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

Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM)

Electronics

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Office of Resource Conservation and Recovery

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Table of Contents

1 ELECTRONICS

1.1 INTRODUCTION TO WARM AND ELECTRONICS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for desktop central processing units (CPUs), portable electronic devices, flat-panel displays, cathode ray tube (CRT) displays, electronic peripherals, and hard-copy devices beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with these six types of electronics in the following four materials management alternatives: source reduction, recycling, landfilling, and combustion. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, Landfilling, and Combustion, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

The following electronic material types are modeled in WARM:

- *Desktop CPUs*. Desktop CPUs include the stand-alone processing unit for a desktop computer and does not include the monitor or any peripherals (e.g., mice, keyboards).
- *Portable electronic devices*. Portable electronic devices include laptops, e-readers, tablets, smart phones, and basic mobile phones.
- *Flat-panel displays.* Flat-panel displays include LED and liquid crystal display (LCD) televisions, plasma televisions, and LED and LCD computer monitors.
- *CRT displays.* CRT displays include CRT televisions and CRT computer monitors. While CRT displays are no longer manufactured, many are still entering the waste stream in the U.S.
- *Electronic peripherals.* Electronic peripherals consist of electronic devices used in conjunction with other products and include keyboards and mice.
- *Hard-copy devices*. Hard-copy devices include electronic devices used for preparing hard-copy documents, including printers and multi-function devices.
- *Mixed electronics.* The weighted average mix of electronic material types represented by the mixed electronics material is based on data from The Electronics Recycling Landscape Report, prepared for the Closed Loop Foundation (Mars et al., 2016) and presented in Exhibit 1-1. This weighting represents the mass of electronics generated for waste in 2015.

Exhibit 1-1: Relative Prevalence of Electronics in the Waste Stream in 2015 (Mars et al., 2016)

Material	Weighting
Desktop CPUs	11%
Portable Electronic Devices	5%
Flat-Panel Displays	23%
CRT Displays	44%
Electronic Peripherals	2%
Hard-Copy Devices	15%

Upon disposal, electronics can be recovered for recycling, sent to a landfill or combusted. Exhibit 1-2 shows the general outline of materials management pathways in WARM. Recycling electronics is an open-loop process, meaning that components are recycled into secondary materials such as steel sheet, lead bullion, copper wire, and aluminum sheet and not necessarily recycled back into new electronics.

Electronics are collected curbside and at special events, or individuals can bring them to designated drop-off sites such as at electronics stores. Once electronics have been collected for recycling, they are sent to Material Recovery Facilities (MRFs) that specialize in separating and recovering materials from electronic products. Building on Exhibit 1-2, a more detailed flow diagram showing the open-loop recycling pathways of electronics is provided in Exhibit 1-3.

Exhibit 1-2: Life Cycle of Electronics in WARM

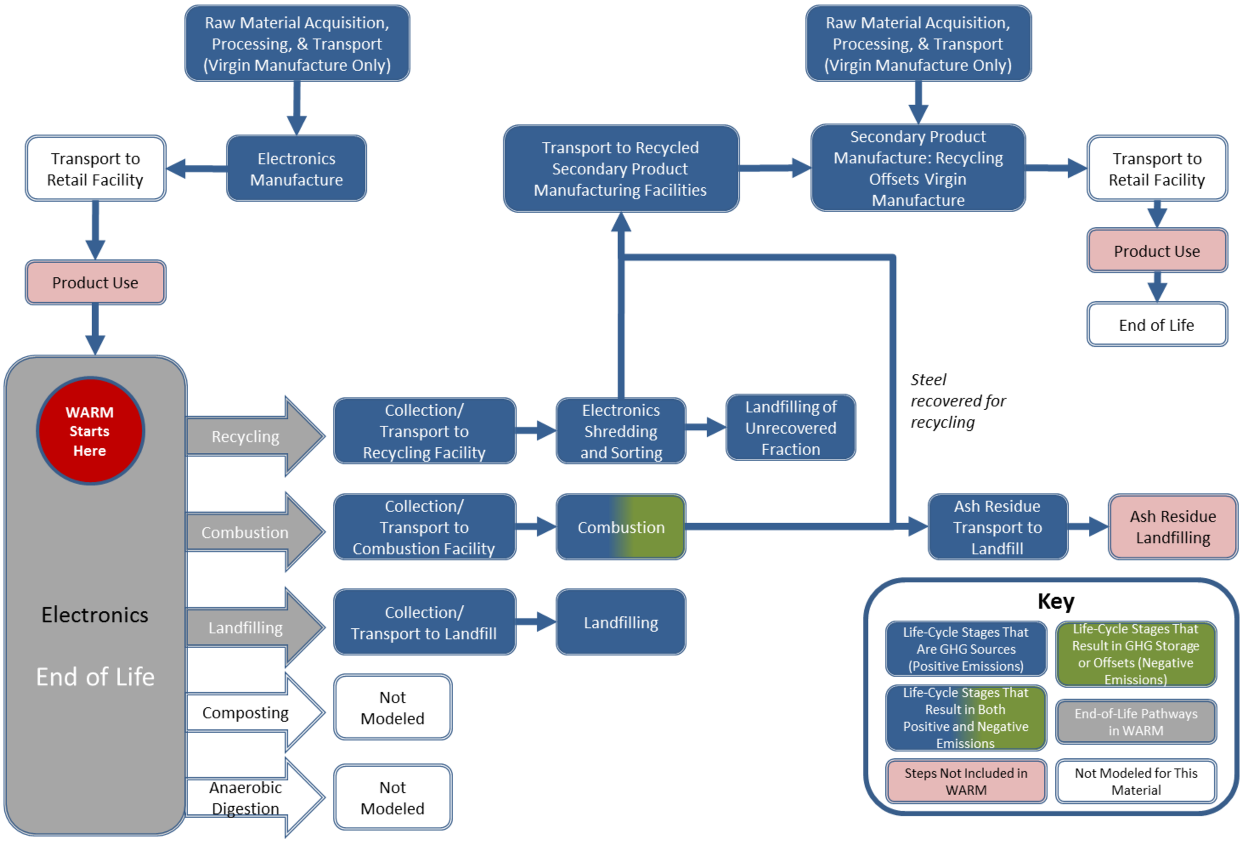
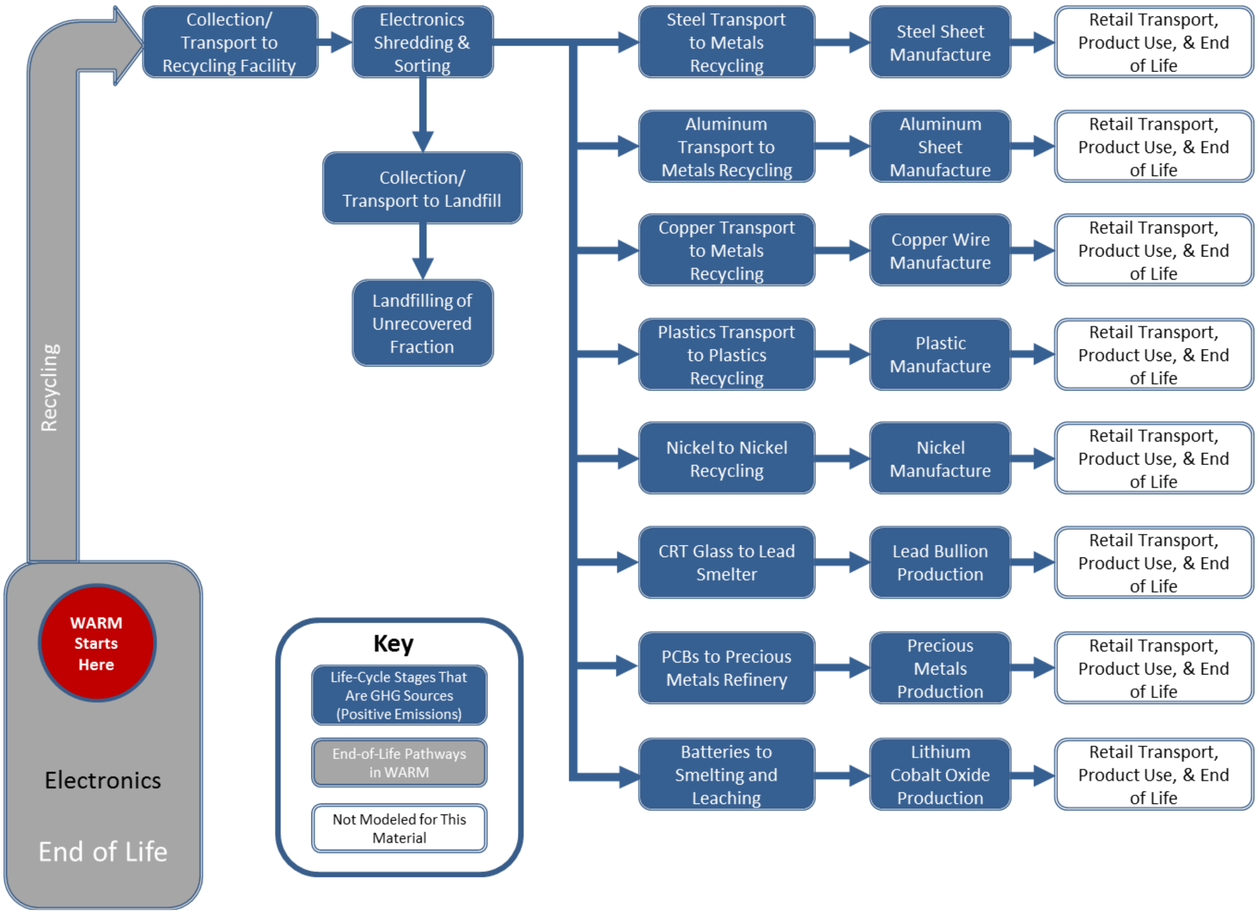


