PERSONAL COMPUTERS

1 INTRODUCTION TO WARM AND PERSONAL COMPUTERS

This chapter describes the methodology used in EPA's Waste Reduction Model (WARM) to estimate streamlined life-cycle greenhouse gas (GHG) emission factors for personal computers (PCs) beginning at the point of waste generation. The WARM GHG emission factors are used to compare the net emissions associated with PCs in the following four materials management alternatives: source reduction, recycling, landfilling and combustion. For background information on the general purpose and function of WARM emission factors, see the Introduction & Overview chapter. For more information on Source Reduction, Recycling, Landfilling and Combustion, see the chapters devoted to those processes. WARM also allows users to calculate results in terms of energy, rather than GHGs. The energy results are calculated using the same methodology described here but with slight adjustments, as explained in the Energy Impacts chapter.

The main components of a PC are the central processing units (CPU) and the monitor. The PC modeled in WARM is based on a typical desktop PC with a cathode ray tube (CRT) monitor. The CPU consists of housing (mostly steel) and internal electronic components, while the monitor's primary components are the CRT, plastic case and circuit boards. The wide range of PC models makes it difficult to specify the exact composition of a typical PC, and PC technology continues to evolve rapidly. For WARM analysis, EPA considers the CPU and CRT monitor, while the peripheral equipment (e.g., keyboards, external cables, printers) are left out of the analysis. Flat-panel monitors are now dominant in today's market, having displaced CRT monitors that were common in the 1990's and early 2000's. Although flat-panel monitors are beginning to enter the MSW stream in larger quantities, CRT monitors are still present and will likely remain a sizable component of end-of-life electronics for a number of years.

Upon disposal, PCs can be recovered for recycling, sent to a landfill or combusted. Exhibit 1 shows the general outline of materials management pathways in WARM. Recycling PCs is an open-loop process, meaning that components are recycled into secondary materials such as asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet. PCs are collected curbside and at special events, or individuals can bring them to designated drop-off sites. Once PCs have been collected for recycling, they are sent to Material Recovery Facilities (MRFs) that specialize in separating and recovering materials from electronic products. Building on Exhibit 1, a more detailed flow diagram showing the open-loop recycling pathways of PCs is provided in Exhibit 2.

