1. LIFE-CYCLE METHODOLOGY

This report is the third edition of *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks*. EPA made the following improvements to the second edition of the report:

- Developed emission factors for seven new material types: copper wire, clay bricks, concrete, fly ash, tires, carpet, and personal computers;

- Incorporated new energy data into calculations of electric utility offsets;

- Revised carbon coefficients and fuel use for national average electricity generation;

- Updated information on landfill gas recovery rates to reflect the latest values from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*;

- Added a discussion of emerging issues in the area of climate change and waste management;

- Provided a revised list of suggested proxy values for voluntary reporting of GHG emission reductions;

- Added a discussion of open-loop recycling, as it relates to emission factors for fly ash, carpet, personal computers, and mixed paper;

- Included emissions from retail transport in the methodology;

- Updated the current mix of postconsumer recycled content for various materials; and

- Updated the analysis of forest carbon sequestration and moved the discussion to the recycling chapter.

All of these changes and/or revisions are described in more detail throughout the body of the report.

In this edition of the report, EPA has moved some of the background information from the body of the report to separate background documents to improve clarity.[1] The technical details remain available to the interested, while keeping the main body of this report straightforward. *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials* provides data on life-cycle energy intensity and fuel mix, provided by Franklin Associates, Ltd. (FAL). *Background Document B: Methodology for Estimating the Amounts and Types of Energy Consumed in Raw Materials Acquisition and Manufacturing of Eight Different Materials* provides a discussion of the review cycles leading up to the first and second editions of the report. *Background Document C: Review Process for the Report* includes a discussion of how the EPA researchers screened materials for the first edition of the report. *Background Document D: Comment-Response Document* presents comments and responses given during expert review of the first edition of the report. In addition to these four background documents, there are several material-specific background documents that explain how EPA developed specific emission factors for materials new to this edition of the report: copper wire, concrete, clay bricks, fly ash, tires, carpet, and personal computers.[2]

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[1] Available at EPA, Global Warming—Waste, "Solid Waste Management and Greenhouse Gases." Go to: http://www.epa.gov/mswclimate, then follow links to Publications → Reports, Papers, and Presentations → This report → Background Documents.

[2] These four background documents all have the same beginning to their titles: *Background Document for Life-Cycle Greenhouse Gas Emission Factors for* (1) *Clay Brick Reuse and Concrete Recycling*, (2) *Fly Ash Used as a*

The remainder of this chapter provides an overview of the methodology used to calculate the GHG emissions associated with various management strategies for MSW. The first section briefly describes the life-cycle framework used for the analysis. Next is a discussion of the materials included in the analysis. The final three sections present a description of key inputs and baselines, a summary of the life-cycle stages, and an explanation of how to estimate and compare net GHG emissions and sinks.

1.1   THE OVERALL FRAMEWORK: A STREAMLINED LIFE-CYCLE INVENTORY

Early in this analysis of the GHG benefits of specific waste management practices, it became clear that all waste management options provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous waste management practices from a GHG perspective, a material-specific comparison of all available waste management options clarifies where the greatest GHG benefits can be obtained for particular materials in MSW. A material-specific comparison can help waste managers and policymakers identify the best options for GHG reductions through alternative waste management practices.

This study 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, 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.

A full LCA is beyond the scope of this analysis. Rather, the streamlined LCA described in this report is limited to an inventory of the emissions and other environmental impacts related to global warming. This study did not assess human health impacts, necessary environmental improvements, and air, water, or environmental impacts that do not have a direct bearing on climate change. This analysis also simplifies the calculation of emissions from points in the life cycle that occur before a material is discarded. For a more extensive explanation of this "waste generation" reference point, see Section 1.5, below.

1.2   MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE-CYCLE INVENTORY

Each material in MSW has different GHG impacts depending on how it is manufactured and disposed of at the end of its useful life. EPA's research into these impacts began with a screening analysis of 37 of the most common materials and products found in MSW.[3] The materials included in screening analysis then were ranked by their potential for GHG reductions.[4] The second edition of the report

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Cement Replacement in Concrete, (3) *Carpet and Personal Computers*, and (4) *Copper Wire*. These are available at the EPA's Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

[3] In addition to the materials and products covered in the report, the screening analysis included the following materials and products: other paper materials (bags and sacks, other paper packaging, books, other paperboard packaging, wrapping papers, paper plates and cups, folding cartons, other nonpackaging paper, and tissue paper and towels), other plastic materials (plastic wraps, plastic bags and sacks, other plastic containers, and other plastic packing), other metal materials (aluminum foil/closures, other steel packaging), and other miscellaneous materials (miscellaneous durable goods, wood packaging, furniture and furnishings, and other miscellaneous packaging).

