electricity, and the electricity produced at the various facilities where tires are used as fuel reduces the demand for conventional, fossil-derived electricity. As a result, the combustion emission factor for tires includes avoided GHG emissions from facilities that would otherwise be using conventional electricity. We calculate the avoided facility CO_2 emissions from electricity production based on (1) the energy content of tires and (2) the carbon-intensity of default (offset) fuel mix at each facility. These avoided GHG emissions are weighted based on the percent of scrap tires used for combustion across three types of facilities (Exhibit 25-20). Exhibit 25-23 shows the electricity offset from combustion of tires.

Exhibit 25-23: Utility GHG Emissions Offset from Combustion of Tires

(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)
Tires	27.8	NA	NA	1.57

NA = Not applicable.

The combustion of tires at pulp and paper mills and utility boilers also includes steel recovery and recycling processes. Recovered steel from cement kilns is used to replace iron used in the cement-making process, so there is no steel recovery credit for scrap tire use at cement kilns. The recycling credit is therefore weighted for two of the three facilities modeled. Since some steel in tires is lost during combustion, we multiplied the percent of tires that is steel (Exhibit 25-5) by a ferrous recovery factor of 98 percent.

Exhibit 25-24: Steel Production GHG Emissions Offset from Steel Recovered from Combustion of Tires

Material/Product	Short Tons of Steel Recovered per Short Ton of Waste Combusted	Avoided CO_2 Emissions per Ton of Steel Recovered ($MTCO_2e$/Short Ton)	Avoided CO_2 Emissions per Ton of Waste Combusted ($MTCO_2e$/Short Ton)
Tires	0.06	1.80	0.10

25.4.5 Landfilling

In WARM, landfill emissions comprise landfill CH_4 and CO_2 from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since tires do not contain biogenic carbon and do not decompose in landfills, there are zero emissions from landfill CH_4, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling tires, as shown in Exhibit 25-25. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling tires represents only the emissions associated with collecting the waste and operating the landfill equipment.

Exhibit 25-25: Landfilling Emission Factor for Tires ($MTCO_2e$/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)
Tires	–	0.04	–	–	–	0.04

– = Zero emissions.
NA = Not applicable.

For more information, refer to the Landfilling chapter.

25.5 Limitations

There are several limitations to this analysis, which is based on several assumptions from expert judgment. The limitations associated with the source reduction emission factor include:

- Scrap tire percent composition by material may not be accurate. EPA uses two data sources for estimating the percent fiber and percent steel content of scrap tires. Upon expert review, Blumenthal (2010) notes that today there is less fiber in tires than estimated by NIST (1997). The percent steel content is believed to be accurate, but because of the possibly high fiber content, the percent rubber by weight may be underestimated. Simultaneously, Blumenthal (2010) reports that tires produced recently may contain non-negligible amounts of silica, whereas the data used here assume that any silica content is negligible. If this is the case, the amount of rubber may be overestimated, so it is also possible that the changing trends in fiber and silica content effectively cancel each other out.

- This analysis assumes that the fuel mix used to manufacture tires is the same as the one used to manufacture synthetic rubber. If tire manufacturers use a different fuel mix, the resulting difference in carbon-intensity would influence the carbon emissions produced by manufacturing tires from virgin materials.

- Upon expert review, Blumenthal (2010) reported that the amount of energy required to produce a tire is outdated and that the tire manufacturing process has changed considerably since 2001, the year of the data that WARM relies on for the process energy requirements. The difference in the energy requirements for tire manufacture today would change the associated process energy emissions for source reduction; however, EPA has been unable to find more recent, publicly available data to update the analysis.

There are also some limitations to the recycling emission factor, including:

- By using European process data from Corti and Lombardi (2004), EPA assumes that tire recycling processes in the United States and Europe are similar. This may or may not be the case.

- The assumption that, when scaling down the amount of steel and rubber recovered during the recycling process from Corti and Lombardi (2004) based on an industry estimate of 80 percent recovery of scrap tires (Blumenthal, 2010), the 80 percent recovery is applicable to both steel and rubber. In actuality the *average* recovery between the two materials may be 80 percent. Any difference in the amount of rubber or steel recoverable during recycling would change the recycling input credits for process energy and steel recovery, respectively.

25.6 References

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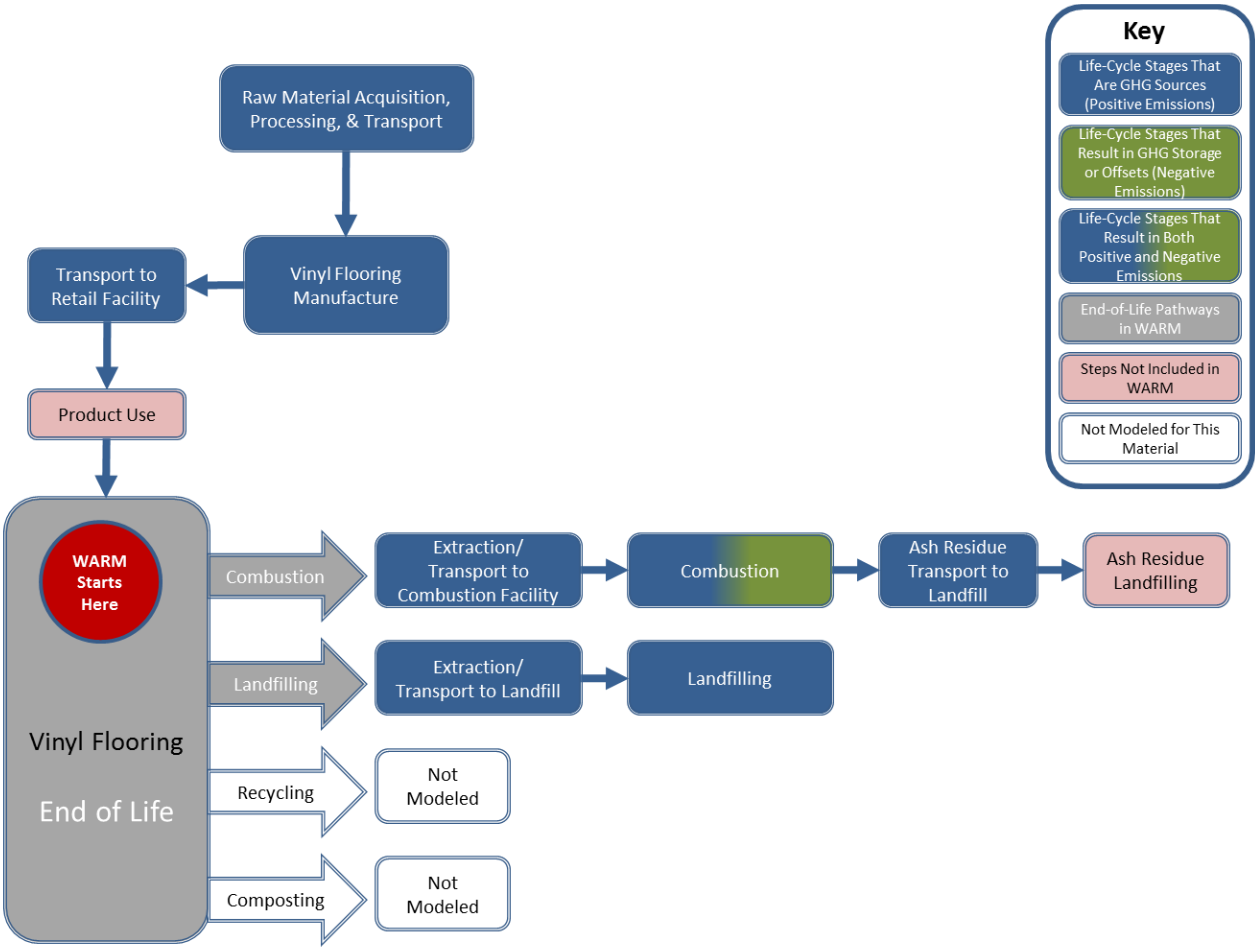
26 VINYL FLOORING

26.1 Introduction to WARM and Vinyl Flooring

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for vinyl flooring beginning at the waste generation reference point.[141] EPA uses the WARM GHG emission factors to compare the net emissions associated with vinyl flooring in the following three waste management alternatives: source reduction, combustion, and landfilling. Exhibit 26-1 shows the general outline of materials management pathways for vinyl flooring in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Combustion, and Landfilling, see the chapters devoted to those processes.

Exhibit 26-1: Life Cycle of Vinyl Flooring in WARM



Two major types of vinyl flooring, (1) sheet flooring and (2) tile, have applications in commercial and residential buildings. Vinyl composition tile (VCT) is the industry standard for most commercial applications because it is durable, resilient, and relatively low cost. Sheet flooring is more commonly used in residential applications, such as kitchens and bathrooms, and generally it contains a higher percentage of vinyl resins, causing it to be more expensive.

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

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

26.2 Life-Cycle Assessment and Emission Factor Results

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

WARM considers emission factors only for source reduction, combustion, and landfilling for vinyl flooring. As Exhibit 26-2 illustrates, all of the GHG sources and sinks relevant to vinyl flooring in this analysis are contained in the raw materials acquisition and manufacturing (RMAM) and materials management sections of the life-cycle assessment.

Exhibit 26-2: Vinyl Flooring GHG Sources and Sinks from Relevant Materials Management Pathways

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

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 26-2 and calculates net GHG emissions per short ton of vinyl flooring inputs. For more detailed methodology on emission factors, see Sections 26.4.2 – 26.4.5. Exhibit 26-3 outlines the net GHG emissions for vinyl flooring under each materials management option.

Exhibit 26-3: Net Emissions for Vinyl Flooring under Each Materials Management Option ($MTCO_2e$/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Vinyl Flooring	-0.61	NA	NA	-0.30	0.04

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

26.3 Raw Materials Acquisition and Manufacturing

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

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

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

The RMAM calculation in WARM also incorporates retail transportation, which includes emissions for the average truck, rail, water, and other modes required to transport vinyl flooring from the manufacturing facility to the retail/distribution point, which may be the customer or various other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation appear in Exhibit 26-4. Transportation emissions from the retail point to the consumer are not included. EPA obtained the miles-travelled fuel-specific information from the 2007 U.S. Census Commodity Flow Survey (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 26-4: Retail Transportation Energy Use and GHG Emissions

Material/Product	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions ($MTCO_2e$ per Short Ton of Product)
Vinyl Flooring	497	0.58	0.04

26.4 Materials Management Methodolgies

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

26.4.1 Source Reduction

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

Exhibit 26-5 outlines the GHG emission factor for source reducing vinyl flooring. EPA calculates the GHG benefits of source reduction as the emissions savings from avoided raw materials acquisition and manufacturing (see Section 26.3) of vinyl flooring produced from 100-percent virgin inputs. EPA assumes the current mix is 100-percent virgin inputs because very little vinyl flooring is produced from recycled inputs.