Exhibit 1: Life Cycle of Personal Computers in WARM

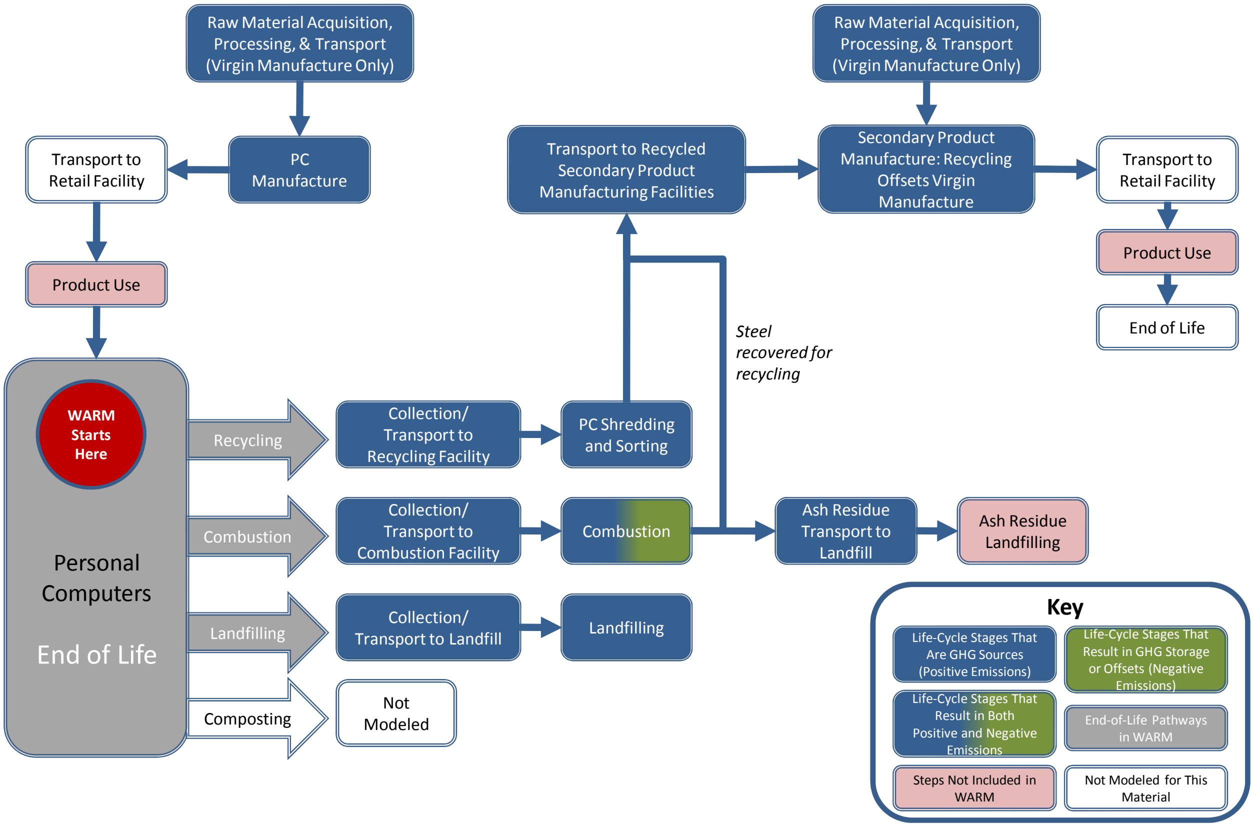
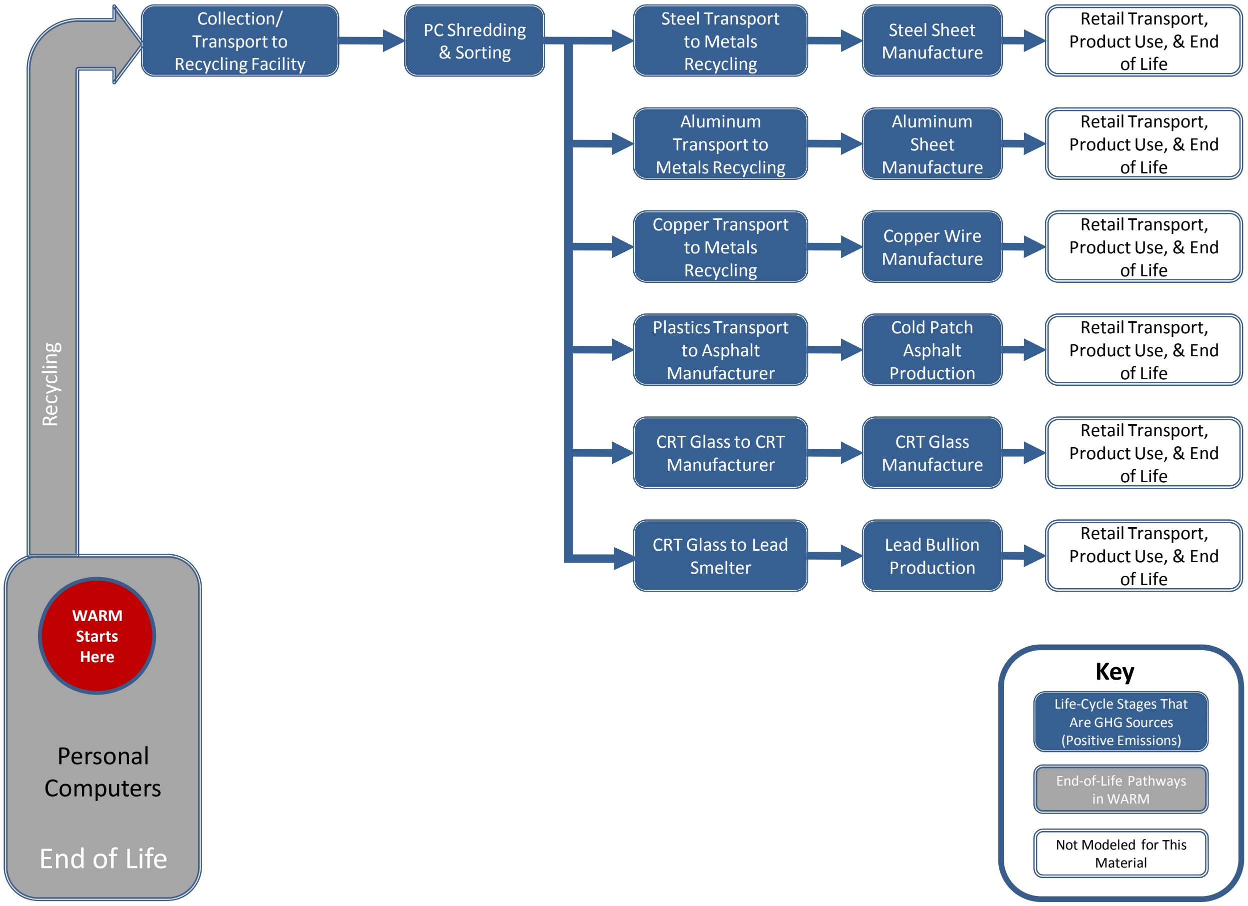