[4] For more information on the screening analysis used to identify materials for the first edition of the report, see Background Document C, available at the EPA, Global Warming—Waste, "Background Documents for Solid Waste Management and GHG Report" website. Op cit.

included 16 materials: aluminum cans, steel cans,[5] glass, high-density polyethylene (HDPE) plastic blow-molded containers, low-density polyethylene (LDPE) plastic blow-molded containers, polyethylene terephthalate (PET) plastic blow-molded containers, corrugated cardboard, newspaper, office paper,[6] magazines and third-class mail, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, food discards, and yard trimmings. In addition to these materials, EPA examined the GHG implications of various management strategies for, mixed MSW, mixed plastics, mixed organics, mixed recyclables, and three grades of mixed paper (broad, residential, and office). Most of the changes between the second and third editions of this report reflect additions of new or updated data. This third edition features a further expanded list of material types, including copper wire, clay bricks, concrete, fly ash, tires, and two composite materials: carpet and personal computers. Some of these new materials require a different approach than has been used in previous editions of the report. For more details on the methodology used to evaluate any of these new materials, please see the Background Documents.[7]

In this edition of the report, EPA has added emission factors for several new material types as described below:

- **Copper Wire**—copper wire was added to broaden the range of materials for which there are emission factors. Life-cycle data for copper wire were obtained in part from research on personal computers and their raw material inputs.

- **Clay Brick**—this material is analyzed for only two management options: source reduction (i.e. reuse of bricks) and landfilling. EPA research indicates that there is very little postconsumer recycling of bricks. Likewise, almost all bricks in this country are made from virgin materials, so EPA has not analyzed the impacts of using recycled material in brick manufacture.

- **Concrete**—in this context, concrete is recycled in a semiopen loop. EPA researchers analyzed concrete that is crushed and used in place of virgin aggregate (sand, gravel, etc.) in the manufacture of new concrete. It replaces virgin aggregate, not virgin concrete, although aggregate is used to create concrete.

- **Fly Ash**—as a byproduct of coal combustion, source reduction of fly ash is not considered to be a viable waste management option. Instead, EPA has modeled recycling of fly ash in an open loop for the purpose of displacing Portland cement in the production of concrete.

- **Tires**—tires were added as a material type due to the large number disposed in the United States every year. EPA has modeled the recycling of tires based on retreading and the combustion of tires based on their use as a tire-derived fuel (TDF).

- **Carpet**—carpet is a composite, meaning that recycling is necessarily more complicated than for single material products (like steel cans). For this analysis, EPA researchers considered only nylon broadloom residential carpet. Carpet consists of carpet fiber (nylon), carpet backing (usually polypropylene), and synthetic-latex-and-limestone adhesive. In this analysis, carpet is recycled only in an open-loop process, into carpet pad, carpet backing, and molded auto parts. Source reduction for carpet consists of making carpets thinner, or procedures to make replacement less frequent (e.g., cleaning and upkeep).

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[5] Other steel materials also may be recycled, but this analysis was limited to steel cans from households.
[6] Office paper refers to the type of paper used in computer printers and photocopiers.
[7] These are available at the EPA's Global Warming—Waste, "Solid Waste Management and Greenhouse Gases" website. Op cit.

- **Personal Computers**—PCs are also a composite and are a complex combination of many types of material; by weight the main components are plastics, glass, lead, steel, copper, and aluminum. PCs are recycled in an open-loop process; this report analyzes the production of asphalt, CRT (cathode ray tube) glass, lead bullion, steel sheet, copper wire, and aluminum sheet from recycled PCs. Source reduction of PCs includes finding ways to make PCs last longer.

This edition of the report also incorporates data developed by ORD through its work on life-cycle management of MSW. ORD's dataset on energy and fuel mix was thoroughly reviewed by industry and other stakeholders, and was more up-to-date than some of the information in the first edition of this report. Thus, where a complete set of energy intensity and fuel mix data was available from ORD, that information was incorporated into the second edition of this report. For other materials—steel cans and mixed paper (broad, residential, and office definitions)—EPA retained the original dataset developed by FAL. This edition includes data (also developed by FAL) on dimensional lumber and medium-density fiberboard. Exhibit 1-1 lists the materials that were analyzed for this report and the energy-related data sources underlying the estimates. All of the material types listed in Exhibit 1-1 are discussed in subsequent chapters and included in exhibits throughout the report, with the exception of three mixed waste categories. Mixed plastics, mixed recyclables, and mixed organics are included only in Chapter 7 because emission factors for these materials simply reflect the weighted average emissions of other material types.