Exhibit 26-5: Source Reduction Emission Factors for Vinyl Flooring ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Vinyl Flooring	-0.61	-0.61	NA	NA	-0.61	-0.61

– = Zero emissions.

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

26.4.1.1 Developing the Emission Factor for Source Reduction of Vinyl Flooring

To calculate the avoided GHG emissions for vinyl flooring, EPA first looked at three components of GHG emissions from RMAM activities: (1) process energy, (2) transportation energy, and (3) non-energy GHG emissions. Exhibit 26-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor follows.

Exhibit 26-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Vinyl Flooring ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Vinyl Flooring	0.52	0.08	0.01	0.61

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

Finally, EPA gathered manufacturing data for vinyl acetate and styrene-butadiene adhesive from ecoinvent version 2.1 (ecoinvent Centre, 2008). The data for vinyl acetate manufacturing represents the European average at the plant, while data for adhesive manufacturing represents styrene-butadiene dispersion for latex at the plant. Both of these life-cycle datasets include infrastructure (i.e., energy and GHG emissions associated with producing the capital equipment used to make the products), which is not included in WARM's life-cycle boundaries. Because energy and GHG emissions associated with infrastructure are typically small, and the vinyl acetate and adhesive GHG emissions contribute to 1 percent and 10 percent of the total process energy respectively, we concluded that the additional inputs associated with infrastructure are likely small.

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

EPA then multiplied the amount of energy required to acquire and produce one short ton of vinyl flooring, broken down by fuel mix, by the fuel-specific carbon content. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions, including both carbon dioxide (CO_2) and methane (CH_4), from all fuel types used in vinyl flooring production. The process energy used to produce vinyl flooring and the resulting emissions appear in Exhibit 26-7.

Exhibit 26-7: Process Energy GHG Emissions Calculations for Virgin Production of Vinyl Flooring

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Vinyl Flooring	9.58	0.52

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

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

The calculations for estimating the transportation energy emission factor for vinyl flooring appear in Exhibit 26-8.

Exhibit 26-8: Transportation Energy Emissions Calculations for Virgin Production of Vinyl Flooring

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Vinyl Flooring	0.65	0.05

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 26-4.

Process non-energy GHG emissions occur during manufacturing, but they are not related to consuming fuel for energy. Petrochemical processes generate process non-energy emissions in the production of PVC for vinyl flooring. To estimate these emissions, we applied non-energy process GHG emission factors for ethylene and ethylene dichloride and vinyl chloride monomer developed by the Intergovernmental Panel on Climate Change (IPCC) (2006, p. 3.74, 3.77). Exhibit 26-9 shows the components for estimating process non-energy GHG emissions for vinyl flooring.

Exhibit 26-9: Process Non-Energy Emissions Calculations for Virgin Production of Vinyl Flooring

Material/Product	**CO_2 Emissions (MT/Short Ton)**	**CH_4 Emissions (MT/Short Ton)**	**CF_4 Emissions (MT/Short Ton)**	**C_2F_6 Emissions (MT/Short Ton)**	**N_2O Emissions (MT/Short Ton)**	**Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)**
Vinyl Flooring	0.00	0.00	–	–	–	0.01

– = Zero emissions.

26.4.2 Recycling

Use of post-consumer recycled PVC is possible, but the number of different VCT manufacturers and an inconsistent supply of post-consumer vinyl material make it difficult to develop a representative estimate. Lippiatt (2007, p. 167) assumes a conservative composition of 1 percent post-consumer recycled PVC. According to Helm (2009), vinyl manufacturers use post-consumer recycled content in the bottom layer of their vinyl products, where less purity is required. Numerous manufacturers, including Mannington, Centiva, and Toli, currently use post-consumer recycled PVC on the back of their products, although the PVC is generally sourced from other PVC products other than discarded vinyl flooring. Because the data available is insufficient, EPA does not include an emission factor in WARM for vinyl flooring recycling.

26.4.3 Composting

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

26.4.4 Combustion

Although vinyl flooring is not typically combusted in the United States, combustion is a common end-of-life pathway for vinyl flooring in other countries, specifically in Europe. Franklin Associates (2007) provides energy content of PVC resin. The combustion emission factor for vinyl flooring is summarized in Exhibit 26-10. For more information on combustion, please see the chapter on Combustion.

Exhibit 26-10: Components of the Combustion Net Emission Factor for Vinyl Flooring ($MTCO_2e$/Short Ton)

Material/Product	**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)**
Vinyl Flooring	–	0.03	0.28	0.00	-0.61	–	-0.30

– = Zero emissions.

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

26.4.4.1 Developing the Emission Factor for Combustion of Vinyl Flooring

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

Transportation to Combustion: EPA estimated GHG emissions from transportation energy use using data from FAL (1994).

CO_2 from Combustion and N_2O from Combustion: Vinyl flooring contains no nitrogen, and therefore, EPA estimates the emission factor for N_2O from combustion[142] to equal zero. EPA calculated CO_2 emissions from combustion based on the carbon contents of the PVC, vinyl acetate, and plasticizer components of vinyl flooring (38-, 49-, and 74-percent carbon, respectively).

Avoided Utility Emissions: Most Waste-to-Energy (WTE) plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with municipal solid waste (MSW) combustion would be in the form of electricity, and thus, we estimated the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant. Avoided utility emissions for vinyl flooring are negative. Exhibit 26-11 shows the calculation for the avoided utility emissions. EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in vinyl flooring to delivered electricity,[143] and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.[144] EPA took the energy content of PVC from FAL (2007, p. 1–12).

Exhibit 26-11: Utility GHG Emissions Offset from Combustion of Vinyl Flooring

(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)
Vinyl Flooring	15.8	17.8%	0.22	0.61

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

26.4.5 Landfilling

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

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

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

[144] 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.

included in WARM's landfilling emission factors. As a result, the landfilling emission factor for vinyl flooring is equal to the GHG emissions generated by transportation to the landfill and operating the landfill equipment. The landfilling emission factor for vinyl flooring appears in Exhibit 26-12. For more information on landfilling, see the chapter on Landfilling.

Exhibit 26-12: Landfilling Emission Factor for Vinyl Flooring ($MTCO_2e$/Short Ton)

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

– = Zero emissions.

26.5 Limitations

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

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

26.6 References

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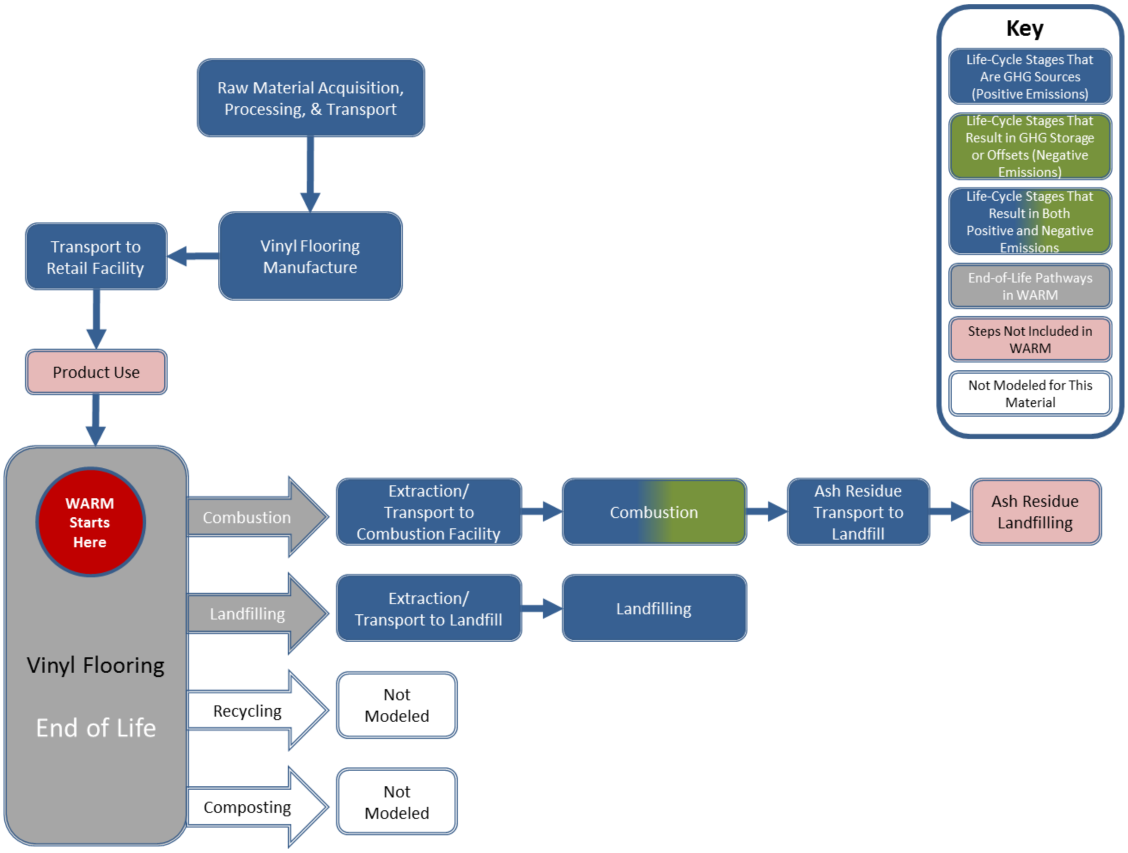
27 WOOD FLOORING

27.1 Introduction to WARM and Wood Flooring

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for wood flooring beginning at the waste generation reference point.[145] The WARM GHG emission factors are used to compare the net emissions associated with wood flooring in the following three waste management alternatives: source reduction, combustion, and landfilling. Exhibit 27-1 shows the general outline of materials management pathways for wood flooring in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Combustion, and Landfilling, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 27-1: Life Cycle of Wood Flooring in WARM



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

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

27.2 Lifecycle Assessment and Emission Factor Results

The streamlined[146] life-cycle boundaries in WARM start at the point of waste generation, or the moment a material is discarded, as the reference point and only considers upstream GHG emissions when the production of new materials is affected by material management decisions. Recycling and Source Reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM considers emission factors for source reduction, combustion, and landfilling for wood flooring. As Exhibit 27-2 illustrates, the GHG sources and sinks relevant to wood flooring in this analysis are spread across all three sections of the life-cycle assessment: raw materials acquisition and manufacturing (RMAM), changes in forest or soil carbon storage, and materials management.