Exhibit 1-3: Detailed Recycling Flows for Electronics in WARM



1.2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

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

WARM includes source reduction, recycling, landfilling and combustion pathways for materials management of electronics. Anaerobic digestion and composting are not included as a pathway for materials management of electronics. As Exhibit 1-4 illustrates, most of the GHG emissions from end-of-life management of electronics occur from the waste management of these products, while most of the GHG savings occur from offsetting upstream raw materials acquisition and manufacturing of other secondary materials that are recovered from electronics.

Exhibit 1-4: Electronics GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for Electronics	GHG Sources and Sinks Relevant to Electronics		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**Materials Management**
Source Reduction	**Offsets** • Transport of raw materials and intermediate products • Virgin process energy • Virgin process non-energy • Transport of electronics to point of sale	NA	NA
Recycling	**Emissions** • Transport of recycled materials • Recycled process energy • Recycled process non-energy **Offsets** • Emissions from producing plastic, steel, copper, aluminum, lead, nickel, precious metals, and lithium cobalt oxide from virgin material	NA	**Emissions** • Collection of electronics and transportation to recycling center • Demanufacturing electronics • Landfilling the faction of electronics not recovered for recycling
Composting	Not applicable because electronics cannot be composted		
Landfilling	NA	NA	**Emissions** • Transport to landfill • Landfilling machinery
Combustion	NA	NA	**Emissions** • Transport to WTE facility • Combustion-related CO_2 and N_2O **Offsets** • Avoided utility emissions • Steel recovery
Anaerobic Digestion	Not applicable because electronics cannot be anaerobically digested		

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 1-4 and calculates net GHG emissions per short ton of electronics inputs as shown in Exhibit 1-5. For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

Exhibit 1-5: Net Emissions for Electronics under Each Materials Management Option ($MTCO_2E$/Short Ton)

Material	Net Source Reduction Emissions for Current Mix of Inputs[a]	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions	Net Anaerobic Digestion Emissions
Desktop CPUs	(20.86)	(1.49)	NA	(0.66)	0.02	NA
Portable Electronic Devices	(29.83)	(1.06)	NA	0.65	0.02	NA
Flat-Panel Displays	(24.19)	(0.99)	NA	0.03	0.02	NA
CRT Displays	NA	(0.57)	NA	0.45	0.02	NA
Electronic Peripherals	(10.32)	(0.36)	NA	2.08	0.02	NA
Hard-Copy Devices	(7.65)	(0.56)	NA	1.20	0.02	NA
Mixed Electronics	NA	(0.79)	NA	0.39	0.02	NA

[a] The current mix of inputs for electronics is considered to be 100% virgin material. Source reduction is not available as a management option for CRT displays and mixed electronics because CRT displays are no longer manufactured and therefore their production cannot be avoided.