Exhibit 1-1 Materials Analyzed and Energy-related Data Sources

Material	Energy Data Source	Material	Energy Data Source
Aluminum Cans	FAL	Clay Bricks	Athena[8]
Steel Cans	FAL	Concrete	USCB; USGS[9]
Copper Wire	FAL; Battelle[10]	Fly Ash	PCA[11]
Glass	ORD	Tires	CIEEDAC; AG[12]
Corrugated Cardboard	ORD	Carpet	FAL
Magazines/Third-class Mail	ORD	Personal Computers	FAL
Newspaper	ORD	Mixed Paper	
Office Paper	ORD	Broad Definition[13]	FAL
Phonebooks	ORD	Residential Definition	FAL
Textbooks	ORD	Office Paper Definition	FAL
Dimensional Lumber	FAL	Mixed Plastics	Weighted Average
Med.-density Fiberboard	FAL	Mixed Recyclables	Weighted Average
Food Discards	NA	Mixed Organics	NA
Yard Trimmings	NA	Mixed MSW	NA

NA = Not applicable (data not energy-related)

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[8] Athena Sustainable Materials Institute, 1998, life-cycle research.

[9] U.S. Census Bureau, 1997 Economic Census; and Aggregates from Natural and Recycled Sources, a U.S. Geological Survey Circular by David Wilburn and Thomas Goonan.

[10] Battelle, 1975. Energy Use Patterns in Metallurgical and Nonmetallic Mineral Processing (Phase 4), Battelle Columbus Laboratories – U.S. Bureau of Mines. 1975.

[11] Portland Cement Association's (PCA) *U.S. Industry Fact Sheet, 2003 Edition*; the 2000 PCA report *Environmental Life Cycle Inventory of Portland Cement Concrete* by Nisbet, et al.; and the IPCC *Revised 1996 Guidelines for National Greenhouse Gas Inventories.*

[12] Canadian Industrial End-Use Energy Data and Analysis Center. Available online at: www.deh.gov.au/settlements/publications/waste/tyres/national-approach/; Atech Group, "A National Approach to Waste Tyres." Prepared for Environment Australia, June 2001. Available online at: www.deh.gov.au/settlements/publications/waste/tyres/national-approach/.

[13] For the composition of these three categories of mixed paper, please see Exhibit 3-2.

1.3   KEY INPUTS FOR THE STREAMLINED LIFE-CYCLE INVENTORY

Evaluating the GHG emissions of waste management requires analysis of three factors: (1) GHG emissions throughout the life cycle of the material (including the chosen disposal option); (2) the extent to which carbon sinks are affected by manufacturing 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 utility GHG emissions.

GHG Emissions Relevant to Waste: The most important GHGs for purposes of analyzing MSW management options are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and perfluorocarbons (PFCs). Of these, CO_2 is by far the most common GHG emitted in the United States. Most CO_2 emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is manufactured and then discarded. This energy is used in the following stages: (1) extracting and processing raw materials; (2) manufacturing products; (3) managing products at the end of their useful lives; and (4) transporting materials and products from one life-cycle stage to another. This study estimated energy-related GHG emissions during all of these stages, except for transportation of products from retailers to consumers (because GHG emissions resulting from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining the methodology employed for quantifying the energy used—and the resulting CO_2 emissions—at each stage in the life cycle of any given material in MSW. Energy consumed in connection with consumer use of products is not evaluated, because it is assumed that energy use for the selected materials would be about the same whether the product is 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.

CH_4, a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. CH_4 from landfills is the largest source of CH_4 in the United States;[14] these emissions are addressed in Chapter 6. CH_4 is also emitted when natural gas is released to the atmosphere during production of coal or oil, production or use of natural gas, and agricultural activities.

N_2O results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. This analysis estimated N_2O emissions from waste combustion.

PFCs (tetrafluoromethane (CF_4) and hexafluoroethane (C_2F_6)) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine for CF_4 and C_2F_6 is the molten cryolite (Na_3AlF_6) where the reduction of alumina occurs. PFCs are formed when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes,

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Comparing GHGs

CO_2, CH_4, N_2O, and PFCs are very different gases in terms of their heat-trapping potential. An international protocol 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 1kilogram (kg) of CO_2 is 1.

CH_4 has a GWP of 21, which means that 1 kg of CH_4 has the same heat-trapping potential as 21 kg of CO_2.

N_2O has a GWP of 310.