Exhibit 27-2: Wood Flooring GHG Sources and Sinks from Relevant Materials Management Pathways

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

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[146] 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.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 27-2 and calculates net GHG emissions per short ton of wood flooring inputs. For more detailed methodology on emission factors, please see the sections below on individual waste management strategies. Exhibit 27-3 below outlines the net GHG emissions for wood flooring under each materials management option.

Exhibit 27-3: Net Emissions for Wood Flooring under Each Materials Management Option (MTCO$_2$e/Short Ton)

Material/Product	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Wood Flooring	-4.05	NE	-0.18	-0.76	-0.83

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

27.3 Raw Materials Acquisition and Manufacturing

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport raw materials, and (3) non-energy GHG emissions resulting from manufacturing processes.[147] For virgin hardwood flooring, process energy GHG emissions result from wood harvesting, lumber production, planing, ripping, trimming, and molding. Transportation emissions are generated from transportation associated with wood harvesting, on-site transportation during lumber production and flooring manufacture, and transportation to the retail facility. EPA assumes that non-energy process GHG emissions from making wood flooring are negligible for two reasons. First, we were unable to locate data on the emissions associated with any sealants or other chemicals applied to wood flooring. Second, of the other processes that were modeled, the available data did not indicate that process non-energy emissions resulted.

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

The RMAM calculation in WARM also incorporates "retail transportation", which includes the average truck, rail, water, and other-modes transportation emissions required to transport wood flooring from the manufacturing facility to the retail/distribution point, which may be the customer or a variety of other establishments (e.g., warehouse, distribution center, wholesale outlet). The energy and GHG emissions from retail transportation are presented in Exhibit 27-4. Transportation emissions from the retail point to the consumer are not included. The miles travelled fuel-specific information is obtained from the *2007 U.S. Census Commodity Flow Survey* (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

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

Exhibit 27-4: Retail Transportation Energy Use and GHG Emissions

Material/Product	Average Miles per Shipment	Retail Transportation Energy (Million Btu per Short Ton of Product)	Retail Transportation Emissions (MTCO₂e per Short Ton of Product)
Wood Flooring	293	0.34	0.02

27.4 Materials Management Methodologies

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

27.4.1 Source Reduction

When a material is source reduced, GHG emissions associated with making the material and managing the postconsumer waste are avoided. As discussed previously, under the measurement convention used in this analysis, the benefits of source reducing wood flooring come primarily from forest carbon sequestration, but additional savings also come from avoided emissions from the lumber harvesting process, production processes, and transportation. Since wood flooring is rarely manufactured from recycled inputs, the avoided emissions from source reducing wood flooring using the "current mix of inputs" is assumed to be the same as from using 100 percent virgin inputs. The avoided emissions are summarized in Exhibit 27-5. For more information about source reduction please refer to the chapter on Source Reduction.

Exhibit 27-5: Source Reduction Emission Factors for Wood Flooring (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
Wood Flooring	-0.39	-0.39	-3.66	-3.66	-4.05	-4.05

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

27.4.1.1 Developing the Emission Factor for Source Reduction of Wood Flooring

To calculate the avoided GHG emissions associated with source reduction of wood flooring, EPA first looks at three components of GHG emissions from RMAM activities: process energy, transportation energy, and non-energy GHG emissions. There are no non-energy process GHG emissions from wood flooring RMAM activities. Exhibit 27-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 27-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Wood Flooring (MTCO₂e/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Wood Flooring	0.29	0.10	–	0.39

– = Zero emissions.

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

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

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

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

The estimates in Venta and Nesbit (2000), Bergman and Bowe (2008), and Hubbard and Bowe (2008) do not include the precombustion energy of the fuels. EPA added precombustion values based on precombustion estimates by fuel types in Franklin Associates (FAL, 2007). The process energy used to produce wood flooring and the resulting emissions are shown in Exhibit 27-7.

Exhibit 27-7: Process Energy GHG Emissions Calculations for Virgin Production of Wood Flooring

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions (MTCO$_2$e/Short Ton)
Wood Flooring	13.13	0.29

Each of the three sources noted above contain transportation data for the various transportation steps required to produce wood flooring. Venta and Nesbit (2000) include data on transportation from the point of harvest to the sawmill. This source assumes a transportation distance of 350 kilometers by diesel-fueled truck. Bergman and Bowe (2008) include on-site transportation at the sawmill, which assumes consumption of off-road diesel, propane, and gasoline. Hubbard and Bowe (2008) include data on transportation from the sawmill to the flooring mills as well as on-site transportation at the flooring mill. This source assumes diesel-fueled trucks provide transportation to the flooring mill; on-site flooring mill transportation assumes consumption of off-road diesel, propane, and gasoline. The transportation energy used to produce wood flooring and the resulting emissions are shown in Exhibit 27-8.

Exhibit 27-8: Transportation Energy Emissions Calculations for Virgin Production of Wood Flooring

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Wood Flooring	1.08	0.08

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 27-4.

27.4.1.2 Forest Carbon Storage

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

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

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

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

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

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

The results of the analysis are shown below in Exhibit 27-9 and Exhibit 27-10. The increase in non-soil forest carbon storage from source reducing flooring begins at 5.03 $MTCO_2e$ per short ton of hardwood flooring in 2030, and declines through 2050, although the rate of decline moderates over this time period. Carbon storage in products decreases as a result of source reducing hardwood, and this effect also declines over time as a greater fraction of hardwood leaves the in-use product pool for end-of-life management.

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

Exhibit 27-9: Components of the Cumulative Net Change in Forest Carbon Storage from Source Reduction of Wood Flooring

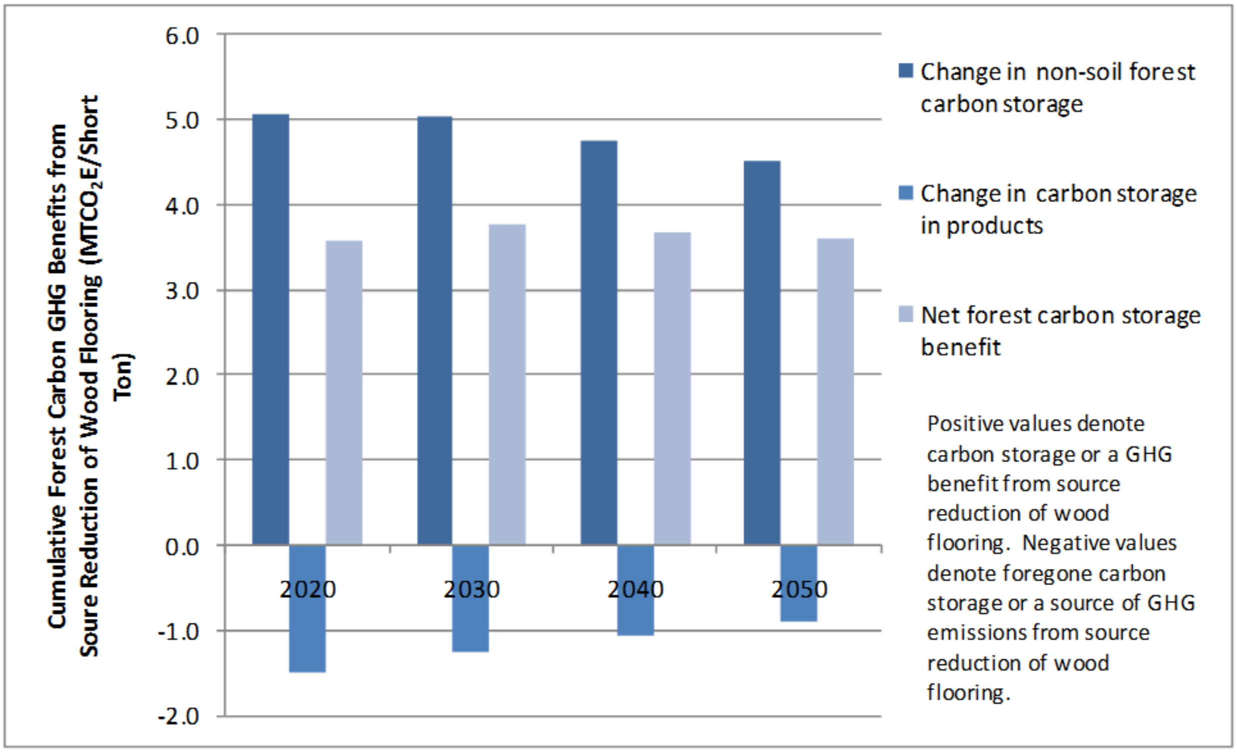

Exhibit 27-10: Forest Carbon Storage Calculations for Virgin Production of Wood Flooring ($MTCO_2e$/Short Ton)

Material/Product	Forest Carbon Released	Carbon Released from Wood Products	Net Carbon Released
Wood Flooring	-4.84	1.18	-3.66

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

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

27.4.2 Recycling

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

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

27.4.3 Composting

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

27.4.4 Combustion

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

To model the combustion of wood flooring, EPA uses wood grinding fuel consumption data from Levis (2008, p. 231). FAL (1994) provides data on the GHG emissions from transporting wood flooring to a waste-to-energy facility and transporting the ash residue to landfill, assuming diesel fuel consumption. We assume the energy content of wood flooring is 9,000 BTU per pound, or 18 million BTU per short ton (Bergman and Bowe, 2008, Table 3, p. 454).

To calculate avoided utility emissions from energy recovery, EPA assumes that wood flooring is combusted in a biomass power plant to produce electricity, with a heat rate of 15,850 BTU per kWh electricity output (ORNL, 2006, Table 3.11). EPA assumes that the energy supplied by wood flooring combustion offsets the national average mix of fossil fuel power plants, since these plants are most likely to respond to marginal changes in electricity demand. Exhibit 27-11 summarizes the combustion emission factor for wood flooring.

Exhibit 27-11: Components of the Combustion Net Emission Factor for Wood Flooring ($MTCO_2e$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Wood Flooring	–	0.05[a]	–	0.04	-0.85	–	-0.76

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

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

27.4.4.1 Developing the Emission Factor for Combustion of Wood Flooring

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 MTCE for one short ton of wood flooring (FAL, 1994).