Exhibit 2: Detailed Recycling Flows for Personal Computers in WARM



2 LIFE-CYCLE ASSESSMENT AND EMISSION FACTOR RESULTS

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

WARM includes source reduction, recycling, landfilling and combustion pathways for materials management of PCs. As Exhibit 3 illustrates, most of the GHG emissions from end-of-life management of PCs occur from the waste management of these products, while most of the GHG savings occur from offsetting upstream raw materials acquisition and manufacturing of other secondary materials that are recovered from PCs.

Exhibit 3: PC GHG Sources and Sinks from Relevant Materials Management Pathways

Materials Management Strategies for PCs	GHG Sources and Sinks Relevant to PCs		
	Raw Materials Acquisition and Manufacturing	**Changes in Forest or Soil Carbon Storage**	**Materials Management**
Source Reduction	**Offsets** - Transport of raw materials and intermediate products - Virgin process energy - Virgin process non-energy - Transport of PCs to point of sale	NA	NA
Recycling	**Emissions** - Transport of recycled materials - Recycled process energy - Recycled process non-energy **Offsets** - Emissions from producing asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet from virgin material	NA	**Emissions** - Collection of PCs and transportation to recycling center - Demanufacturing PCs
Landfilling	NA	NA	**Emissions** - Transport to landfill - Landfilling machinery
Combustion	NA	NA	**Emissions** - Transport to WTE facility - Combustion-related CO_2 and N_2O **Offsets** - Avoided utility emissions - Steel recovery

NA = Not applicable.

WARM analyzes all of the GHG sources and sinks outlined in Exhibit 3 and calculates net GHG emissions per short ton of PC inputs as shown in Exhibit 4. For more detailed methodology on emission factors, please see the sections below on individual materials management strategies.

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

Product/Material	Net Source Reduction (Reuse) Emissions for Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
PCs	-55.78	-2.26	NA	-0.17	0.04

[a] The current mix of inputs for PCs is considered to be 100% virgin material.

3 RAW MATERIALS ACQUISITION AND MANUFACTURING

Exhibit 5 provides the assumed material composition of the typical PC used for this analysis.

Exhibit 5: Material Composition of a Desktop PC (CPU and CRT Monitor)

Product/Material	Application(s)	% of Total Weight	Weight (lbs.) (Assuming a 70-lb. Computer)
Plastics	Monitor case and other molded parts		
ABS[a]		8.0%	5.6
PPO/HIPS[b]		5.3%	3.7
TBBPA[c] (flame retardant)		5.7%	4.0
Glass	CRT glass/substrate for PWBs[d]	22.0%	15.4

Lead	CRT glass/electronic connections	8.0%	5.6
Steel	CPU case/CRT shield	28.6%	20.0
Copper	PWB conductor/wiring	6.6%	4.6
Zinc	Galvanization of CPU case	3.0%	2.1
Aluminum	Structural components/ PWB conductor	9.5%	6.7
Other	Metals and plastics for disk drives, fasteners and power supplies	3.3%	2.3
Total		**100.0%**	**70.0 lbs**

Source: FAL (2002).