PFCs are the most potent GHG included in this analysis; GWPs are 6,500 for CF_4 and 9,200 for C_2F_6.

In this report, emissions of CO_2, CH_4, N_2O, and PFCs have been converted to their "carbon equivalents." Because CO_2 is 12/44 carbon by weight, 1 metric ton of CO_2 is equal to 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for 1 metric ton of each of the other gases is determined by multiplying its GWP by a factor of 12/44. (All data provided here are from the IPCC, *Climate Change 1995: The Science of Climate Change*, 1996, p. 121.)

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[14] EPA. 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2003*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-430-R-05-003.

or prebaked carbon blocks) and in the carbon lining that serves as the cathode. Although the quantities of PFCs emitted are small, these gases are significant because of their high global warming potential.

Carbon Stocks, Carbon Storage, and Carbon Sequestration: This analysis includes carbon storage to the extent that it is due to waste management practices. Carbon storage involves taking carbon-rich (biogenic) waste, such as wood products, and managing it so that the carbon is stored, rather than released to the atmosphere through burning or decay. For example, landfilled organic materials result in landfill carbon storage, as carbon is moved from a product pool (e.g., furniture) to the landfill pool. The same is true for composted organics that lead to carbon storage in soil.

Carbon sequestration differs from carbon storage because it represents a transfer of carbon from the atmosphere to a carbon pool, rather than the preservation of materials already containing carbon, as in landfilling. Carbon sequestration occurs when trees or other plants undergo photosynthesis, converting CO_2 in the atmosphere to carbon in their biomass. In this analysis, EPA considers the impact of waste management on forest carbon sequestration. The amount of carbon stored in forest trees is referred to as a forest's carbon stock.

The baseline against which changes in carbon stocks are measured is a projection by the U.S. Forest Service of forest growth, mortality, harvests, and other removals under anticipated market conditions for forest products. One of the assumptions for the projections is that U.S. forests will be harvested on a sustainable basis (i.e., trees will be grown at a rate at least equal to the rate at which they are cut).[15] Thus, the baseline assumes that harvesting trees at current levels results in no diminution of the forest carbon stock and no additional CO_2 in the atmosphere. On the other hand, forest carbon sequestration *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.

Although source reduction and recycling are associated with forest carbon sequestration, composting—in particular, application of compost to degraded soils—enhances soil carbon storage. Four mechanisms of increased carbon storage are hypothesized in Chapter 4; a modeling approach is used to estimate the magnitude of carbon storage associated with three of those mechanisms.

Finally, landfills are another means by which carbon is removed from the atmosphere. 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. However, not all carbon in landfills is counted in determining the extent to which landfills are carbon stocks. For example, the analysis does not count plastic in landfills toward carbon storage. Plastic in a landfill represents simply a transfer from one carbon stock (the oil field containing the petroleum or natural gas from which the plastic was made) to another carbon stock (the landfill); thus, no change has occurred in the overall amount of carbon stored. On the other hand, the portion of organic matter (such as yard trimmings) that does not decompose in a landfill represents an addition to a carbon stock, because it would have largely decomposed into CO_2 if left to deteriorate on the ground.

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[15] Assuming a sustainable harvest in the United States is reasonable because from 1952 to 1997 U.S. forest carbon stocks steadily increased. In the early part of this period, the increases were mostly due to reversion of agricultural land to forest land. More recently, improved forest management practices and the regeneration of previously cleared forest areas have resulted in a net annual uptake (sequestration) of carbon. The steady increase in forest carbon stocks implies sustainable harvests, and it is reasonable to assume that the trend of sustainable harvests will continue.

Although changes in fossil fuel carbon stocks (i.e., reductions in oil field stores that result from the extraction and burning of oil resources) are not measured *directly* in this analysis, the reduction in fossil fuel carbon stocks is indirectly captured by counting the CO_2 emissions from fossil fuel combustion in calculating GHG emissions.

Avoided Electric Utility GHG Emissions Related to Waste: Waste that is used to generate electricity (either through waste combustion or recovery 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 fuel 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.

Reference Years: The reference year selected for most parts of the analysis is the most recent year for which data are available. However, for the system efficiency and ferrous recovery rate at waste combustors, this study uses values previously projected for the year 2000. For paper recycling, annual projections through 2019 were used to develop an average forest carbon storage value for the period from 2005 through 2019.[16] The compost analysis relied on model simulations of compost application, beginning in 1996 and ending in 2005. The carbon storage estimates resulting from these model runs correspond to model outputs in 2010. The EPA researchers developed "future"[17] scenarios for paper recycling, composting, and carbon storage analyses because some of the underlying factors that affect GHG emissions are changing rapidly, and this study seeks to define relationships (e.g., between tonnage of waste landfilled and CH_4 emissions) that represent an average over the next several years. Some of these scenarios are described in more detail below.