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

Avoided Utility Emissions: Most waste-to-energy (WTE) plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, EPA assumed that the energy recovered with MSW combustion would be in the form of electricity, and thus estimated the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant (Exhibit 27-12).

Exhibit 27-12: Utility GHG Emissions Offset from Combustion of Wood Flooring

(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) ($e = b \times c \times d$)
Wood Flooring	18.0	21.5%	0.22	0.85

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

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

27.4.5 Landfilling

Landfill emissions in WARM include landfill methane and carbon dioxide from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. Wood flooring is an biodegradable material that results in some landfill methane emissions and carbon sequestration. Because C&D landfills generally do not have flaring systems, most of that methane is released to the atmosphere (Barlaz, 2009). In addition to these emissions, we assume the standard WARM landfilling emissions related to transportation and equipment use (EPA, 2006, p. 93). Several sources provide data on the moisture content, carbon storage factor, and methane yield of wood flooring (Levis et al., 2013; Wang et al., 2013; Wang et al., 2011). Due to lack of information about the decay conditions in C&D landfills, the landfilling emission factor assumes that the same conditions prevail as at municipal solid waste landfills, except that no collection of methane occurs. The methane and transportation emissions outweigh the carbon sequestration benefits, resulting in net emissions from the landfill, as illustrated in Exhibit 27-13. For more information on Landfilling, please see the chapter on Landfilling.

Exhibit 27-13: Landfilling Emission Factor for Wood Flooring (MTCO$_2$e/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH$_4$	Avoided CO$_2$ Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Wood Flooring	–	0.04	0.22	0.00	-1.09	-0.83

— = Zero emissions.

27.5 Limitations

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

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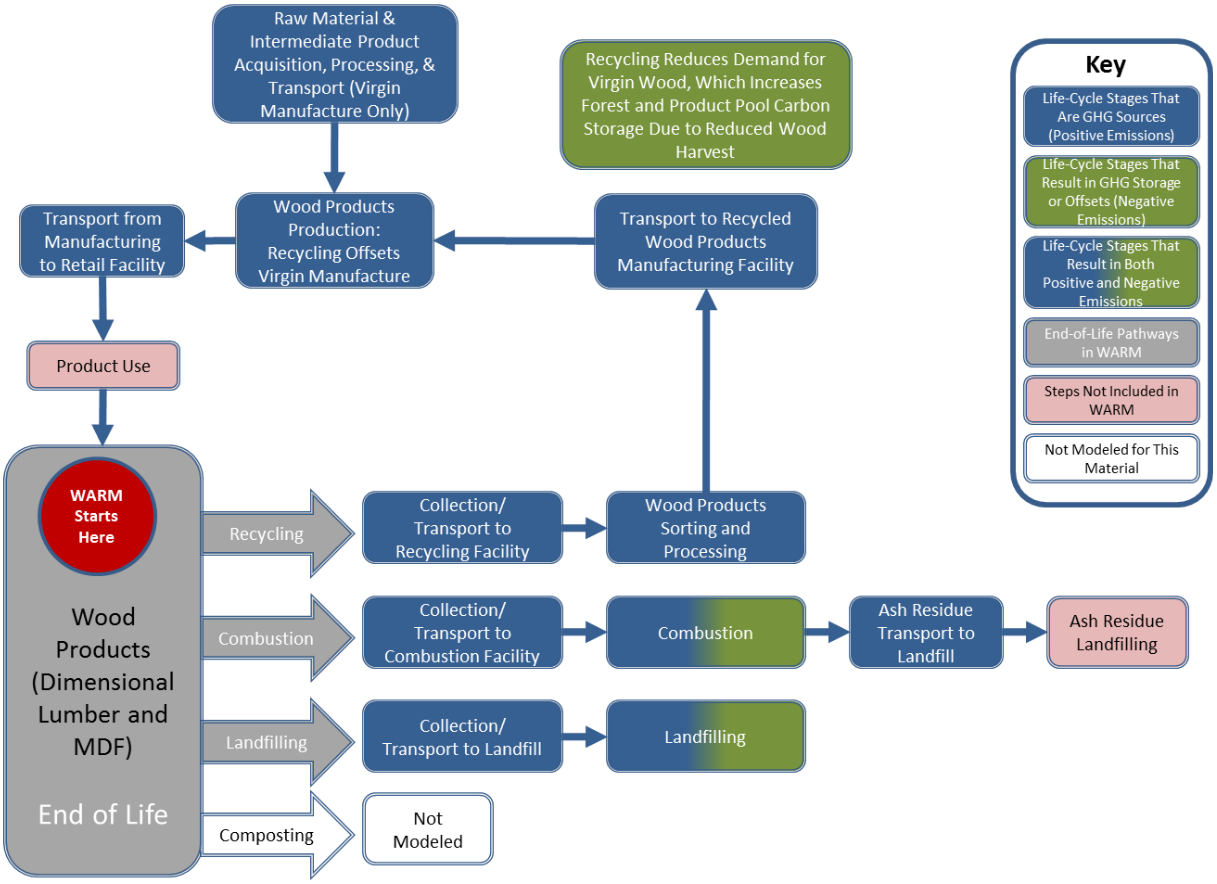
28 WOOD PRODUCTS

28.1 Introduction to WARM and Wood Products

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for wood products beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with wood products in the following four materials management alternatives: source reduction, recycling, landfilling, and combustion. Exhibit 28-1 shows the general outline of materials management pathways in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, Combustion, and Landfilling, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

Exhibit 28-1: Life Cycle of Wood Products in WARM



The category "wood products" in WARM comprises dimensional lumber and medium-density fiberboard (MDF). Dimensional lumber includes wood used for containers, packaging and buildings and includes crates, pallets, furniture and lumber such as two-by-fours (EPA, 2014b). Fiberboard, including MDF, is a panel product that consists of wood chips pressed and bonded with a resin and is used primarily to make furniture (EPA, 1995). At end of life, wood products can be recovered for recycling, sent to a landfill or combusted.

28.2 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.

Composting is not included as a materials management pathway due to a lack of information on the GHG implications of composting wood products.[148] Exhibit 28-2 illustrates the GHG sources and offsets that are relevant to wood products in this analysis.

Exhibit 28-2: Wood Products GHG Sources and Sinks from Relevant Materials Management Pathways

MSW Management Strategies for Wood Products	**GHG Sources and Sinks Relevant to Wood Products**		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**End of Life**
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Transport of wood products to point of sale	**Losses** • Decrease in carbon storage in products **Offsets** • Increase in forest carbon storage	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled process energy **Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Transport of wood products to point of sale	**Losses** • Decrease in carbon storage in products **Offsets** • Increase in forest carbon storage	**Emissions** • Collection of wood products and transportation to recycling center
Composting	Not Modeled in WARM		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related N_2O **Offsets** • Avoided utility emissions
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery **Offsets** • Carbon storage • Energy recovery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 28-2 and calculates net GHG emissions per short ton of inputs, shown in Exhibit 28-3 for the four materials management pathways.

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

For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

Exhibit 28-3: Net Emissions for Wood Products 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
Dimensional Lumber	-2.02	-2.46	NA	-0.58	-0.98
MDF	-2.23	-2.47	NA	-0.58	-0.86

NA = Not applicable.

28.3 Raw Materials Acquisition and Manufacturing

GHG emissions associated with raw materials acquisition and manufacturing (RMAM) from the manufacturing of wood 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.

Dimensional lumber is mechanically shaped to standard dimensions in sawmills. Sawmill operations vary widely, but typically full logs are transported by truck to the mill, where they are graded for different uses. Electrically powered saws are used to cut the logs into different lengths, widths and thicknesses. The cut boards are then stacked and placed in drying kilns. Waste wood from the process is used to generate process heat and, in some cases, electricity.[149] Once dry, the boards are planed to specific dimensions and a smooth finish before being shipped (NFI, 2010b).

In addition to serving as a source of energy for the lumber manufacturing process, waste wood is also used in the manufacture of structural panels, including MDF. The first step in manufacturing MDF is breaking down waste woodchips into their cellulosic fibers and resin. The fibers and resin are combined with wax or other binders and then subjected to high temperatures and pressure, requiring energy inputs that result in GHG emissions, to form the MDF (English et al., 1994; NFI, 2010a). Drying and heating the MDF components results in non-energy carbon dioxide (CO_2) and methane emissions (CH_4).

The RMAM calculation in WARM also incorporates "retail transportation," which includes the average emissions from truck, rail, water and other modes of transportation required to transport wood products from the manufacturing facility to the retail/distribution point, which may be the 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 28-4. Transportation emissions from the retail point to the consumer are not included in WARM. The miles travelled fuel-specific information is obtained from the 2012 *U.S. Census Commodity Flow Survey* (BTS, 2013) and *Greenhouse Gas Emissions from the Management of Selected Materials* (EPA, 1998).

Exhibit 28-4: 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)
Dimensional Lumber	246	0.29	0.02
MDF	675	0.79	0.05

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

28.4 Materials Management Methodologies

WARM models four materials management alternatives for wood products: source reduction, recycling, combustion, and landfilling. For source reduction, net emissions depend not only on the management practice but also on the recycled content of the wood products. While MDF can be made from a combination of virgin and post-consumer recycled materials, EPA has not located evidence that MDF is manufactured with recycled material in the United States. Dimensional lumber cannot be manufactured from recycled material. As a result, WARM assumes that wood products that are source reduced or recycled in the United States will offset 100% virgin inputs. Although all materials management options have negative emissions—driven primarily by carbon storage—as Exhibit 28-3 indicates, recycling wood products is the most beneficial.

28.4.1 Source Reduction

Source reduction activities reduce the quantity of dimensional lumber and MDF manufactured, reducing the associated GHG emissions. Recovering and reusing dimensional lumber or MDF from construction sites is one form of source reduction for these building materials. For more information on source reduction in general see the Source Reduction chapter.

Exhibit 28-5 provides the breakdown of the GHG emissions factors for source reducing wood products. GHG benefits of source reduction are calculated as the avoided emissions from RMAM of each product. The GHG emission sources and sinks from source reduction include:

- *Process energy, transportation and non-energy process GHG emissions.* Producing dimensional lumber and MDF results in GHG emissions from energy consumption in manufacturing processes and transportation, as well as non-energy related CO_2 emissions in the production of MDF.
- *Carbon storage.* Reducing the quantity of dimensional lumber and MDF manufactured results in increased forest carbon stocks from marginal changes in harvest rates, but also reduces the carbon stored in in-use wood products. For more information, see the Forest Carbon Storage chapter.