1.3 RAW MATERIALS ACQUISITION AND MANUFACTURING

The wide range of different electronic products entering the waste stream every year makes it difficult to specify the exact composition of a typical electronic product, and the technology for new electronics continues to evolve rapidly. Electronics products can have a large amount of complexity in design, using a wide array of materials and components. Fortunately, these materials and components are similar across electronics products, where similar metals, plastics, display technologies, batteries and circuit boards can be found in many common products. To streamline the process of developing life-cycle GHG emission factors for a range of electronic products, EPA modeled the life-cycle GHG emission factors for electronics in WARM based on the assumption that the same material components are shared across the types of electronics in WARM. Babbitt et al. (2017) provides a detailed summary of recent trends in U.S. electronics sales and the material make-up of these electronics. The study closely examined 19 different products and generated mass characteristics for 12 component categories. Based on this study, the components modeled in WARM include:

- *Ferrous metal*. Ferrous metal in electronics is assumed to be composed of stamped, cold rolled steel.
- *Aluminum.* Aluminum in electronics is assumed to be composed of shape cast aluminum components.
- *Copper.* Copper in electronics is assumed to be composed primarily of copper wire.
- *Other metals.* Other common metals frequently found in electronics include nickel, zinc, and tin (Andrea et al., 2014).
- *Plastic*. A wide range of plastic resins are commonly found in electronics. For the purpose of modeling in WARM, EPA assumed that electronics contain a mix of acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PET), polycarbonate (PC), polyamide (PA), polyvinyl chloride (PVC), high-density polyethylene (HDPE), polypropylene (PP), polyurethane (PUR), and epoxy (Andrea et al., 2014).
- *Printed circuit board (PCB)*. PCBs consist of electronic components connected via laminated copper and non-conductive materials.
- *Flat panel display module*. Flat panel display modules are composite devices typical composed of cold cathode fluorescent lamps (CCFL) or light-emitting diodes (LED).
- *CRT glass and lead*. CRT displays include a large component of panel glass and funnel glass coated in lead.
- *Battery*. Batteries used to power portable electronic devices are assumed to be predominately lithium-ion systems (Babbitt et al., 2017).

These components are shared across the electronic materials modeled in WARM, which are intended to be representative of electronics entering the waste stream based on units sold in the U.S. from 1990 to 2017 (Babbitt et al., 2017). Exhibit 1-6 presents the component mass share of each electronic material type in WARM using data from Babbitt et al. (2017) and Hikwama (2005).

Exhibit 1-6: Component Mass Share for Electronics in WARM (Babbitt et al., 2017; Hikwama, 2005)

Material	Ferrous Metal	Aluminum	Copper	Other Metals	Plastic	Printed Circuit Board	Flat Panel Display Module	CRT Glass and Lead	Battery
Desktop CPUs	59%	11%	4%	0%	12%	14%	0%	0%	0%
Portable Electronic Devices	7%	12%	2%	4%	27%	14%	16%	0%	18%
Flat-Panel Displays	37%	7%	1%	0%	22%	6%	26%	0%	0%
CRT Displays	5%	1%	3%	0%	19%	11%	0%	61%	0%
Electronic Peripherals	2%	0%	26%	0%	68%	4%	0%	0%	0%
Hard-Copy Devices	37%	0%	1%	0%	59%	3%	0%	0%	0%

1.4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction, recycling, landfilling, and combustion pathways for materials management of electronics. It is important to note that electronics are not necessarily recycled into new electronics, however; they are recycled in an open loop. The LCA of their disposal must take into account the variety of second-generation products from recycling electronics. Information on electronics recycling and the resulting second-generation products is sparse; however, EPA has modeled pathways for which consistent LCA data are available for recycled electronics components. The second-generation products considered in this analysis are: steel into scrap steel, aluminum into scrap aluminum, copper into scrap copper, plastics into ground plastic, nickel into scrap nickel, CRT glass into lead bullion, precious metals into scrap precious metals, and batteries into scrap lithium cobalt oxide.

Source reduction leads to the largest reduction in GHG emissions for electronics, since manufacturing electronics and their components is especially energy intensive. Recycling electronics leads to greater reductions than combustion and landfilling, since it also reduces similarly energy-intensive product manufacturing. Combustion has a positive net emission factor for most electronic materials that is driven by the plastic content in electronics, while landfilling has a slightly positive emission factor due to the emissions from landfill operation equipment.

1.4.1 Source Reduction

Source reduction activities reduce the number of electronics that are produced, thereby reducing GHG emissions from electronics production. Increasing the lifetime of an electronic product (e.g., through upgrades in software) or finding alternatives to purchasing new electronics (e.g., using a donated product) are examples of source reduction. For more information on this practice, see the Source Reduction chapter.

Exhibit 1-7 outlines the GHG emission factor for source reducing electronics. GHG benefits of source reduction are calculated as the avoided emissions from raw materials acquisition and manufacturing (RMAM) of new electronics. Source reduction is not modeled for CRT displays because CRT displays are no longer manufactured. Similarly, source reduction is not modeled for mixed electronics because CRT displays are a component of mixed electronics.

Exhibit 1-7. Electronics Source Reduction Emission Factor ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon Storage for Current Mix of Inputs	Forest Carbon Storage for 100% Virgin Inputs	Net Emissions for Current Mix of Inputs	Net Emissions for 100% Virgin Inputs
Desktop CPUs	(20.86)	(20.86)	NA	NA	(20.86)	(20.86)
Portable Electronic Devices	(29.83)	(29.83)	NA	NA	(29.83)	(29.83)
Flat-Panel Displays	(24.19)	(24.19)	NA	NA	(24.19)	(24.19)
CRT Displays	NA	NA	NA	NA	NA	NA
Electronic Peripherals	(10.32)	(10.32)	NA	NA	(10.32)	(10.32)
Hard-Copy Devices	(7.65)	(7.65)	NA	NA	(7.65)	(7.65)
Mixed Electronics	NA	NA	NA	NA	NA	NA

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

1.4.1.1 Developing the Emission Factor for Source Reduction of Electronics

To calculate the avoided GHG emissions for electronics, EPA looked at three broad sources of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 1-8 shows the results for each broad source and the total GHG emission factor for source reduction for each of the electronics components modeled in WARM. More information on each component and broad emissions source making up the final emission factor is provided below.

Exhibit 1-8: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of Electronics by Component ($MTCO_2E$/Short Ton)

(a)	(b)	(c)	(d)	(e)
Component	Process Energy	Transportation Energy	Process Non-Energy	Net Emissions (e = b + c + d)
Ferrous Metal	2.32	IE	–	2.32
Aluminum	5.90	IE	–	5.90
Copper	6.72	0.03	–	6.76
Other Metals	4.82	IE	0.28	5.10
Plastic	4.28	0.11	0.38	4.76
Printed Circuit Board	126.70	IE	–	126.70
Flat Panel Display Module	54.59	IE	–	54.59
CRT Glass and Lead	NA	NA	NA	NA
Battery	4.79	IE	–	4.79

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
NA = Not applicable.
IE = Included elsewhere. Process energy emissions are assumed to encompass transportation energy.
– = Zero emissions.