- When the first edition of this report was published in 1998, there were some small municipal waste combustors that did not recover energy. The modeling summarized in the report assumed that those facilities will be closed in the near future; all combustors are assumed to recover energy. The initial study also used an estimate provided by the combustion industry for anticipated levels of ferrous recovery.

- For paper recycling, earlier analyses indicated that the marginal impact of increased paper recycling on forest carbon sequestration changes over time. The impact also differs depending on the initial paper recycling rate and how that rate changes over time. To estimate the impact of increased paper recycling on forest carbon sequestration, the study needed to account for these influences. First, EPA used the American Forest and Paper Association's estimate of a 50 percent paper recycling rate in 2003.[18] The trajectory for a baseline scenario for paper recycling passes through 50 percent in 2000, with continued modest increases in the following years. Because of the need to estimate the impact of efforts (e.g., by EPA) to enhance recycling beyond the baseline projected rate, the researchers developed a plausible scenario for enhanced paper recycling rates and then compared the projected forest carbon sequestration under the baseline and increased recycling scenarios.[19] (This approach is fully described in Chapter 3.)

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[16] The models EPA used simulated carbon sequestration through 2040, but the researchers selected a value based on average conditions through 2020.

[17] In the case of system efficiency and ferrous recovery at waste combustors, the year 2000 represented a future value when the first edition of this report was published. The 2000 values have not been updated; therefore, the values in this report no longer reflect future conditions. This edition of the report does not reflect these updated values.

[18] Actual paper recovery in 2003 (taken from EPA's *Municipal Solid Waste in the United States: 2003 Facts and Figures*) averaged about 48 percent, confirming that 50 percent is a reasonable approximation for 2003.

[19] Note that this estimate is necessary for analyzing the scenarios; however, it does not represent a plan of action by EPA.

- The landfill recovery scenario is based on estimated recovery rates and percentages of waste disposed in landfills with no recovery, landfills with only flaring, and landfills with landfill-gas-to-energy projects for the year 2004. According to the researchers' estimates, 59 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 41 percent was generated at landfills without landfill gas (LFG) recovery.[20] Of the 59 percent of all CH_4 generated at landfills with LFG recovery, 53 percent (or 31 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 47 percent (or 28 percent of all CH_4) at landfills that flare LFG.[21]

1.4 SUMMARY OF THE LIFE-CYCLE STAGES

Exhibit 1-2 shows the GHG sources and carbon sinks associated with the manufacture of various materials and the postconsumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from (1) the preconsumer stages of raw materials acquisition and manufacturing, and (2) the postconsumer stage of waste management. No GHG emissions are attributed to the consumer's use of any product.

The remainder of this chapter describes how this study analyzed each of the upstream (raw materials acquisition, manufacturing, and forest carbon sequestration) and downstream (source reduction, recycling, composting, combustion, and landfilling) stages in the life cycle. The following sections explain stages of the life cycle (Exhibit 1-2) and the corresponding emission factor components (Exhibit 1-3), and outline the GHG emissions and carbon sinks associated with each stage. These GHG emissions and carbon sinks are described in detail and quantified for each material in Chapters 2 through 6.

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

The top left corner of Exhibit 1-2 shows inputs for *raw materials acquisition*. These virgin inputs are used 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 used to obtain or extract these material inputs.

The inputs used in *manufacturing* are (1) energy and (2) either virgin raw materials or recycled materials. In the exhibit, these inputs are identified with arrows that point to the icon labeled "Manufacturing."

For source reduction, the "baseline" GHG emissions from raw materials acquisition and manufacturing are avoided. This analysis thus estimates, for source reduction, the GHG *reductions* (relative to a baseline of initial manufacture) at the raw materials acquisition and manufacturing stages. Source reduction is assumed to entail more efficient use of a given material. Examples are lightweighting (reducing the quantity of raw material in a product), double-sided photocopying, and extension of a product's useful life). In the case of clay bricks, source reduction refers to the reuse of old bricks. No other material substitutions are assumed for source reduction; therefore, this report does not

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[20] Based on landfill CH_4 generation and collection data from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2004*), and an estimated national average landfill CH_4 recovery efficiency of 75 percent.

[21] The assumption that 53 percent of landfills recovering CH_4 use it to generate electricity is subject to change over time based upon changes in the cost of recovery, and the potential payback. Additionally, new technologies may arise that use recovered CH_4 for purposes other than generating electricity.