Exhibit 28-5: Source Reduction Emission Factors for Wood Products ($MTCO_2e$/Short Ton)

Material/Product	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Dimensional Lumber	-0.18	-0.18	-1.84	-1.84	-2.02	-2.02
MDF	-0.39	-0.39	-1.84	-1.84	-2.23	-2.23

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

28.4.1.1 Developing the Emission Factor for Source Reduction of Wood Products

To calculate the avoided GHG emissions for wood products, EPA first looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 28-6 shows the results for each component and the total GHG emission factors for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 28-6: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Wood Products ($MTCO_2e$/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
Dimensional Lumber	0.10	0.08	0.00	0.18
MDF	0.26	0.12	0.00	0.39

– = Zero emissions.

Exhibit 28-7, Exhibit 28-8, and Exhibit 28-9 provide the calculations for each source of RMAM emissions: process energy, transportation energy and non-energy processes. Data on the energy requirements for processing and transportation, and data on non-energy emissions from processing, are provided by FAL (1998). WARM includes energy and GHG emissions associated with retail transportation of wood products from the manufacturing plant to the point of sale based on transportation modes and distances provided by the U.S. Census Bureau's *Commodity Flow Survey* (BTS, 2013), and transportation energy requirements provided by EPA (1998).

Exhibit 28-7: Process Energy GHG Emissions Calculations for Virgin Production of Wood Products

Material/Product	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2e$/Short Ton)
Dimensional Lumber	2.53	0.10
MDF	10.18	0.26

Exhibit 28-8: Transportation Energy Emissions Calculations for Virgin Production of Wood Products

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2e$/Short Ton)
Dimensional Lumber	0.88	0.07
MDF	1.01	0.07

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 28-4.

Exhibit 28-9: Process Non-Energy Emissions Calculations for Virgin Production of Wood Products

Material/Product	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2e$/Short Ton)
Dimensional Lumber	–	–	–	–	–	–
MDF	0.00	0.00	–	–	–	0.00

– = Zero emissions.

In addition to RMAM emissions, forest carbon sequestration is factored into each wood product's total GHG emission factor for source reduction. Reducing the quantity of dimensional lumber and MDF manufactured increases forest carbon stocks from marginal changes in harvest rates, resulting in increased forest carbon storage. Conversely, source reduction also reduces the quantity of carbon stored in in-use wood products. Exhibit 28-10 provides the components of the overall forest carbon sequestration factor for wood products. For more information, see the Forest Carbon Storage chapter.

Exhibit 28-10: Net Change in Carbon Storage per Unit of Reduced Wood Product Production

(a) Material/ Product	(b) Reduction in Timber Harvest per Unit of Reduced Wood Product Production (Short Tons Timber/ Short Ton of Wood Recycled)	(c) Change in Forest C Storage per Unit of Reduced Timber Harvest (Metric Tons Forest C/ Metric Ton Timber)	(d) Change in C Storage in In-use Products per Unit of Increased Wood Product Recycling ($MTCO_2e$/Short Ton)	(e) Net Change in C Storage per Unit of Reduced Wood Product Production ($MTCO_2e$/Short Ton) (e = b × c × 0.907 + d)
Wood Products	1.10	0.99	-1.77	1.84

Note: Positive values denote an *increase* in carbon storage; negative values denote a *decrease* in carbon storage.
One metric ton = 0.907 short tons.

28.4.2 Recycling

In theory, dimensional lumber and MDF can be recycled in a closed-loop process (i.e., back into dimensional lumber and MDF). While EPA does not believe this is commonly practiced in the United States, WARM nevertheless models emission factors for closed-loop recycling for both dimensional lumber and MDF. The upstream GHG emissions from manufacturing the wood products are included as a “recycled input credit” by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the wood products from virgin inputs. Consequently, GHG emissions associated with management (i.e., collection, transportation and processing) of waste wood products are included in the recycling credit calculation. In addition, there are forest carbon benefits associated with recycling. Each component of the recycling emission factor as provided in Exhibit 28-11 is discussed further in Section 4.2.1. For more information on recycling in general, see the Recycling chapter.

Exhibit 28-11: Recycling Emission Factor for Wood Products ($MTCO_2e$/Short Ton)

Material/Product	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)
Dimensional Lumber	–	–	0.07	0.01	–	-2.53	-2.46
MDF	–	–	0.05	0.02	–	-2.53	-2.47

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.

28.4.2.1 Developing the Emission Factor for Recycling of Wood Products

EPA calculates the GHG benefits of recycling wood products by taking the difference between producing wood products from virgin inputs and producing wood products from recycled inputs, after accounting for losses that occur during the recycling process. This difference is called the “recycled input credit” and represents the net change in GHG emissions from process and transportation energy sources in recycling wood products relative to virgin production of wood products. The data sources consulted indicated no process non-energy emissions from recycling of wood products.

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 wood products.* The GHG emissions from virgin production of wood products are provided in Exhibit 28-7, Exhibit 28-8, and Exhibit 28-9.

Step 2. *Calculate GHG emissions for recycled production of wood products.* Exhibit 28-12 and Exhibit 28-13 provide the process and transportation energy emissions associated with producing recycled wood products. Data on these energy requirements and the associated emissions are from FAL (1998).

Exhibit 28-12: Process Energy GHG Emissions Calculations for Recycled Production of Wood Products

Material/Product	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2e$/Short Ton)
Dimensional Lumber	3.17	0.18
MDF	10.99	0.32

Exhibit 28-13: Transportation Energy GHG Emissions Calculations for Recycled Production of Wood Products

Material/Product	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2e$/Short Ton)
Dimensional Lumber	0.97	0.07
MDF	1.27	0.09

Note: The transportation energy and emissions in this exhibit do not include retail transportation, which is presented separately in Exhibit 28-4.

Step 3. *Calculate the difference in emissions between virgin and recycled production.* To calculate the GHG emissions implications of recycling one short ton of wood 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 28-14. For both dimensional lumber and MDF, the energy and GHG emissions from recycling are less than those associated with virgin production of these materials.

Exhibit 28-14: Differences in Emissions between Recycled and Virgin Wood Product Manufacture ($MTCO_2e$/Short Ton)

	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)		
Material/Product	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Dimensional Lumber	0.10	0.08	–	0.18	0.09	–	0.08	0.01	–
MDF	0.26	0.12	0.00	0.32	0.14	0.00	0.06	0.02	–

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.* The recycled input credits calculated above are then 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 (FAL, 1998), which is calculated as follows:

Net Retention Rate for Wood Products = Recovery Stage Retention Rate × Manufacturing Stage Retention Rate

= 88.0% × 90.9% = 80.8%

Step 5. *Calculate the net change in carbon storage associated with recycling wood products.* These adjusted credits are then combined with the estimated forest carbon sequestration from recycling wood products to calculate the final GHG emission factor for recycling dimensional lumber and MDF. EPA estimates forest carbon storage in wood products, involving three parameters, as mentioned in the section on source reduction:

1. The change in timber harvests resulting from increased recycling of wood products;
2. The change in forest carbon storage as a result of a reduction in timber harvests; and
3. The change in carbon stored in in-use wood products from increased recycling.

Exhibit 28-15 provides data on these components of the overall forest carbon sequestration factor for both wood products. Compared to source reduction of wood products, recycling results in a larger increase in net carbon storage (i.e., an additional 0.7 $MTCO_2e$ of carbon storage from recycling compared to source reduction, or the difference between 2.5 and 1.8 $MTCO_2e$). This result is driven by the change in carbon storage in in-use products. When wood products are recycled, the recycled wood remains in in-use products; when virgin wood products are avoided through source reduction, however, they do not enter the in-use pool of wood products. Consequently, the reduction in carbon storage in in-use wood products is less for recycling than it is for source reduction. For more information on forest carbon storage and each component of the overall factor, see the Forest Carbon Storage chapter.

Exhibit 28-15: Net Change in Carbon Storage per Unit of Increased Wood Product Recycling

(a) Material/Product	(b) Reduction in Timber Harvest per Unit of Increased Wood Product Recycling (Short Tons Timber/ Short Ton of Wood Recycled)	(c) Change in Forest C Storage per Unit of Reduced Timber Harvest (Metric Tons Forest C/ Metric Ton Timber)	(d) Change in C Storage in In-use Products per Unit of Increased Wood Product Recycling ($MTCO_2e$/Short Ton)	(e) Net Change in C Storage per Unit of Increased Wood Product Recycling ($MTCO_2e$/Short Ton) ($e = b \times c \times 0.907 + d$)
Wood products	0.88	0.99	-0.35	2.53

Note: Positive values denote an increase in carbon storage; negative values denote a decrease in carbon storage.
One metric ton = 0.907 short tons.

Step 6. *Calculate the net GHG emission factor for recycling wood products.* The recycling credit calculated in Step 4 is added to the estimated forest carbon sequestration from recycling wood products to calculate the final GHG emission factor for recycling dimensional lumber and MDF, as shown in Exhibit 28-11.

28.4.3 Composting

While composting wood products is technically feasible, there is not much information available on composting wood products or the associated GHG emissions. As such, WARM does not consider GHG emissions or storage associated with composting wood products. However, this is a potential area for future research for EPA.

28.4.4 Combustion

Because carbon in wood products is considered to be biogenic, CO_2 emissions from combustion of wood products are not considered in WARM.[150] Combusting wood products results in emissions of nitrous oxide (N_2O), however, and these emissions are included in WARM's GHG emission factors for wood products. Transporting wood products to combustion facilities also results in GHG emissions from the combustion of fossil fuels in vehicles. Finally, electricity produced from waste combustion energy recovery is used to offset the need for electricity production at power plants, consequently reducing the power sector's consumption of fossil fuels. WARM takes this into account by calculating an avoided

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[150] WARM assumes that biogenic CO_2emissions are balanced by CO_2 captured by regrowth of the plant sources of the material. Consequently, these emissions are excluded from net GHG emission factors in WARM.

utility emission offset.[151] Exhibit 28-16 provides the breakdown of each wood product's emission factor into these components.

Exhibit 28-17 provides the calculation for the avoided utility emissions. EPA used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a waste-to-energy (WTE) plant: (1) the energy content of each waste material,[152] (2) the combustion system efficiency in converting energy in municipal solid waste (MSW) to delivered electricity,[153] and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants. For more information on combustion in general, see the Combustion chapter.