First, EPA obtained an estimate of the amount of energy required to produce one short ton of each component. Next, we determined the fuel mix that comprises this Btu estimate using data from the same sources for each component and then multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. The sum of the resulting GHG emissions by fuel type comprises the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in electronics production. The process energy used to produce electronic components and the resulting emissions are presented in Exhibit 1-9, including the source for the process energy data.

Exhibit 1-9: Process Energy GHG Emissions Calculations for Virgin Production of Electronics by Component

Component	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)	Data Source(s)
Ferrous Metal	28.95	2.32	ANL, 2018
Aluminum	127.37	5.90	ANL, 2018
Copper	122.52	6.72	FAL, 2002
Other Metals	77.85	4.82	ANL, 2018; Ecoinvent Centre, 2015
Plastic	71.12	4.28	ANL, 2018; FAL, 2011a
Printed Circuit Board	607.07	126.70	Teehan and Kandlikar, 2013
Flat Panel Display Module	202.22	54.59	Teehan and Kandlikar, 2013
CRT Glass and Lead	NA	NA	NA
Battery	24.09	4.79	Teehan and Kandlikar, 2013

NA = Not applicable.

Transportation energy emissions come from fossil fuels used to transport component raw materials and intermediate products. The methodology for estimating these emissions is the same as that used for process energy emissions. Based upon an estimated total component transportation energy in Btu, EPA calculated the total emissions using fuel-specific carbon coefficients. For several of the components, transportation energy could be not be disaggregated from overall process energy; for these materials EPA assumed that the process energy was inclusive of transportation energy. The transportation energy used to produce electronic components and the resulting emissions are presented in Exhibit 1-10, including the source for the transportation energy data.

Exhibit 1-10: Transportation Energy Emissions Calculations for Virgin Production of Electronics by Component

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)	Data Source(s)
Ferrous Metal	IE	IE	ANL, 2018
Aluminum	IE	IE	ANL, 2018
Copper	0.46	0.03	FAL, 2002
Other Metals	IE	IE	ANL, 2018; Ecoinvent Centre, 2015
Plastic	0.69	0.69	ANL, 2018; FAL, 2011a
Printed Circuit Board	IE	IE	Teehan and Kandlikar, 2013
Flat Panel Display Module	IE	IE	Teehan and Kandlikar, 2013
CRT Glass and Lead	NA	NA	NA
Battery	IE	IE	Teehan and Kandlikar, 2013

Note: The transportation energy and emissions in this exhibit do not include retail transportation.
NA = Not applicable.
IE = Included elsewhere. Process energy emissions are assumed to encompass transportation energy.

Non-energy GHG emissions occur during manufacturing but are not related to combusting fuel for energy. For electronics, non-energy GHGs are emitted in the virgin production of plastic resins, copper, and tin (ANL, 2018; Ecoinvent Centre, 2015; FAL, 2011a; FAL, 2002). The various data sources provide data on GHG emissions from non-energy-related processes in units of pounds of native gas. EPA converted pounds of gas per 1,000 lbs. of component to metric tons of gas per short ton of component and then multiplied that by the ratio of carbon to gas to produce the emission factor in $MTCO_2E$ per short ton of component. Exhibit 1-11 shows the components for estimating process non-energy GHG emissions for electronics.

Exhibit 1-11: Process Non-Energy Emissions Calculations for Virgin Production of Electronics by Component

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Ferrous Metal	–	–	–	–	–	–
Aluminum	–	–	–	–	–	–
Copper	0.00	–	–	–	–	0.00
Other Metals	0.28	–	–	–	–	0.28
Plastic	0.20	0.01	–	–	0.00	0.38
Printed Circuit Board	–	–	–	–	–	–
Flat Panel Display Module	–	–	–	–	–	–
CRT Glass and Lead	NA	NA	NA	NA	NA	NA
Battery	–	–	–	–	–	–

– = Zero emissions.

1.4.2 Recycling

According to EPA (2015), 40 percent of consumer electronics were recycled in 2015. EPA and other organizations are focused on improving the recycling of electronics because of several factors: (1) rapid sales growth and change are generating a growing stream of obsolete products, (2) manufacturing electronics consumes large amounts of energy and materials, (3) electronics contain toxic substances, and (4) convenient and widespread systems for collecting and recycling electronics are not yet fully established. This section describes the development of the emission factor, which is shown in the final column of Exhibit 1-12. For more information on recycling in general, please see the Recycling chapter.

Exhibit 1-12: Recycling Emission Factor for PCs ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Storage	Net Emissions (Post-Consumer)
Desktop CPUs	–	0.01	(1.47)	0.00	(0.04)	–	(1.49)
Portable Electronic Devices	–	0.02	(1.14)	0.01	0.04	–	(1.06)
Flat-panel Displays	–	0.02	(1.00)	0.01	(0.02)	–	(0.99)
CRT Displays	–	0.02	(0.55)	0.00	(0.04)	–	(0.57)
Electronic Peripherals	–	0.02	(0.38)	0.02	(0.03)	–	(0.36)
Hard-copy Devices	–	0.02	(0.56)	0.00	(0.02)	–	(0.56)
Mixed Electronics	–	0.02	(0.78)	0.01	(0.03)	–	(0.79)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
[a] Includes emissions from the virgin production of secondary materials

WARM models electronics as being recycled in an open loop into the following secondary materials: steel sheet, aluminum sheet, copper wire, post-consumer HDPE and PET plastics, post-consumer nickel, lead bullion, post-consumer precious metals, and lithium cobalt oxide (Exhibit 1-13).

