METALS

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

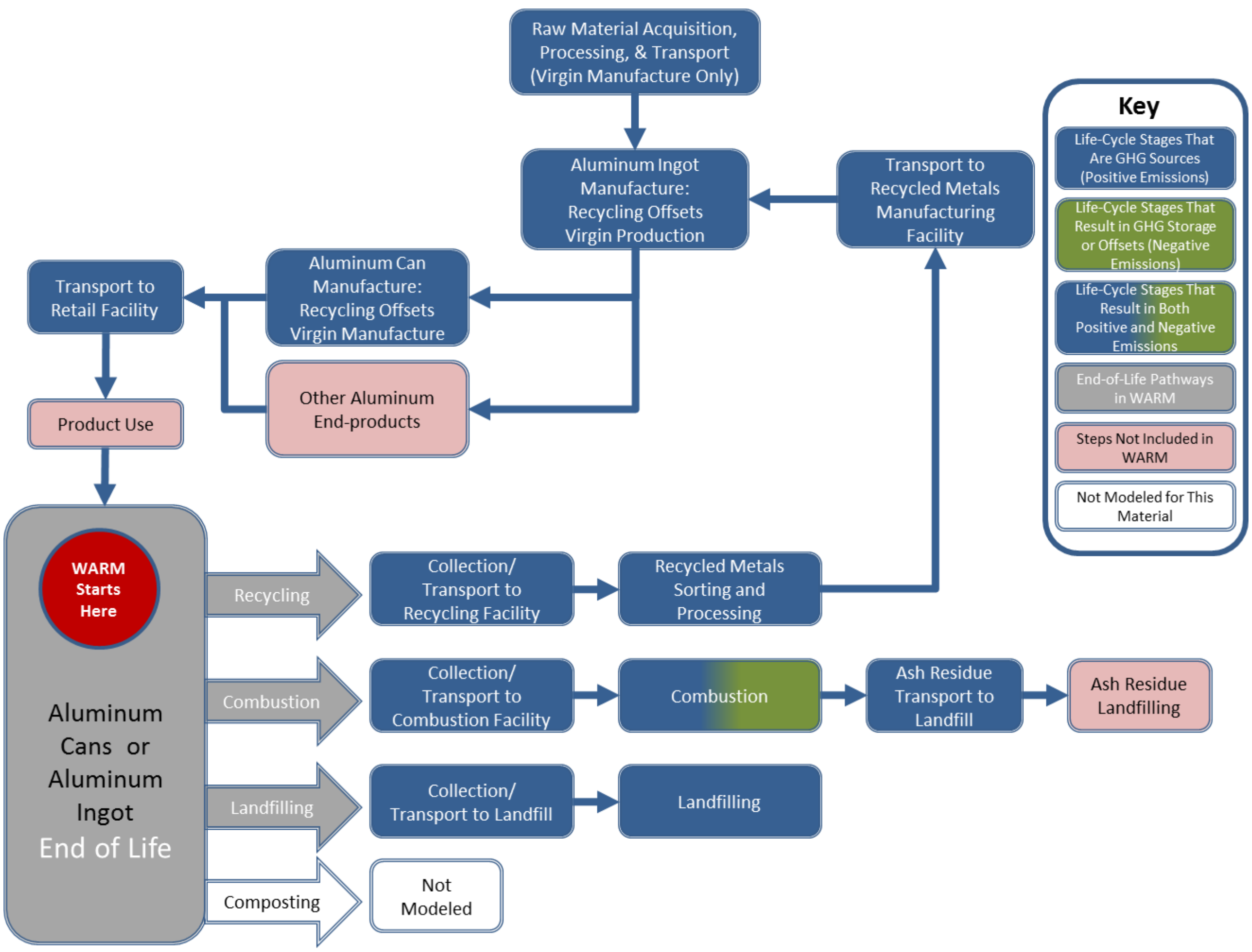