Exhibit 28-16: Components of the Combustion Net Emission Factor for Wood Products ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion[a]	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Dimensional Lumber	–	0.03	–	0.04	-0.65	–	-0.58
MDF	–	0.03	–	0.04	-0.65	–	-0.58

– = Zero emissions.

[a] CO_2 emissions from combustion of wood products are assumed to be biogenic and are excluded from net emissions.

Exhibit 28-17: Utility GHG Emissions Offset from Combustion of Wood Products

(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) ($e = b \times c \times d$)
Wood products	16.6	17.8%	0.22	0.65

28.4.5 Landfilling

Wood products are often sent to landfills at the end of life. When wood products are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2. Only CH_4 emissions are counted in WARM, because the CO_2 emissions are considered to be biogenic. In addition, because wood products are not completely decomposed by anaerobic bacteria, some of the carbon in these materials remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation. In addition, WARM factors in transportation of wood products to landfill, which results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in vehicles and landfilling equipment. Exhibit 28-18 provides the emission factors for dimensional lumber and MDF broken down into these components. More information on the development of the emission factor is provided in section 4.5.1. For more information on landfilling in general, see the Landfilling chapter.

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[151] 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.

[152] Based on the higher end of the heat content range of basswood from the USDA Forest Service (Fons et al., 1962). Basswood is relatively soft wood, so it's high-end energy content value is likely most representative of dimensional lumber and MDF wood products.

[153] EPA used a net value of 550 kWh generated by mass burn plants per ton of mixed MSW combusted (Zannes, 1997) and accounted for transmission and distribution losses.

Exhibit 28-18: Landfilling Emission Factors for Wood Products ($MTCO_2e$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Dimensional Lumber	–	0.04	0.07	-0.00	-1.09	-0.98
MDF	–	0.04	0.02	-0.00	-0.92	-0.86

– = Zero emissions.
Negative values denote GHG emission reductions or carbon storage.
Note: The emission factors for landfill CH_4 presented in this table are based on national-average rates of landfill gas capture and energy recovery. Avoided CO_2 emissions from energy recovery are calculated based on the non-baseload GHG emissions intensity of U.S. electricity generation, since it is non-baseload power plants that will adjust to changes in the supply of electricity from energy recovery at landfills.

28.4.5.1 Developing the Emission Factor for Landfilling of Wood Products

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. As detailed in the Landfilling chapter, there are three categories of landfills modeled in WARM: (1) landfills that do not recover landfill gas (LFG), (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. Direct use of landfill gas for process heat is not modeled. WARM calculates emission factors for each of these three landfill types and uses the national average mix of collection systems installed at landfills in the United States to calculate a national average emission factor that accounts for the extent to which CH_4 (1) is not captured, (2) is flared without energy recovery, or (3) is combusted on-site for energy recovery.[154, 155] The Landfill CH_4 column of Exhibit 28-18 presents emission factors based on the national average of LFG collection usage.

Exhibit 28-19 depicts the specific emission factors for each landfill gas collection type. Overall, landfills that do not collect LFG produce the most CH_4 emissions.

Exhibit 28-19: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2e$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material/ Product	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation	Net Landfill Carbon Storage	GHG Emissions from Transport-ation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generatio n
Dimensional Lumber	0.15	0.06	0.05	-1.09	0.04	-0.90	-0.99	-1.00
MDF	0.05	0.02	0.01	-0.92	0.04	-0.83	-0.86	-0.87

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

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[154] 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.

[155] For the year 2012, an estimated 38 percent of landfill CH_4 was generated at landfills with landfill gas recovery systems and flaring, while 44 percent was generated at landfills with gas collection and energy recovery systems (EPA, 2014a).

WARM calculates landfill carbon storage from wood products based on laboratory test data on the ratio of carbon storage per wet short ton of wood landfilled documented in Barlaz (1998), Wang et al. (2013), and Wang et al. (2011). Exhibit 28-20 provides the landfill carbon storage calculation used in WARM.

Exhibit 28-20: Calculation of the Carbon Storage Factor for Landfilled Wood Products

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (g C Stored/Dry g)	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of C Storage to Wet Weight (g C/Wet g) (d = b × c)	(e) Amount of C Stored ($MTCO_2e$ per Wet Short Ton)
Dimensional Lumber	0.44	0.75	0.33	1.09
MDF	0.37	0.75	0.28	0.92

28.5 Limitations

In addition to the limitations associated with the forest carbon storage estimates as described in the Forest Carbon Storage chapter, the following limitations are associated with the wood products emission factors:

- The emission factors associated with producing and recycling dimensional lumber and MDF are representative of manufacturing processes in the mid-1990’s and may have changed since the original life-cycle information was collected; depending upon changes in manufacturing process, such as efficiency improvements and fuel inputs, energy use and GHG emissions from virgin and recycled production of these products may have increased or decreased.
- Composting is not included as a material management pathway because of a lack of information on the GHG implications of composting wood products. The composting factor in WARM, described in the Composting chapter, assumes a generic compost mix, rather than looking at materials in isolation. It is not currently known what effect adding large amounts of wood would have at a composting site, whether the GHG emissions/sequestration would be altered, or whether the carbon/nitrogen ratio would be affected. As a result, EPA has not estimated emission factors for composting. However, EPA is planning to conduct further research in this area that could enable better assessments of composting emission factors for wood products.
- The energy content (by weight) for dimensional lumber and MDF is assumed to be the same, while in fact they may be different since MDF contains resins that bind the wood fibers together. EPA does not expect that this difference would have a large influence of the combustion emission factors.

28.6 References

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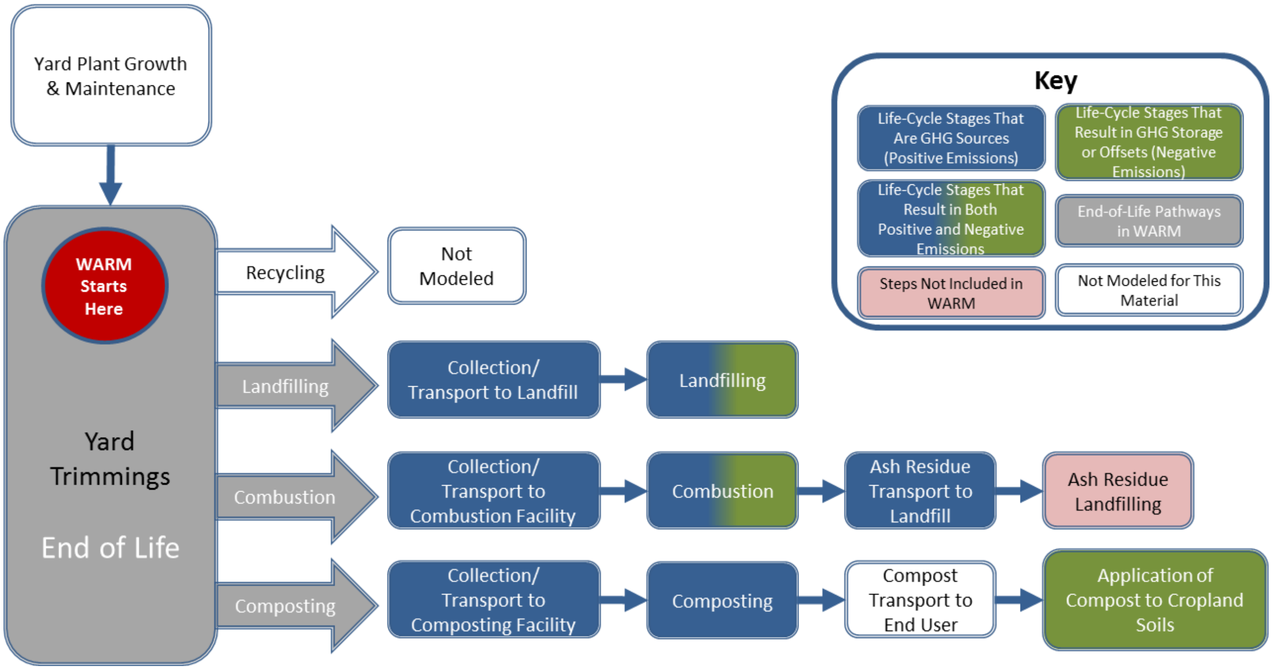
29 YARD TRIMMINGS

29.1 Introduction to WARM and Yard Trimmings

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for yard trimmings beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated yard trimmings in the following three materials management options: composting, landfilling, and combustion. Exhibit 29-1 shows the general outline of materials management pathways for these materials in WARM. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Composting, 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 29-1: Life Cycle of Yard Trimmings in WARM



Yard trimmings fall under the category of "organics" in WARM. Although paper, wood products and plastics are organic materials in the chemical sense, these categories of materials have very different life-cycle and end-of-life characteristics than yard trimmings and are treated separately in the municipal solid waste (MSW) stream. Yard trimmings are grass clippings, leaves and branches. WARM also calculates emission factors for a mixed organics category, which is a weighted average of the food waste and yard trimmings emission factors for the waste management pathways relevant to both materials (i.e., landfilling, combustion, and composting). For more information, see the Food Waste chapter. The weighting is based on the relative prevalence of these two categories in the waste stream, according to the latest (2014b) version of EPA's annual report, *Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures for 2012,* and as shown in column (c) of Exhibit 29-2.[156]

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[156] Note that, unlike for other materials in WARM, the "mixed" category is based on organics' relative prevalence among materials *generated* rather than *recovered*. This is because WARM assumes that users interested in

Exhibit 29-2: Relative Prevalence of Yard Trimmings and Food Waste in the Waste Stream in 2012

(a) Material	(b) Generation (Short Tons)	(c) % of Total Organics Generation	(d) Recovery (Short Tons)	(e) Recovery Rate
Food Waste	36,430,000	52%	1,740,000	4.8%
Yard Trimmings	33,960,000	48%	19,590,000	57.7%

Source: EPA (2014b).

29.2 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.[157] Recycling and source reduction are the two materials management options that impact the upstream production of materials, and consequently are the only management options that include upstream GHG emissions. For more information on evaluating upstream emissions, see the chapters on Recycling and Source Reduction.

WARM does not include recycling or source reduction management options for yard trimmings. Yard trimmings cannot be recycled in the traditional sense and sufficient data are not currently available to model the material and energy inputs for trees and grass prior to becoming yard trimmings waste. As Exhibit 29-3 illustrates, most of the GHG sources relevant to yard trimmings in this analysis are contained in the waste management portion of the life cycle assessment, with the exception of increased soil carbon storage associated with composting of yard trimmings.