Exhibit 1-13: Fate of Recycled Electronics

Primary Component from Recycled Electronics	Secondary Product from Recycled Electronics	Data Source(s)
Ferrous metal	Steel sheet	ANL, 2018; Vanegas et al., 2017
Aluminum	Aluminum sheet	ANL, 2018; Vanegas et al., 2017
Copper	Copper wire	FAL, 2002; Bigum et al 2012.
Other metals	Nickel	ANL, 2018; Bigum et al 2012.
Plastic	HDPE	FAL, 2011a; FAL, 2018
	PET	FAL, 2011a; FAL, 2018
Printed circuit board	Steel sheet	ANL, 2018; Vanegas et al., 2017
	Aluminum sheet	ANL, 2018; Vanegas et al., 2017
	Copper wire	FAL, 2002; Vanegas et al., 2017
	Precious metals (gold, silver, and palladium)	Ecoinvent Centre, 2015; Bigum et al 2012.
Flat panel display module	Aluminum sheet	ANL, 2018; Vanegas et al., 2017
	Copper wire	FAL, 2002; Vanegas et al., 2017
CRT glass and lead	Lead bullion	ANL, 2018; Turner et al., 2015
Battery	Lithium cobalt oxide	ANL, 2018; Dewulf et al., 2010

The materials management emissions shown in Exhibit 1-12 include all of the GHG emissions associated with collecting, transporting, and processing electronics at end of life. The recycled input credits includes all of the GHG emissions associated with recycling or remanufacturing electronics into secondary materials. None of the upstream GHG emissions from manufacturing the electronics in the first place are included; instead, WARM calculates a "recycled input credit" by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of secondary materials from virgin inputs. Because electronics do not contain any wood products, there are no recycling benefits associated with forest carbon sequestration. The GHG benefits from the recycled input credits are discussed in greater detail below.

1.4.2.1 Developing the Emission Factor for Recycling of Electronics

EPA calculated the GHG benefits of recycling electronics by comparing the difference between the emissions associated with manufacturing a short ton of each of the secondary products from recycled electronic components and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. These results were then weighted by the component mass share in Exhibit 1-6 to obtain a composite emission factor for recycling one short ton of each electronics material. 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 followed six steps, which are described in detail below.

Step 1. *Calculate emissions from virgin production of one short ton of secondary product.* EPA applied fuel-specific carbon coefficients to the data for virgin RMAM of each secondary product based on data from the sources cited in Exhibit 1-13. This estimate was then summed with the emissions from transportation and process non-energy emissions to calculate the total emissions from virgin production of each secondary product. The calculations for virgin process, transportation and process non-energy emissions for the secondary products are presented in Exhibit 1-14, Exhibit 1-15 and Exhibit 1-16, respectively.

Exhibit 1-14: Process Energy GHG Emissions Calculations for Virgin Production of Electronics Secondary Products

Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Steel	28.95	2.32
Aluminum	127.37	5.90
Copper	122.52	6.72
Nickel	111.97	6.88
HDPE	23.59	1.13
PET	28.06	1.72
Gold	59,843.50	3,970.29
Silver	2,136.28	122.02
Palladium	25,675.12	1,746.35
Lead	23.08	2.03
Lithium cobalt oxide	32.11	1.76

Exhibit 1-15: Transportation Energy Emissions Calculations for Virgin Production of Electronics Secondary Products

Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Steel	IE	IE
Aluminum	IE	IE
Copper	0.46	0.03
Nickel	IE	IE
HDPE	2.74	0.15
PET	1.00	0.07
Gold	IE	IE
Silver	IE	IE
Palladium	IE	IE
Lead	IE	IE
Lithium cobalt oxide	IE	IE

Note: The transportation energy and emissions in this exhibit do not include retail transportation
IE = Included elsewhere. Process energy emissions are assumed to encompass transportation energy.

Exhibit 1-16: Process Non-Energy Emissions Calculations for Virgin Production of Electronics Secondary Products

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Steel	–	–	–	–	–	–
Aluminum	–	–	–	–	–	–
Copper	0.00	–	–	–	–	0.00
Nickel	–	–	–	–	–	–
HDPE	0.06	0.01	–	–	–	0.20
PET	0.27	0.00	–	–	–	0.39
Gold	700.12	–	–	–	–	700.12
Silver	30.78	–	–	–	–	30.78
Palladium	258.27	–	–	–	–	258.27
Lead	–	0.00	–	–	–	0.09
Lithium cobalt oxide	–	–	–	–	–	–

– = Zero emissions.

Step 2. *Calculate GHG emissions for recycled production of one short ton of the secondary product.* EPA then applied the same carbon coefficients to the energy data for the production of the secondary products from recycled electronics, and calculates non-energy process GHGs by converting data found in the sources cited in Exhibit 1-13 to metric tons of gas per short ton of secondary product.

Exhibit 1-17, Exhibit 1-18 and Exhibit 1-19 present the results for secondary product process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

Exhibit 1-17: Process Energy GHG Emissions Calculations for Recycled Production of Electronics Secondary Products

Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Steel	18.07	1.12
Aluminum	26.37	1.38
Copper	101.05	5.34
Nickel	19.28	1.20
HDPE	5.87	0.35
PET	12.00	0.72
Precious metals (gold, silver, and palladium)	9.17	0.58
Lead	4.23	0.40
Lithium cobalt oxide	5.31	0.29

Exhibit 1-18: Transportation Energy GHG Emissions Calculations for Recycled Production of Electronics Secondary Products

Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Steel	IE	IE
Aluminum	IE	IE
Copper	2.17	0.16
Nickel	IE	IE
HDPE	1.86	0.14
PET	1.55	0.11
Precious metals (gold, silver, and palladium)	IE	IE
Lead	IE	IE
Lithium cobalt oxide	IE	IE

Note: The transportation energy and emissions in this exhibit do not include retail transportation
IE = Included elsewhere. Process energy emissions are assumed to encompass transportation energy.

Exhibit 1-19: Process Non-Energy Emissions Calculations for Recycled Production of Electronics Secondary Products

Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Steel	–	–	–	–	–	–
Aluminum	–	–	–	–	–	–
Copper	0.00	–	–	–	–	0.00
Nickel	–	–	–	–	–	–
HDPE	0.00	–	–	–	–	0.00
PET	0.00	–	–	–	–	0.00
Precious metals (gold, silver, and palladium)	–	–	–	–	–	–
Lead	–	–	–	–	–	–
Lithium cobalt oxide	1.5	–	–	–	–	1.49

– = Zero emissions.

Step 3. *Account for recycling losses.* In the case of electronics, data indicated that the recovery rate varies by component. EPA assumed that the portion of electronics components not recovered for recycling were landfilled. Exhibit 1-20 shows the recovery rates for each electronics component based on data found in the sources cited in Exhibit 1-13.