Exhibit 2: Life Cycle of Steel Cans in WARM

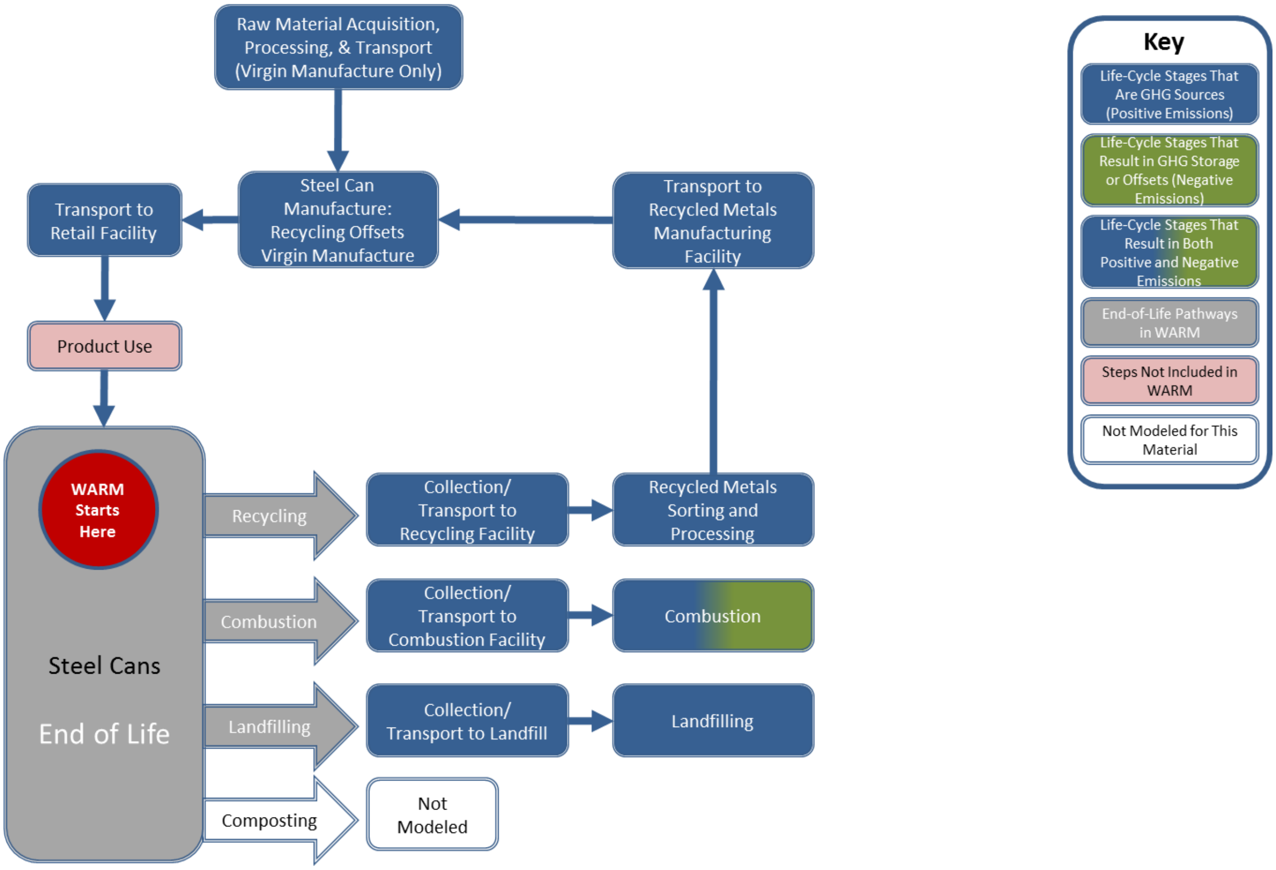
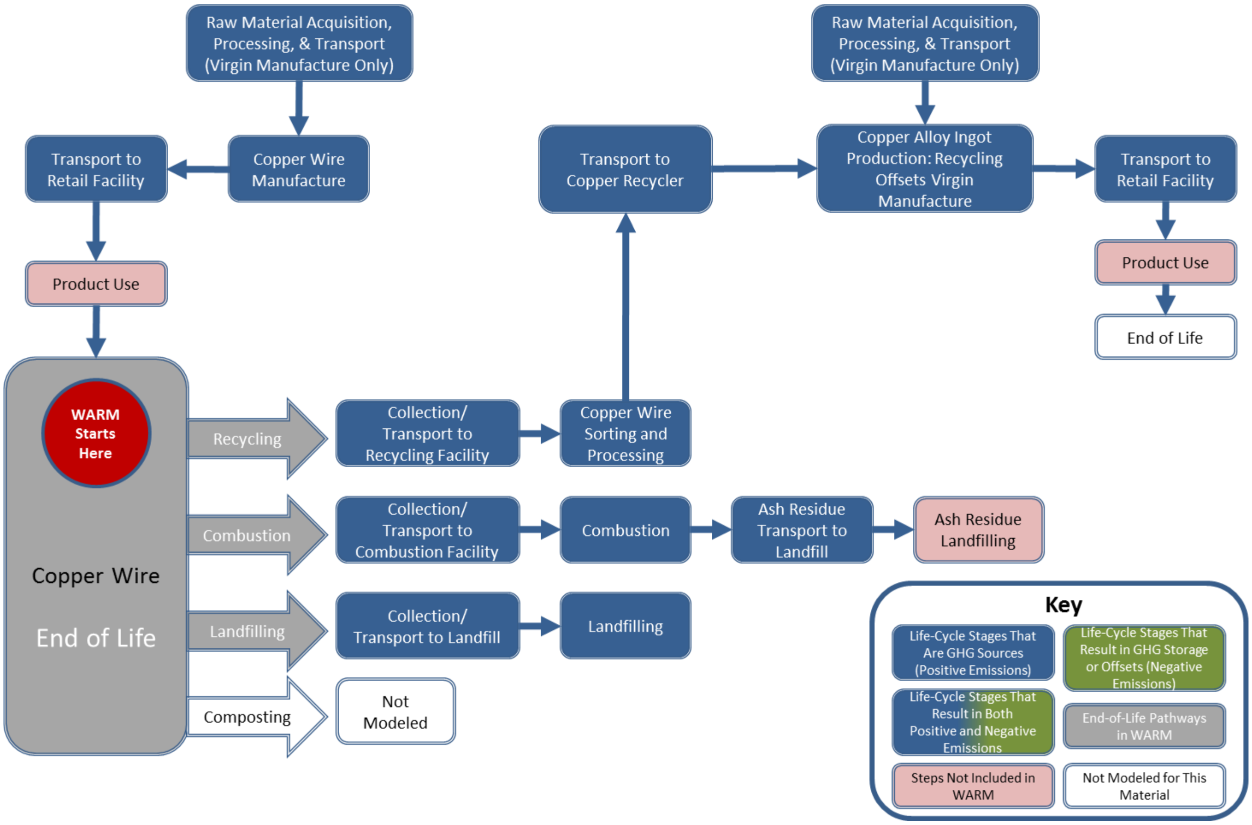