[a] Acrylonitrile butadiene styrene.

[b] Polyphenylene oxide/High-impact polystyrene.

[c] Tetrabromobisphenol A.

[d] Printed wiring boards.

The quantity of components and the complexity of their manufacturing processes require that the analysis focus only on the key materials and processes. In particular, the life-cycle assessment (LCA) of PC production includes the following steps:

Chip manufacture (including wafer production, fabrication and packaging). A chip (or integrated circuit) is a compact device made of a semi-conducting material such as silicon. Although chip manufacture requires thousands of steps, the primary steps are wafer production, wafer fabrication and chip packaging.

Printed wiring board production. Printed wiring boards (PWBs) are part of the circuitry in electronic products.

CRT production. Computer monitors and televisions are the two largest applications for CRTs. A CRT is made of many materials and sub-assemblies, including a glass funnel, glass neck, faceplate (screen), electron gun, shadow mask, phosphors and PWBs.

Monitor housing production. The monitor case is made of one or more types of plastic resin including acrylonitrile-butadiene-styrene (ABS), polyphenylene ether alloys (referred to as PPE or PPO), and high impact polystyrene (HIPS). Monitor production also involves incorporation of flame retardants into the monitor housing.

CPU housing production. CPU cases are made of plastic panels and face plates and steel for structural stability. Much of the steel used in CPU cases is scrap steel; the rest is manufactured from virgin inputs.

PC assembly. PCs are assembled manually; the main energy requirement is the operation of conveyor belts for the assembly line.

4 MATERIALS MANAGEMENT METHODOLOGIES

This analysis considers source reduction, recycling, landfilling and combustion pathways for materials management of PCs. It is important to note that PCs are not recycled into new PCs, however; they are recycled in an open loop. The LCA of their disposal must take into account the variety of second-generation products from recycling PCs. Information on PC recycling and the resulting second-generation products is sparse; however, EPA has modeled pathways for which consistent LCA data are available for recycled PC components. The second-generation products considered in this analysis are: non-leaded CRT glass into glass cullet, recovered lead into lead bullion, steel into scrap steel, copper into scrap copper, aluminum into scrap aluminum, and plastic into ground plastic as an input to asphalt manufacturing.

The data source used to develop these emissions factors is a 2002 report published by Franklin Associates, Limited (FAL) on energy and GHG emission factors for the manufacture and end-of-life management of PCs. These data are based on a number of industry and academic data sources dating from the 1990's and 2000's. The data sources for ABS resin production and silicon wafer production rely on older sources; the ABS resin data are taken from confidential industry data sources in the 1970's and the silicon wafer production data are based on photovoltaic-grade silicon production in the 1980's (FAL, 2002).

Source reduction leads to the largest reduction in GHG emissions for PCs, since manufacturing PCs and their components is especially energy intensive. Recycling PCs leads to greater reductions than combustion and landfilling, since it also reduces similarly energy-intensive product manufacturing. Combustion still has a negative net emission factor that is driven by the GHG savings associated with recovered steel, while landfilling has a slightly positive emission factor due to the emissions from landfill operation equipment.

4.1 SOURCE REDUCTION

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

Exhibit 6 outlines the GHG emission factor for source reducing PCs. GHG benefits of source reduction are calculated as the avoided emissions from raw materials acquisition and manufacturing (RMAM) of new PCs.

Exhibit 6. PC Source Reduction Emission Factor for PCs (MTCO$_2$E/Short Ton)

Product/Material	Raw Material Acquisition and Manufacturing for Current Mix of Inputs	Raw Material Acquisition and Manufacturing for 100% Virgin Inputs	Forest Carbon 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
PCs	-55.78	-55.78	NA	NA	-55.78	-55.78

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

4.1.1 Developing the Emission Factor for Source Reduction of PCs

To calculate the avoided GHG emissions for PCs, EPA looks at three components of GHG emissions from RMAM activities: process energy, transportation energy and non-energy GHG emissions. Exhibit 7 shows the results for each component and the total GHG emission factor for source reduction. More information on each component making up the final emission factor is provided below.