Exhibit 29-3: Yard Trimmings GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Yard Trimmings	GHG Sources and Sinks Relevant to Yard Trimmings		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Source Reduction	Not modeled in WARM due to data limitations		
Recycling	Not applicable since yard trimmings cannot be recycled		
Composting	Not applicable	**Offsets** • Increase in soil carbon storage	**Emissions** • Transport to compost facility • Compost machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related nitrous oxide **Offsets** • Avoided utility emissions

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composting would be dealing with a mixed organics category that is closer to the current rate of generation, rather than the current rate of recovery. Since the fraction of recovered food waste is so low, if the shares of yard trimmings and food waste recovered were used, the mixed organics factor would be essentially the same as the yard trimmings factor, rather than a mix of organic materials.

[157] 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.

Materials Management Strategies for Yard Trimmings	GHG Sources and Sinks Relevant to Yard Trimmings		
	Raw Materials Acquisition and Manufacturing	Changes in Forest or Soil Carbon Storage	End of Life
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery • Landfill methane **Offsets** • Avoided utility emissions due to landfill gas combustion • Landfill carbon storage

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 29-3 to calculate net GHG emissions per short ton of organic materials generated. GHG emissions arising from the consumer's use of any product are not considered in WARM's life-cycle boundaries. Exhibit 29-4 presents the net GHG emission factors for each materials management strategy calculated in WARM for organic materials.

Additional discussion on the detailed methodology used to develop these emission factors may be found in sections 18.4.1 through 29.4.5.

Exhibit 29-4: Net Emissions for Yard Trimmings and Mixed Organics 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
Yard Trimmings	NA	NA	-0.12	-0.15	-0.19
Grass	NA	NA	-0.12	-0.15	0.17
Leaves	NA	NA	-0.12	-0.15	-0.47
Branches	NA	NA	-0.12	-0.15	-0.65
Mixed Organics	NA	NA	-0.14	-0.14	0.29

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

29.3 Raw Materials Acquisition and Manufacturing

WARM does not consider GHG emissions associated with raw materials acquisition or manufacturing for yard trimmings because this life-cycle stage is only applicable to the source reduction and recycling pathways, which are not modeled in WARM for yard trimmings, as explained previously.

29.4 Materials Management Methodologies

Landfilling, composting, and combustion are the three management options used to manage yard trimmings. Residential and commercial land management activities such as landscaping and gardening generate yard trimmings, which are typically either composted onsite, shredded with a mulching mower and used for landscaping onsite, or placed on the curb for transport to central facilities for either combustion, composting or landfilling. Since 1990, many municipalities have implemented programs and policies designed to divert yard trimmings from landfills, and as a result, yard trimmings are increasingly composted or mulched onsite or collected for mulching and composting at a central facility (EPA, 2014a).

29.4.1 Source Reduction

Unlike food waste, yard trimmings do not generally require extensive material or fossil fuel energy inputs prior to becoming waste. While some material and energy inputs are used during the life of trees and grasses (i.e., fuel for lawn mowing, fertilizers), sufficient data needed to model raw material acquisition and production emissions or storage from yard trimmings are not currently available. Therefore, WARM does not consider GHG emissions or storage associated with source reduction of yard trimmings.

29.4.2 Recycling

Recycling, as modeled in WARM (i.e., producing new products using end-of-life materials), does not commonly occur with the yard trimmings materials modeled in WARM. Therefore, WARM does not consider GHG emissions or storage associated with the traditional recycling pathway for yard trimmings. However, yard trimmings can be converted to compost, a useful soil amendment, as described in section 29.4.3.

29.4.3 Composting

29.4.3.1 Developing the Emissions Factor for the Composting of Yard Trimmings

Composting yard trimmings results in increased carbon storage when compost is applied to soils. The net composting emission factor is calculated as the sum of emissions from transportation, processing of compost, the carbon storage resulting from compost application, and the fugitive emissions of methane (CH_4) and nitrous oxide (N_2O) produced during decomposition.[158] WARM currently assumes that carbon dioxide (CO_2) emissions that occur as a result of the composting process are biogenic and are not counted (for further explanation, see the text box on biogenic carbon in the Introduction and Background chapter). Exhibit 29-5 details these components for yard trimmings and mixed organics. For additional information on composting in WARM, see the Composting chapter. The two emission sources and one emission sink resulting from the composting of organics are:

- *Nonbiogenic CO_2 emissions from collection and transportation*: Transportation of yard trimmings to the central composting site results in nonbiogenic CO_2 emissions.[159] In addition, during the composting process the compost is mechanically turned, and the operation of this equipment also results in nonbiogenic CO_2 emissions.
- *Fugitive Emissions of CH_4 and N_2O:* Microbial activity during composting decomposes waste into a variety of compounds, which generates small amounts of CH_4 and N_2O 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).
- *Carbon Storage*: When compost is applied to the soil, some of the carbon contained in the compost does not decompose for many years and therefore acts as a carbon sink.

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[158] These fugitive emission sources were added in June 2014 to WARM Version 13.

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

Exhibit 29-5: Components of the Composting Net Emission Factor for Yard Trimmings and Mixed 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)
Yard Trimmings[a]	NA	0.04	–	0.07	-0.24	-0.12
Grass	NA	0.04	–	0.07	-0.24	-0.12
Leaves	NA	0.04	–	0.07	-0.24	-0.12
Branches	NA	0.04	–	0.07	-0.24	-0.12
Mixed Organics	NA	0.04	–	0.07	-0.24	-0.14

NA = Not applicable.

[a] Yard trimmings are a 50%, 25%, 25% weighted average of grass, leaves, and branches, based on U.S. generation data from EPA (2014b).

Transportation energy emissions occur when fossil fuels are used to collect and transport yard trimmings to a composting facility, and then to operate the composting equipment that turns the compost. To calculate these emissions, WARM relies on assumptions from FAL (1994), which are detailed in Exhibit 29-6.

Exhibit 29-6: 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)
All Material Types	0.36	0.22	0.58	0.04

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

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)[160] and carbon stored in non-reactive humus compounds (the "increased humus formation" effect)[161]. 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 29-7.

Exhibit 29-7: Soil Carbon Effects as Modeled in Century Scenarios (MTCO$_2$e/Short Ton of Organics)

	Soil Carbon Restoration				
Scenario	Unweighted	Proportion of C that is Not Passive	Weighted estimate	Increased Humus Formation	Net Carbon Flux[a]
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 MTCO$_2$e.

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[160] 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.

[161] 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 CO$_2$. For more information, see the Composting chapter.

The nonbiogenic CO_2 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. As Exhibit 29-5 illustrates, WARM estimates that the net composting GHG factor for yard trimmings is the same for all sources of compost.

29.4.4 Combustion

29.4.4.1 Developing the Emissions Factor for the Combustion of Yard Trimmings

Combusting organics results in a net emissions offset (negative emissions) due to the avoided utility emissions associated with energy recovery from waste combustion. The combustion net emission factor is calculated as the sum of emissions from transportation of waste to the combustion facility, nitrous oxide emissions from combustion, and the avoided CO_2 emissions from energy recovery in a waste-to-energy (WTE) plant. Although combustion also releases the carbon contained in yard trimmings in the form of CO_2, these emissions are considered biogenic and are not included in the WARM net emission factor. Exhibit 29-8 presents these components of the net combustion emission factor for each organic material. For additional information on combustion in WARM, see the Combustion chapter. The two emissions sources and one emissions offset that result from the combusting of organics are:

- *CO_2 emissions from transportation of waste.* Transporting waste to the combustion facility and transporting ash from the combustion facility to a landfill both result in transportation CO_2 emissions.
- *Nitrous oxide emissions from combustion.* Waste combustion results in measurable emissions of nitrous oxide (N_2O), a GHG with a high global warming potential (EPA, 2014a).
- *Avoided utility CO_2 emissions*. Combustion of MSW with energy recovery in a WTE plant also results in *avoided* CO_2 emissions at utilities.

Exhibit 29-8: Components of the Combustion Net Emission Factor for Yard Trimmings and Mixed Organics ($MTCO_2e$/Short Ton)

	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)
Yard Trimmings	NA	0.03	–	0.04	-0.22	–	-0.15
Grass	NA	0.03	–	0.04	-0.22	–	-0.15
Leaves	NA	0.03	–	0.04	-0.22	–	-0.15
Branches	NA	0.03	–	0.04	-0.22	–	-0.15
Mixed Organics	NA	0.03	–	0.04	-0.20	–	-0.14

NA = Not applicable

For the CO_2 emissions from transporting waste to the combustion facility, and ash from the combustion facility to a landfill, EPA used an estimate of 60 lbs CO_2 per ton of MSW for transportation of mixed MSW developed by FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2e$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW and the resulting ash. WARM assumes that transportation of yard trimmings and mixed organics uses the same amount of energy as transportation of mixed MSW.

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (IPCC, 2006). The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. WARM averages the midpoints of each range and converts the units to $MTCO_2e$ of N_2O per ton of MSW. Because the IPCC did not report N_2O values for combustion of individual components of MSW, WARM uses the same value for yard trimmings and mixed organics.

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 MSW combustion would be in the form of electricity, as shown in Exhibit 29-9. 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 CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy content of each waste material, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour (kWh) of electricity delivered by WTE plants.

Exhibit 29-9: Utility GHG Emissions Offset from Combustion of Yard Trimmings

(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) ($e = b \times c \times d$)
Yard Trimmings	5.6	17.8%	0.22	0.22

To estimate the gross GHG emissions per ton of waste combusted, EPA sums emissions from combustion N_2O and transportation CO_2. These emissions were then added to the avoided utility emissions in order to calculate the net GHG emission factor, shown in Exhibit 29-9. WARM estimates that combustion of yard trimmings results in a net emission reduction.

29.4.5 Landfilling

29.4.5.1 Developing the Emissions Factor for the Landfilling of Yard Trimmings

Landfilling organics can result in either net carbon storage or net carbon emissions, depending on the specific properties of the organic material. 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 landfilling, and the carbon storage resulting from undecomposed carbon remaining in landfills. Exhibit 29-10 presents the components of the landfilling emission factor for each yard trimmings material. For additional information on landfilling in WARM, see the Landfilling chapter. The two emissions sources and one emissions sink that result from the landfilling of organics are:

- *Transportation of organic waste*. Transportation of yard trimmings to landfill results in anthropogenic CO_2 emissions, due to the combustion of fossil fuels in the vehicles used to haul the wastes.
- *Methane emissions from landfilling*. When yard trimmings are landfilled, anaerobic bacteria degrade the materials, producing CH_4 and CO_2, collectively referred to as landfill gas (LFG). Only the CH_4 portion of LFG is counted in WARM, because the CO_2 portion is considered of biogenic

origin and therefore is assumed to be offset by CO_2 captured by regrowth of the plant sources of the material.