Exhibit 1-20: Recovery Rates for Electronics Components Recycled into Secondary Products

Primary Component from Recycled Electronics	Secondary Product from Recycled Electronics	Short Tons Product Made per Short Ton Component Recycled
Ferrous metal	Steel sheet	95.00%
Aluminum	Aluminum sheet	87.00%
Copper	Copper wire	57.00%
Other metals	Nickel	28.94%
Plastic	HDPE	9.03%
	PET	3.12%
Printed circuit board	Steel sheet	20.34%
	Aluminum sheet	3.60%
	Copper wire	11.91%
	Precious metals (gold, silver, and palladium)	0.14%
Flat panel display module	Aluminum sheet	0.66%
	Copper wire	35.92%
CRT glass and lead	Lead bullion	17.60%
Battery	Lithium cobalt oxide	33.47%

Step 4. *Calculate the difference in emissions between virgin and recycled production.* EPA then subtracted the recycled product emissions (Step 2) from the virgin product emissions (Step 1) and multiplied by the recovery rate (Step 3) to get the GHG savings. These results are shown in Exhibit 1-21. The differences in emissions from process energy, transportation energy and non-energy processing were then adjusted to account for the loss rates by multiplying the final three columns of Exhibit 1-21 by the retention rates in Exhibit 1-20.

Exhibit 1-21: Differences in Emissions between Recycled and Virgin Electronics Secondary Products Manufacture ($MTCO_2E$/Short Ton)

Primary Component	Secondary Product	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
		Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy	Process Energy	Transportation Energy	Process Non-Energy
Ferrous metal	Steel sheet	2.32	–	–	1.12	–	–	(1.14)	–	–
Aluminum	Aluminum sheet	5.90	–	–	1.38	–	–	(3.93)	–	–
Copper	Copper wire	6.72	0.03	0.00	5.34	0.16	0.00	(0.79)	0.07	–
Other metals	Nickel	6.88	–	–	1.20	–	–	(1.64)	–	–
Plastic	HDPE	0.06	0.00	0.01	0.03	0.00	0.00	(0.03)	0.00	(0.01)
	PET	0.12	0.02	0.02	0.04	0.01	0.00	(0.06)	(0.00)	(0.02)
Printed circuit board	Steel sheet	0.47	–	–	0.23	–	–	(0.25)	–	–
	Aluminum sheet	0.21	–	–	0.05	–	–	(0.16)	–	–
	Copper wire	0.80	0.00	0.00	0.64	0.02	0.00	(0.16)	0.01	–
	Precious metals (gold, silver, and palladium)	2.23	–	0.34	0.58	–	0.07	(1.65)	–	(0.27)

Primary Component	Secondary Product	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
		Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy
Flat panel display module	Aluminum sheet	0.04	–	–	0.01	–	–	(0.03)	–	–
	Copper wire	2.42	0.01	0.00	1.92	0.06	0.00	(0.50)	0.04	–
CRT glass and lead	Lead bullion	0.36	–	0.02	0.07	–	–	(0.29)	–	(0.02)
Battery	Lithium cobalt oxide	0.59	–	–	0.10	–	0.50	(0.49)	–	0.50

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
Totals may not sum due to independent rounding.
– = Zero emissions.

Step 5. *Weight the results by the percentage of recycled electronics that the component makes up.* Using the percentages provided in Exhibit 1-6, EPA weighted the individual GHG differences from Step 4 for each of the components in a given electronics material. Each product's process energy, transportation energy and process non-energy emissions were weighted by the percentages in Exhibit 1-6 and then summed as shown in the final column of Exhibit 1-22.

Exhibit 1-22: Electronics Recycling Emission Factors ($MTCO_2E$/Short Ton)

Material	Recycled Input Credit for Recycling One Short Ton of Electronics			
	Weighted Process Energy ($MTCO_2E$/Short Ton of Each Material)	Weighted Transport Energy ($MTCO_2E$/Short Ton of Each Material)	Weighted Process Non-Energy ($MTCO_2E$/Short Ton of Each Material)	Total ($MTCO_2E$/Short Ton of Electronics Recycled)
Desktop CPUs	(1.47)	0.00	(0.04)	(1.50)
Portable Electronic Devices	(1.14)	0.01	0.04	(1.08)
Flat-panel Displays	(1.00)	0.01	(0.02)	(1.01)
CRT Displays	(0.55)	0.00	(0.04)	(0.59)
Electronic Peripherals	(0.38)	0.02	(0.03)	(0.39)
Hard-copy Devices	(0.56)	0.00	(0.02)	(0.58)
Mixed Electronics	(0.78)	0.01	(0.03)	(0.81)

Note: Negative values denote net GHG emission reductions or carbon storage from a materials management practice.
Totals may not sum due to independent rounding.

Step 6. *Factor in materials management emissions for process emissions from demanufacturing electronics and landfilling unrecovered materials.* EPA assumed that electronics are shredded to extract the materials that are recycled into secondary products. The act of shredding electronics consumes electricity, and the GHG emissions associated with this electricity use are allocated to the total emission factor for recycling one short ton of electronics (Bigum et al., 2012). The unrecovered materials are landfilled, resulting in process and transportation energy emissions as described in Section 1.4.5. The final electronics recycling emission factor is the sum of the weighted secondary products' emission factors from Exhibit 1-22 and the process emissions from demanufacturing electronics and landfilling unrecovered materials as shown in Exhibit 1-23.

Exhibit 1-23: Calculation of Recycling Emission Factor for Electronics

Material	Demanufacturing Process Energy ($MTCO_2E$/Short Ton)	Landfilling Process and Transportation Energy ($MTCO_2E$/Short Ton)	Total Waste Management Emissions ($MTCO_2E$/Short Ton)	Net Recycling Emissions ($MTCO_2E$/Short Ton)
Desktop CPUs	0.01	0.00	0.01	(1.49)
Portable Electronic Devices	0.01	0.01	0.02	(1.06)
Flat-panel Displays	0.01	0.01	0.02	(0.99)
CRT Displays	0.01	0.01	0.02	(0.57)
Electronic Peripherals	0.01	0.01	0.02	(0.36)
Hard-copy Devices	0.01	0.01	0.02	(0.56)
Mixed Electronics	0.01	0.01	0.02	(0.79)

Totals may not sum due to independent rounding.

1.4.3 Composting

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

1.4.4 Combustion

GHG emissions from combusting electronics result from the combustion process as well as from indirect emissions from transporting electronics to the combustor. Combustion also produces energy that can be recovered to offset electricity and GHG emissions that would have otherwise been produced from non-baseload power plants feeding into the national electricity grid. Finally, most waste-to-energy (WTE) plants recycle steel that is left after combustion, which offsets the production of steel from other virgin and recycled inputs. All of these components make up the combustion factors calculated for electronics.