Exhibit 7: Raw Material Acquisition and Manufacturing Emission Factor for Virgin Production of PCs (MTCO$_2$E/Short Ton)

(a) Material/Product	(b) Process Energy	(c) Transportation Energy	(d) Process Non-Energy	(e) Net Emissions (e = b + c + d)
PCs	-55.32	-0.37	-0.10	-55.78

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

First, EPA obtained an estimate of the amount of energy required to produce one short ton of PCs, which is reported as 945 million Btu (FAL, 2002). Next, we determined the fuel mix that comprises this Btu estimate using data from FAL (2002) and then multiplied the fuel consumption (in Btu) by the fuel-specific carbon contents. The sum of the resulting GHG emissions by fuel type comprise the total process energy GHG emissions, including both CO_2 and CH_4, from all fuel types used in PC production. The process energy used to produce PCs and the resulting emissions are presented in Exhibit 8.

Exhibit 8: Process Energy GHG Emissions Calculations for Virgin Production of PCs

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
PCs	945.13	55.32

Transportation energy emissions come from fossil fuels used to transport PC raw materials and intermediate products. The methodology for estimating these emissions is the same as that used for process energy emissions. Based upon an estimated total PC transportation energy in Btu, EPA calculates the total emissions using fuel-specific carbon coefficients. Exhibit 9 shows the calculations for estimating 0.37 $MTCO_2E$ per short ton of PCs.

Exhibit 9: Transportation Energy Emissions Calculations for Virgin Production of PCs

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
PCs	5.03	0.37

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

Non-energy GHG emissions occur during manufacturing but are not related to combusting fuel for energy. For PCs, non-energy GHGs are emitted in the virgin CRT glass manufacturing process by the production of lime and in the evaporation of solvent vapors from photolithography procedures that are used to apply phosphors onto the screen (FAL, 2002, pp. 8, 10). Production of virgin steel and aluminum generate non-energy process GHG emissions from the use of limestone as a fluxing agent, and from the use of coke as a reducing agent (EPA, 2006, p. 11). Perfluorocarbons (PFCs) are also emitted from the smelting stage of virgin aluminum production. FAL provided data on GHG emissions from non-energy-related processes in units of pounds of native gas (2002). We convert pounds of gas per 1,000 lbs. of PCs to metric tons of gas per short ton of PCs and then multiply that by the ratio of carbon to gas to produce the emission factor in $MTCO_2E$ per short ton of PCs, as detailed in the example below, which shows the calculation of CH_4 process emissions for PCs.

$$\text{1.01 lbs } CH_4\text{/1,000 lbs PC} \times \text{2,000 lbs PC/1 short ton PC} \times \text{1 metric ton } CH_4\text{/2,205 lbs } CH_4 \times 21\ \text{MTCO2E/metric ton } CH_4 = 0.10\ MTCO_2E\text{/short ton PC}$$

Exhibit 10 shows the components for estimating process non-energy GHG emissions for PCs.

Exhibit 10: Process Non-Energy Emissions Calculations for Virgin Production of PCs

Product/Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
PCs	0.08	0.00	–	–	–	0.10

– = Zero emissions.

4.2 RECYCLING

According to EPA (2010), 39 percent of CPUs and 29 percent of computer displays are recycled annually. EPA and other organizations have recently been increasing their focus on improving the recycling of PCs and other electronics because of several factors: (1) rapid sales growth and change are generating a growing stream of obsolete products, (2) manufacturing PCs and other electronics consumes large amounts of energy and materials, (3) electronics contain toxic substances, and (4) convenient and widespread systems for collecting and recycling PCs are not yet fully established. This section describes the development of the emission factor, which is shown in the final column of Exhibit 11. For more information on recycling in general, please see the Recycling chapter.