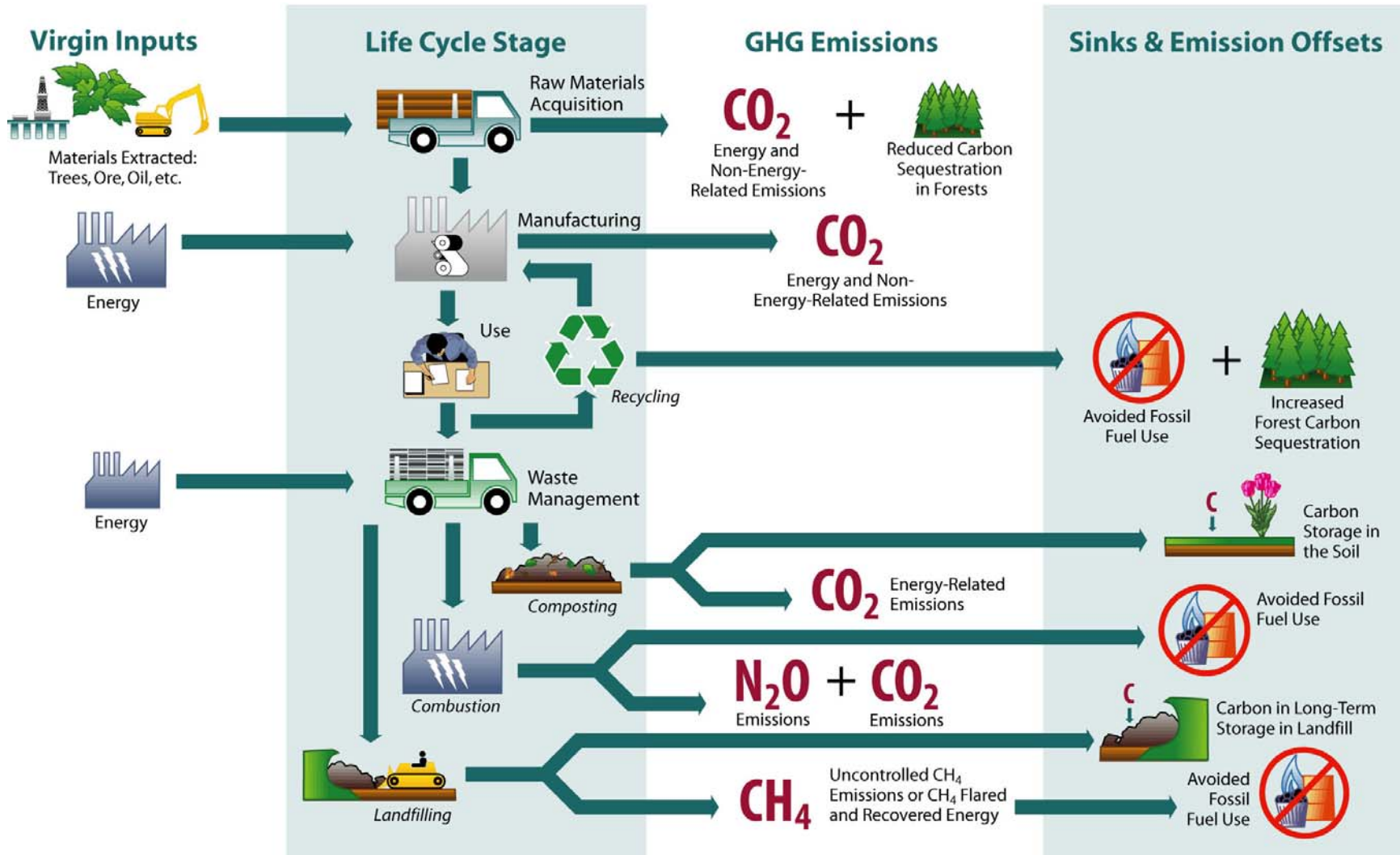**Exhibit 1-2 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle**

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

MSW Management Strategy	GHG Sources and Sinks		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	**Forest Carbon Sequestration or Soil Carbon Storage**	**Waste Management GHGs**
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration	NA
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process nonenergy GHGs	Increase in forest carbon sequestration	Process and transportation emissions are counted in the manufacturing stage
Composting	No emissions/sinks[a]	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	NA	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	NA	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

[a] No manufacturing transportation GHG emissions are considered for composting of food discards and yard trimmings because these materials are not considered to be manufactured.
NA = Not Applicable

analyze any corresponding increases in production and disposal of other materials (which could result in GHG emissions).[22] For some materials, such as fly ash, food discards, yard trimmings, and concrete, source reduction was not considered a possible management strategy.