It is likely that very few whole electronics are combusted, since components of electronics can interfere with the combustion process and the combustion of CRT monitors in particular can deposit lead that exceeds permitted levels in the combustion ash. Consequently, some level of disassembly and sorting is likely required to separate combustible plastics from other electronic components (EPA, 2008; FAL, 2002), although this is not included in WARM's combustion modeling approach. WARM accounts for the GHG emission implications of combusting electronics, but material managers should ensure that electronics are appropriately processed and sorted before sending the components to combustors.

For further information, see the Combustion chapter. Because WARM's analysis begins with materials at end of life, emissions from RMAM are zero. Exhibit 1-24 shows the components of the emission factor for combustion of electronics. Further discussion on the development of each piece of the emission factor is provided below.

Exhibit 1-24: Components of the Combustion Net Emission Factor for Electronics ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Desktop CPUs	–	0.01	0.40	–	(0.12)	(0.95)	(0.66)
Portable Electronic Devices	–	0.01	0.88	–	(0.12)	(0.12)	0.65
Flat-panel Displays	–	0.01	0.73	–	(0.12)	(0.60)	0.03
CRT Displays	–	0.01	0.63	–	(0.12)	(0.08)	0.45

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
Electronic Peripherals	–	0.01	2.22	–	(0.12)	(0.03)	2.08
Hard-copy Devices	–	0.01	1.91	–	(0.12)	(0.60)	1.20
Mixed Electronics	–	0.01	0.86	–	(0.12)	(0.37)	0.39

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

1.4.4.1 Developing the Emission Factor for Combustion of Electronics

EPA estimated that electronics have a carbon content ranging from 12 percent to 68 percent, depending on the material type. This carbon is contained within the plastics in electronics. EPA also assumed that 98 percent of that carbon is converted to CO_2 during combustion. The resulting direct CO_2 emissions from combustion of carbon in electronics are presented in Exhibit 1-25.

Exhibit 1-25: Electronics Combustion CO_2 Emission Factor Calculation ($MTCO_2E$/Short Ton)

Material	Non-Biomass Carbon Content	Carbon Converted to CO_2 during Combustion	Combustion CO_2 Emissions ($MTCO_2E$/Short Ton)
Desktop CPUs	12%	98%	0.40
Portable Electronic Devices	27%	98%	0.88
Flat-panel Displays	22%	98%	0.73
CRT Displays	20%	98%	0.63
Electronic Peripherals	68%	98%	2.22
Hard-copy Devices	59%	98%	1.91
Mixed Electronics	27%	98%	0.86

EPA estimated CO_2 emissions from transporting electronics to the WTE plant and transporting ash from the WTE plant to the landfill using data provided by FAL.

Most utility power plants use fossil fuels to produce electricity, and the electricity produced at a WTE plant reduces the demand for fossil-derived electricity. As a result, the combustion emission factor for electronics includes avoided GHG emissions from utilities. EPA calculated the avoided utility CO_2 emissions based on the energy content of the plastics within electronics; the combustion efficiency of the WTE plant, including transmission and distribution losses; and the national average carbon-intensity of electricity produced by non-baseload power plants. Exhibit 1-26 shows utility offsets from electronics combustion.

Exhibit 1-26: Utility GHG Emissions Offset from Combustion of Electronics

(a) Material	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
Desktop CPUs	3.07	17.8%	0.21	0.12
Portable Electronic Devices	3.07	17.8%	0.21	0.12
Flat-panel Displays	3.07	17.8%	0.21	0.12
CRT Displays	3.07	17.8%	0.21	0.12
Electronic Peripherals	3.07	17.8%	0.21	0.12
Hard-copy Devices	3.07	17.8%	0.21	0.12
Mixed Electronics	3.07	17.8%	0.21	0.12

The combustion of electronics at WTE facilities also includes steel recovery and recycling processes. Approximately 90 percent of combustion facilities have ferrous recovery systems. The steel content of electronics varies by material. Since some of this steel is lost during combustion, we included a ferrous recovery factor of 98 percent. The emission impacts of recycling of this recovered steel are shown in Exhibit 1-27.

Exhibit 1-27: Steel Production GHG Emissions Offset from Steel Recovered from Combustion of Electronics

Material	Short Tons of Steel Recovered per Short Ton of Waste Combusted	Avoided CO_2 Emissions per Ton of Steel Recovered ($MTCO_2E$/Short Ton)	Avoided CO_2 Emissions per Ton of Waste Combusted ($MTCO_2E$/Short Ton)
Desktop CPUs	0.52	1.83	0.95
Portable Electronic Devices	0.06	1.83	0.12
Flat-panel Displays	0.33	1.83	0.60
CRT Displays	0.04	1.83	0.08
Electronic Peripherals	0.02	1.83	0.03
Hard-copy Devices	0.33	1.83	0.60
Mixed Electronics	0.20	1.83	0.37

1.4.5 Landfilling

1.4.5.1 Overview and Developing the Emission Factor for Landfilling of Electronics

In WARM, landfill emissions comprise landfill CH_4 and CO_2 from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since electronics are inorganic and do not contain biogenic carbon, there are zero emissions from landfill CH_4, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling electronics, as shown in Exhibit 1-28. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling electronics represents only the emissions associated with collecting the waste and operating the landfill equipment. For more information, refer to the Landfilling chapter.

Exhibit 1-28: Landfilling Emission Factor for Electronics ($MTCO_2E$/Short Ton)

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
Desktop CPUs	–	0.02	–	–	–	0.02
Portable Electronic Devices	–	0.02	–	–	–	0.02
Flat-panel Displays	–	0.02	–	–	–	0.02

Material	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Landfill	Landfill CH_4	Avoided CO_2 Emissions from Energy Recovery	Landfill Carbon Storage	Net Emissions (Post-Consumer)
CRT Displays	–	0.02	–	–	–	0.02
Electronic Peripherals	–	0.02	–	–	–	0.02
Hard-copy Devices	–	0.02	–	–	–	0.02
Mixed Electronics	–	0.02	–	–	–	0.02

NA = Not applicable.
– = Zero emissions.