- *Landfill carbon storage.* Because yard trimmings are not completely decomposed by anaerobic bacteria, some of the carbon in them remains stored in the landfill. This stored carbon constitutes a sink (i.e., negative emissions) in the net emission factor calculation.

Exhibit 29-10: Landfilling Emission Factors for Yard Trimmings and Mixed Organics ($MTCO_2e$/Short Ton)

Material Type	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)
Yard Trimmings	–	0.04	0.32	-0.01	-0.54	-0.19
Grass	–	0.04	0.29	-0.01	-0.14	0.17
Leaves	–	0.04	0.30	-0.01	-0.79	-0.47
Branches	–	0.04	0.40	-0.02	-1.06	-0.65
Mixed Organics	–	0.04	0.57	-0.03	-0.30	0.29

Note: The emission factors for landfill CH_4 presented in this table assume that the methane management practices and decay rates at the landfill are an average of national practices.
Negative values denote GHG emission reductions or carbon storage.
NA = Not applicable; upstream raw material acquisition and manufacturing GHG emissions are not included in landfilling since the life-cycle boundaries in WARM start at the point of waste generation and landfilling does not affect upstream GHG emissions.

Transportation energy emissions occur when fossil fuels are used to collect and transport yard trimmings to a landfill, and then to operate the landfill equipment. To calculate these emissions, WARM relies on assumptions from FAL (1994). EPA then converted the Franklin Associates estimate from pounds of CO_2 per ton of mixed MSW to $MTCO_2e$ per ton of mixed MSW and applied it to estimate CO_2 emissions from transporting one short ton of mixed MSW. WARM assumes that transportation of yard trimmings uses the same amount of energy as transportation of mixed MSW.

WARM calculates CH_4 emission factors for landfilled materials based on the CH_4 collection system type installed at a given landfill. There are three categories of landfills modeled in WARM: (1) landfills that do not recover LFG, (2) landfills that collect the LFG and flare it without recovering the flare energy, and (3) landfills that collect LFG and combust it for energy recovery by generating electricity. The Excel version of WARM allows users to select component-specific decay rates based on different assumed moisture contents of the landfill and landfill gas collection efficiencies for a series of landfill management scenarios. The tables in this section show values using the national average moisture conditions, based on the national average precipitation at landfills in the United States and for landfill gas collect efficiency from “typical” landfill operations in the United States. The decay rate and management scenario assumed influences the landfill gas collection efficiency. For further explanation, see the Landfilling chapter.

Exhibit 29-11 depicts the emission factors for each LFG collection type based on the national average landfill moisture scenario and “typical” landfill management operations. Overall, landfills that do not collect LFG produce the most CH_4 emissions. The emissions generated per short ton of material drop by approximately half for yard trimmings if the landfill recovers and flares CH_4 emissions. These emissions are even lower in landfills where LFG is recovered for electricity generation because LFG recovery offsets emissions from avoided electricity generation.[162]

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[162] These values include a utility offset credit for electricity generation that is avoided by capturing and recovering energy from landfill gas to produce electricity. 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.

Exhibit 29-11: Landfill CH_4 Emissions for Three Different Methane Collection Systems, National "Average" Landfill Moisture Conditions, Typical Landfill Management Operations, and National Average Grid Mix ($MTCO_2e$/Wet Short Ton)

Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation
Yard Trimmings	0.59	0.28	0.24
Grass	0.51	0.25	0.23
Leaves	0.59	0.26	0.22
Branches	0.77	0.38	0.26

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

A portion of the carbon contained in yard trimmings does not decompose after disposal and remains stored in the landfill. Because this carbon storage would not normally occur under natural conditions (virtually all of the carbon in the organic material would be released as CO_2, completing the photosynthesis/respiration cycle), this is counted as an anthropogenic carbon sink. The carbon storage associated with each material type depends on the initial carbon content, the extent to which that carbon decomposes into CH_4 in landfills, and temperature and moisture conditions in the landfill. The background and details of the research underlying the landfill carbon storage factors are detailed in the Landfilling chapter. As Exhibit 29-12 illustrates, branches and leaves result in the highest amount of carbon storage.

Exhibit 29-12: Calculation of the Carbon Storage Factor for Landfilled Yard Trimmings

(a) Material	(b) Ratio of Carbon Storage to Dry Weight (grams of Carbon Stored/dry gram of Material)[a]	(c) Ratio of Dry Weight to Wet Weight	(d) Ratio of Carbon Storage to Wet Weight (grams of Carbon/wet gram of Material) (d = b × c)	(e) Amount of Carbon Stored ($MTCO_2e$ per Wet Short Ton)
Yard Trimmings				0.54
Grass	0.24	0.18	0.04	0.14
Leaves	0.39	0.62	0.24	0.79
Branches	0.38	0.84	0.32	1.06

Note: Yard trimmings are calculated as a weighted average of grass, leaves and branches, currently based on an estimate in the *Facts and Figures* report for 2007 (EPA, 2008, p. 58). This information is not updated annually by EPA.

[a] Based on estimates developed by James W. Levis, Morton Barlaz, Joseph F. DeCarolis, and S. Ranji Ranjithan at North Carolina State University; see Levis et al. (2013).

The landfill CH_4 and transportation emissions sources are added to the landfill carbon sink in order to calculate the net GHG landfilling emission factors for each yard trimmings material, shown in the final three columns of Exhibit 29-13 for landfills equipped with different LFG collection systems. The final net emission factors indicate that landfilling leaves and branches results in a net carbon sink. This negative net emission factor is due to the fact that these materials do not readily degrade in landfills and a substantial fraction of the carbon in these materials remains in the landfill permanently.

Exhibit 29-13: Components of the Landfill Emission Factor for the Three Different Methane Collection Systems Typically Used In Landfills ($MTCO_2e$/Short Ton)

(a)	(b) Net GHG Emissions from CH_4 Generation			(c)	(d)	(e) Net GHG Emissions from Landfilling (e = b + c + d)		
Material	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electric Generation	Net Landfill Carbon Storage	GHG Emissions From Transportation	Landfills without LFG Recovery	Landfills with LFG Recovery and Flaring	Landfills with LFG Recovery and Electricity Generation
Yard Trimmings	0.59	0.28	0.24	-0.54	0.04	0.10	-0.21	-0.29
Grass	0.51	0.25	0.23	-0.14	0.04	0.41	0.14	0.10
Leaves	0.59	0.26	0.22	-0.79	0.04	-0.16	-0.49	-0.57
Branches	0.77	0.38	0.26	-1.06	0.04	-0.26	-0.64	-0.82

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

29.5 Limitations

The results of the analysis presented in this chapter are limited by the reliability of the various data elements used. This section details limitations, caveats and areas of current and future research.

29.5.1 Composting

EPA is currently conducting research into process emissions from composting, carbon storage due to compost application, and other issues that are relevant to these calculations.

- As in the other chapters of this report, the GHG impacts of composting reported in this chapter evaluate emissions relative to other possible disposal options for yard trimmings (i.e., landfilling and combustion). This assumes that yard trimmings will be collected for end-of-life management by one of these alternative materials management practices. Yard trimmings, however, can also be simply left on the ground to decompose. This pathway is not modeled in WARM, since EPA would need to analyze the effect of decomposing yard trimmings in their home soil—and the associated soil carbon storage benefits—to develop absolute GHG emission factors for composting yard trimmings at a central facility relative to a baseline of leaving yard trimmings on the ground where they fall.
- Due to data and resource constraints, the analysis considers a small sampling of feedstocks and a single compost application (cropland soil). EPA analyzed two types of compost feedstocks—yard trimmings and food waste—although sewage sludge, animal manure and several other compost feedstocks also may have significant GHG implications. Similarly, it was assumed that compost was applied to degraded agricultural soils growing corn, despite widespread use of compost in specialty crops, land reclamation, silviculture, horticulture and landscaping.
- This analysis did not consider the full range of soil conservation and management practices that could be used in combination with application of compost, and the impacts of those practices on carbon storage. Research indicates that adding compost to agricultural soils in conjunction with various conservation practices enhances the generation of soil organic matter to a much greater degree than applying compost alone. Examples of these conservation practices include conservation tillage, no-till, residue management, crop rotation, wintering and summer fallow elimination.

- In addition to the carbon storage benefits of adding compost to agricultural soils, composting may lead to improved soil quality, improved plant productivity, improved soil water retention and cost savings. As discussed earlier, nutrients in compost tend to foster soil fertility (Brady and Weil, 1999). In fact, composts have been used to establish plant growth on land previously unable to support vegetation. In addition to these biological improvements, compost also may lead to cost savings associated with avoided waste disposal, particularly for feedstocks such as sewage sludge and animal manure.

29.5.2 Landfilling

- WARM currently assumes that 82 percent of MSW landfill CH_4 is generated at landfills with LFG recovery systems (EPA, 2014a). The net GHG emissions from landfilling each material are quite sensitive to the LFG recovery rate, so the application of landfill gas collection systems at landfills will have an effect on lowering the emission factors presented here over time. WARM is updated annually to account for changes in the percent of MSW landfill CH_4 that is collected at U.S. landfills.

29.5.3 Combustion

- Opportunities exist for the combustion system efficiency of WTE plants to improve over time. As efficiency improves, more electricity can be generated per ton of waste combusted (assuming no change in utility emissions per kWh), resulting in a larger utility offset, and the net GHG emissions benefit from combustion of MSW will increase.

- The reported ranges for N_2O emissions from combustion of organics were broad. In some cases, the high end of the range was ten times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. In the absence of better data on the composition and N_2O emissions from organics combustion on a national scale in the United States , the average value used for yard trimmings should be interpreted as an approximate value.

- This analysis used the non-baseload mix of electricity generation facilities as the proxy for calculating the GHG emissions intensity of electricity production that is displaced at the margin from energy recovery at WTE plants and LFG collection systems. Actual avoided utility GHG emissions will depend on the specific mix of power plants that adjust to an increase in the supply of electricity, and could be larger or smaller than estimated in these results.

29.6 References

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