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,[23] and (3) nonenergy GHG emissions resulting from manufacturing processes (for aluminum, steel, plastics, and office paper). Each type of emission is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper products.

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.)

The majority of process energy CO_2 emissions are 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 those fuels to the place where they are used. Thus, indirect CO_2 emissions from this "precombustion energy" are counted in this category as well.

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[22] Although material substitution is not quantitatively addressed in the report, it is discussed from a methodological standpoint in Chapter 2 and also is discussed briefly in Chapter 3, Section 3.4.

[23] For some materials (plastics, magazines/third-class mail, office paper, phonebooks, 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.

When electricity generated by combustion of fossil fuels is used in manufacturing, the CO_2 emissions from the fossil fuels also are counted.

To estimate process energy GHG emissions, the study 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, emissions factors for each type of fuel were used to convert fuel consumption to GHG emissions. 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.

The fuel mixes used in these calculations reflect the 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 be different. For example, China relies heavily on coal and generally uses energy less efficiently than the United States. Consequently the GHG emissions associated with the manufacture of a material in China may be higher than 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 report, which focuses only on domestic production, transportation, consumption, and disposal.

Details of the methodology for estimating process energy GHG emissions are provided in Chapter 2.

Transportation Energy GHG Emissions: Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fuels used to transport raw materials and intermediate products 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 1 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 (this information can be found in Background Document A[24]). Then an emission factor for each type of fuel was used to convert the amount of each type of fuel consumed to the GHG emissions produced.

This edition includes estimates of GHG emissions from transporting manufactured products or materials from the manufacturing point to the retail/distribution point. The U.S. Census Bureau along with the Bureau of Transportation Statistics recently conducted a Commodity Flow Survey that determined the average distance commodities were shipped in the United States and the percentage each of the various transportation modes was used to ship these commodities.[25] However, there is large variability in the shipping distance and modes used, and so transportation emission estimates given here are somewhat uncertain. More detail on the methodology used to estimate transportation energy GHG emissions is provided in Chapter 2.

Process Nonenergy 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 nonenergy 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. Other process nonenergy GHG emissions are associated

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[24] *Background Document A: A Life Cycle of Process and Transportation Energy for Eight Different Materials*. Available at EPA's Global Warming—Waste, "Background Documents for Solid Waste Management and GHG Report" website. Op cit.

[25] U.S. Census Bureau, 2003. *Commodity Flow Survey*. United States Census Bureau. December, 2003. Available online at: http://www.census.gov/prod/ec02/02tcf-usp.pdf.

with the manufacture of plastics, office paper, and medium-density fiberboard. In some cases, process nonenergy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are described in Chapter 2.

Carbon Sinks: The only carbon sink associated with the raw materials acquisition and manufacturing stage is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. The methodology for estimating forest carbon sequestration is described in Chapter 3.

1.4.2   GHG Emissions and Carbon Sinks Associated with Waste Management

As shown in Exhibit 1-3, there are up to five postconsumer waste management options, depending on the material: source reduction, recycling, composting, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with each option.

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 source reduction. The avoided GHG emissions are based on raw material acquisition and manufacturing processes for the average current mix of virgin and recycled inputs for materials in the marketplace.[26] There are no emissions from MSW management.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs (including the process of collecting and transporting the recyclables). No GHG emissions occur at the MSW management stage because the recycled material is diverted from waste management facilities.[27] (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.) Chapter 3 details GHG emissions from recycling.

Materials are recycled either in "closed-loop" or "open-loop" processes. Closed loop means that a product is recycled into the same product; an example is an aluminum can recycled into another aluminum can. Open loop means that the secondary product is different than the primary product and often occurs when a material is degraded or changed by the recycling process. Most of the materials considered in this analysis are modeled as being recycled in a closed loop. However, a variety of paper types are recycled under the general heading of "mixed paper." Mixed paper can be remanufactured, via an open loop, into boxboard or paper towels. Other materials are recycled in open-loop processes, but due to limited resources, this study could not analyze all open-loop processes.[28] Three newly added materials, fly ash, carpet, and PCs, are analyzed only in an open-loop process. In the case of PCs, the used computers are sent to a processing facility where various components, such as copper, lead, glass, and plastic, are put into separate streams. Carpet is also remanufactured into secondary materials other than carpet.

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[26] 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.

[27] 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.