Exhibit 3: Life Cycle of Copper Wire in WARM



The metals category in WARM comprises copper wire, steel cans, and aluminum cans and ingot.[1] 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 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.

[1] 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 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[2], 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 4).

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

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.[3] 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 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 5.

Exhibit 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 8.

As Exhibit 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.[4] 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.

[3] 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.

[4] 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 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 • Sorting and processing energy
Composting	Not applicable since metals cannot be composted		
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Energy required for combustion **Offsets** • Steel recovery and recycling
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 6 and calculates net GHG emissions per short ton of metal generated for each materials management alternative as shown in Exhibit 7. For additional discussion on the detailed methodology used to develop these emission factors, see sections 3 and 4.

Exhibit 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.

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 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 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 ($MTCO_2E$ 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.

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.[5] 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

[5] 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.[6] 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).

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

[6] 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.[7]

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.

3.3 COPPER WIRE

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

4. MATERIALS MANAGEMENT

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 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 9 shows the range of recycled content used for manufacturing steel, and value for "virgin" steel used in WARM.

Exhibit 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)

[7] 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 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 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 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.

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 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 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.

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 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 4.2, Recycling.

Exhibit 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 13.

Exhibit 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 14.

Exhibit 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
Aluminum Ingot	0.56	0.04

Material/Product	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
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 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 15 shows the components for estimating process non-energy GHG emissions for each category of metals.

Exhibit 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_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/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.

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 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"[8] 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,[9] 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).[10]

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 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 16: Copper Wire Scrap Mix Used to Create Copper Ingot

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

Source: USGS (2004b).

[8] 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.
[9] 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 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 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.

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 13, Exhibit 14, and Exhibit 15 in the source reduction section for aluminum and steel and in Exhibit 18 and Exhibit 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 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 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 (MTCO2E/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 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, Exhibit 21, and Exhibit 22 present the results for recycled or secondary product process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

Exhibit 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 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 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 23.

Exhibit 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 24 are the product of the recovery and manufacturing retention rates.

Exhibit 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 23 by the retention rates in the last column of Exhibit 24.

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.

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 25 provides the emission factors related to combusting of metals.

Exhibit 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.

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.[11] 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).[12] 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 26.

Exhibit 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

[11] 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.

[12] 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.

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 27 provides the net emission factor for landfilling of metals.

Exhibit 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

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[13]), 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

[13] 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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