1.4.6 Anaerobic Digestion

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

1.5 LIMITATIONS

There are several limitations to this analysis, which is based on several assumptions from expert judgment. The limitations associated with the source reduction and recycling emission factors include:

- The primary source for characterizing the components of electronics (Babbitt et al., 2017) provides a recent, comprehensive data set for electronic product material make-up. However, the authors aggregated component data into a select number of component types, with several products having a mass percentage listed as "uncategorized". Based on discussions with the authors, EPA assumed excluded the "uncategorized" mass percentage and scaled-up the remaining component mass percentages to account for the complete product mass.
- Whenever possible, EPA used the most recent, comprehensive and relevant LCI data in developing the source reduction and recycling emission factors. However, product design and recycling practices can vary across electronics materials and components, and there can be inaccuracies when using a limited set of component-specific data sources and assumptions that often do not account for these variations.
- The open-loop recycling process has several limitations, including limited availability of representative life-cycle data for electronics and the materials recovered from them as well as the high variability in electronics recycling practices in the United States.
- Data sources used in modeling source reduction and recycling of electronics often do not distinguish between process energy (e.g., fossil fuels combusted on-site during production) and transportation energy (i.e., fuel used to transport raw materials to manufacturing facilities). Where transport energy was not disaggregated in the underlying data sources, EPA assumed it was included as part of the process energy.
- Recycling rates can have a significant impact when estimating the energy and GHG emission impacts of recycling operations. EPA sought to apply the most recent and relevant recycling rates from available literature, but these rates may not reflect variations across different recycling systems, programs, and technologies.
- Existing literature indicates that lithium-ion batteries have been used in the majority of portable electronics for several years, largely replacing nickel-based batteries (Deng 2015). EPA was unable to locate available data from the literature that quantitatively documented the share of battery types currently entering the waste stream; however, EPA (2016a) estimates of average

product lifespan suggest that there should be a minimal number of products relying on nickel-based batteries still in circulation, limiting the impact of these batteries on overall battery modeling results. Based on this understanding, EPA limited the modeling for source reduction and recycling to lithium-ion batteries.

- The electronics updates in WARM Version 15 do not include the addition of a separate management practice for product reuse. EPA may consider including the addition of a reuse pathway for electronics and other materials (e.g., food donation, C&D material reuse) as part of future WARM updates using a consistent methodology and assumptions. To address reuse in the near term, EPA my consider addressing reuse through updates to the existing "Modeling Reuse in EPA's Waste Reduction Model" guidance document, which suggests ways that the source reduction pathway can be used as a proxy for reuse.
- EPA has not conducted a comprehensive analysis of the degree to which the electronics materials modeled in WARM can serve as reasonable proxies for other electronics not modeled in WARM. However, some preliminary, high-level review by EPA indicates that the following reasonable proxies
    - Video game consoles can be modeled using the Desktop CPUs material
    - Audio/video players (i.e., VCRs, DVD players, and Blu-Ray players) can be modeled using the Mixed Electronics material
    - Digital cameras can be modeled using the Portable Electronic Devices material

1.6 REFERENCES

Andrea, A.S.G. and Vaija, M.S. (2014). To Which Degree Does Sector Specific Standardization Make Life Cycle Assessments Comparable?—The Case of Global Warming Potential of Smartphones. Challenges. 5(2), 409-429. Available at: https://www.mdpi.com/2078-1547/5/2/409/htm.

Argonne National Laboratory (ANL). (2018). Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model. GREET 2018 version. Available at: https://greet.es.anl.gov/.

Babbitt, C.W., Althaf, S., and Chen R. (2017). Sustainable Materials Management for the Evolving Consumer Technology Ecosystem. Available at: https://www.rit.edu/gis/ssil/docs/Final%20Report%20SMM%20Phase%201%202017.pdf. Accessed January 24, 2018.

Bigum, M., Brogaard, L., and Christensen, T.H. (2012). Metal recovery from high-grade WEEE: A life cycle assessment. Journal of Hazardous Materials. 207-208: 8-14. Available at: https://www.sciencedirect.com/science/article/pii/S0304389411012283.

Dewulf, J., Van der Vorst, G., Denturk, K., Van Langenhove, H., Ghyoot, W., Tytgat, J., and Vandeputte, K. (2010). Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings. Resources, Conservation and Recycling. 54(4): 229-234. Available at: https://www.sciencedirect.com/science/article/pii/S0921344909001815.

Ecoinvent Centre. (2015). *Ecoinvent data v3.2*. Ecoinvent reports No.1-25, Swiss Centre for Life Cycle Inventories, Dübendorf, 20015. Retrieved from: www.ecoinvent.org.

EPA. (2018). Advancing Sustainable Materials Management: Facts and Figures 2015. (EPA530-F-18-004).Washington, DC: U.S. Government Printing Office. Retrieved from https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management.

EPA. (2008). *Electronics Waste Management in the United States: Approach I.* (EPA publication no. EPA530-R-07-004b.) Washington, DC: U.S. Environmental Protection Agency.

FAL. (2018). Life Cycle Impacts for Postconsumer Recycled Resins: PET, HDPE, and PP. December 2018. Conducted by Franklin Associates for APR. Available at https://plasticsrecycling.org/images/apr/2018-APR-Recycled-Resin-Report.pdf

FAL. (2011a). *Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Two Polyurethane Precursors. Revised Final Report*. Prairie Village, KS: Franklin Associates, Ltd.

FAL. (2011b). *Life Cycle Inventory of 100% Postconsumer HDPE and PET Recycled Resin from Postconsumer Containers and Packaging*. Prairie Village, KS: Franklin Associates, Ltd.

FAL. (2002). *Energy and Greenhouse Gas Factors for Personal Computers.* Final Report. Prairie Village, KS: Franklin Associates, Ltd. August 7, 2002.

Hikwama, B.P. (2005). Life Cycle Assessment of a Personal Computer. October 2005. Available online at: https://eprints.usq.edu.au/492/1/BaipakiPaksonHIKWAMA-2005.pdf

Mars, C., Nafe, C., and Linnell, J. (2016). The Electronics Recycling Landscape Report. Prepared for the Closed Loop Foundation. May 2016. Available at: https://www.sustainabilityconsortium.org/downloads/tsc-electronics-recycling-landscape-report/.

Teehan, P. and Kandlikar, M. (2013). Comparing embodies greenhouse gas emissions of modern computing and electronics products. Environmental Science and Technology. 47(9): 3997-4003. Available at: https://www.ncbi.nlm.nih.gov/pubmed/23458212.

Turner, D.A., Williams, I.D., Kemp, S. (2015). Greenhouse gas emission factors for recycling of source-segregated waste materials. Resources, Conservation and Recycling. 105(2015): 186-197. Available at: https://www.sciencedirect.com/science/article/pii/S0921344915301245.

Vanegas, P., Peeters, J.R., Dewulf, W., Cattrysse D., and Duflou, J.R. (2015). Improving Resource Efficiency through Recycling Modelling: A Case Study for LCD TVs. Procedia CIRP. 26 (2015): 601-606. Available at: https://www.sciencedirect.com/science/article/pii/S2212827114009020.