[28] For example, not all steel cans are recycled into more steel cans; not all aluminum cans are recycled into more aluminum cans, but for the purposes of this report, EPA assumes they are.

CO$_2$ Emissions from Biogenic Sources

The United States and all other parties to the UNFCCC agreed to develop inventories of GHG emissions as part of its stated goals of stabilizing emissions and preventing dangerous anthropogenic climate change. The IPCC developed a set of inventory methods to be used as the international standard. (IPCC 1997. *IPCC Guidelines for National Greenhouse Gas Inventories*, three volumes.) 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$_2$ releases 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 the CO$_2$ emissions are not anthropogenic and therefore *not* included in emission inventories. (For purposes of this analysis, biogenic materials are paper, 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), it is treated the same.

Composting: When organic materials are composted, the anaerobic decomposition of materials produces CH$_4$. Similarly, the collection and transportation of organics produces nonbiogenic emissions. During the composting process and after the compost is added to the soil, the decomposition of plants produces biogenic CO$_2$ emissions. All of the materials that may be composted (e.g., leaves, brush, grass, food waste, newspaper) originally are produced by trees or other plants. As described in the above "CO$_2$ Emissions from Biogenic Sources," the biogenic CO$_2$ emitted from these materials during composting is not counted toward GHG emissions. However, composting does result in increased soil carbon storage due to increased production of humic material (natural organic polymers, which degrade at a slow rate) and several other factors, which are described in Chapter 4.

Although composting may result in some production of CH$_4$ (due to anaerobic decomposition in the center of the compost pile), compost researchers believe that the CH$_4$ almost always oxidizes to CO$_2$ before it escapes from the compost pile.

Because the CO$_2$ emissions from composting are biogenic, and well-managed compost piles are not believed to produce CH$_4$, the only GHG emissions from composting result from transportation of compostable materials to composting facilities and mechanical turning of the compost piles. GHG emissions associated with compost application are discussed in Chapter 4.

Combustion: When waste is combusted, two GHGs are emitted: CO_2 and N_2O. 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 is not. Because most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described in Chapter 5.

Landfilling: When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4, a GHG. 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 that CO_2 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 Chapter 6.

1.5   ESTIMATING AND COMPARING NET GHG EMISSIONS

To calculate the net GHG implications of a waste management strategy for a given material, baseline and alternative scenarios must be established. For example, a baseline scenario in which 10 tons of office paper are manufactured, used, and landfilled could be compared with an alternative scenario in which 10 tons are manufactured, used, and recycled. For this example, net GHG emissions are calculated as the difference between landfilling emissions and the emissions/emission reductions associated with recycling. The general formula for net GHG emissions for each scenario is as follows:

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

Comparing net GHG emissions for the two scenarios enables the lowest net GHG emissions to be identified. 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* results in carbon sequestration of organic materials.

- *Landfilling* results in CH_4 emissions. 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 emissions offset if the waste is burned in a waste-to-energy facility, which displaces fossil-fuel derived electricity.

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In calculating emissions for the life-cycle scenarios, one can utilize a "raw material extraction" reference point, or a "waste generation" reference point. The raw material extraction reference point is a cradle-to-grave approach, in which emissions are calculated starting with the extraction of raw materials (e.g., ore) used to create virgin inputs. Since this report is designed to be used mainly by solid waste managers, the emission factors presented in the main body of the document are based on the waste generation reference point, one that starts when a material is discarded. Emission factors using a raw material extraction reference point are presented in the Appendices.

Exhibit 1-3 indicates how GHG sources and sinks have been counted for each MSW management strategy in order to estimate net GHG emissions using the postconsumer waste generation reference point. 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, and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions. Section 7.2, "Accounting for Emission Reductions and Energy Savings," describes how waste managers and companies have used these emission factors to estimate GHG emissions and potential GHG emission reductions associated with integrated waste management. In addition, EPA uses these emission factors to develop WARM, which enables users to analyze the GHG savings associated with changing their waste management practices. EPA also recently developed the ReCon Tool and the Durable Goods Calculator (DGC). The ReCon tool helps both individual and corporate consumers calculate the GHG and energy benefits of purchasing or manufacturing materials with varying recycled content; the DGC allows consumers to calculate the GHG and energy impacts of different disposal methods for durable goods such as refrigerators and televisions. As with WARM, the ReCon Tool is available as both an online calculator and as a spreadsheet tool, while the DGC is currently available only as a spreadsheet tool.[29]

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[29] Available at the EPA, Global Warming—Waste website. Op cit. WARM and ReCon are available at: http://www.epa.gov/mswclimate, then follow link to Tools.