Exhibit 11: Recycling Emission Factor for PCs (MTCO$_2$E/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Materials Management Emissions	Recycled Input Credit[a] Process Energy	Recycled Input Credit[a] – Transportation Energy	Recycled Input Credit[a] – Process Non-Energy	Forest Carbon Sequestration	Net Emissions (Post-Consumer)
PCs	–	–	-1.50	-0.04	-0.73	–	-2.26

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

[a] Includes emissions from the virgin production of secondary materials

WARM models PCs as being recycled in an <u>open loop</u> into the following secondary materials: asphalt, steel sheet, lead bullion, CRT glass, copper wire and aluminum sheet (Exhibit 12). Specifically, recovered plastic can be used as a filler component in the production of cold-patch asphalt for road construction. Steel and aluminum sheet become scrap metal that can be used to produce a wide range of materials, from auto parts to cookware. Recovered CRT glass can be used for the production of new CRTs or processed to recover lead bullion that can be used to produce items such as batteries and X-ray shielding. Recycled copper wire can be used in various electrical applications, depending on its grade.

The recycled input credits shown in Exhibit 11 include all of the GHG emissions associated with collecting, transporting, processing, and recycling or remanufacturing PCs into secondary materials. None of the upstream GHG emissions from manufacturing the PC in the first place are included; instead, WARM calculates a “recycled input credit” by assuming that the recycled material avoids—or offsets—the GHG emissions associated with producing the same amount of secondary materials from virgin inputs. Consequently, GHG emissions associated with management (i.e., collection, transportation and processing) of end-of-life PCs are included in the recycling credit calculation. Because PCs do not contain any wood products, there are no recycling benefits associated with forest carbon sequestration. The GHG benefits from the recycled input credits are discussed in greater detail below.

Exhibit 12: Fate of Recycled PCs

Primary Material from Recycled PCs	Secondary Product from Recycled PCs	% Composition of Original PC, by Weight
Plastic from CRT monitor and CPU housing	Asphalt	38%
Steel from CPU frame	Steel Sheet	27%
Lead from CRT monitor glass and electronic connections	Lead Bullion	10%
CRT glass from CRT monitor	CRT Glass	2%
Copper from wiring and PWBs	Copper Wire	5%
Aluminum from structural components and PWBs	Aluminum Sheet	18%

Note that the copper industry identifies two types of copper scrap, with No. 1 being cleaner and purer (therefore more desirable) and No. 2 being less pure. USGS (2004) indicates that consumption of purchased copper-base scrap in the United States comprises approximately 93 percent No. 1 scrap and 7 percent No. 2 scrap. WARM uses these percentages to create a weighted average of the two scrap types to represent copper wire manufacture from recycled inputs, as the two types of scrap display different process and transportation energy characteristics.

4.2.1 Developing the Emission Factor for Recycling of PCs

EPA calculates the GHG benefits of recycling PCs by comparing the difference between the emissions associated with manufacturing a short ton of each of the secondary products from recycled PCs and the emissions from manufacturing the same ton from virgin materials, after accounting for losses that occur in the recycling process. These results are then weighted by the distribution shown in Exhibit 12 to obtain a composite emission factor for recycling one short ton of PCs. This recycled input credit is composed of GHG emissions from process energy, transportation energy and process non-energy.

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

Step 1. *Calculate emissions from virgin production of one short ton of secondary product.* We apply fuel-specific carbon coefficients to the data for virgin RMAM of each secondary product (FAL, 2002). This estimate is then summed with the emissions from transportation and process non-energy emissions to calculate the total emissions from virgin production of each secondary product. The calculations for virgin process, transportation and process non-energy emissions for the secondary products are presented in Exhibit 13, Exhibit 14 and Exhibit 15, respectively.

Exhibit 13: Process Energy GHG Emissions Calculations for Virgin Production of PC Secondary Products

Product/Material	Process Energy per Short Ton Made from Virgin Inputs (Million Btu)	Process Energy GHG Emissions ($MTCO_2E$/Short Ton)
Asphalt	0.50	0.03
Steel Sheet	14.60	0.85
Lead Bullion	19.46	1.13
CRT Glass	9.16	0.53
Copper Wire	122.52	7.39
Aluminum Sheet	213.33	12.46

Exhibit 14: Transportation Energy Emissions Calculations for Virgin Production of PC Secondary Products

Product/Material	Transportation Energy per Short Ton Made from Virgin Inputs (Million Btu)	Transportation Energy GHG Emissions ($MTCO_2E$/Short Ton)
Asphalt	0.20	0.01
Steel Sheet	1.41	0.10
Lead Bullion	0.63	0.05
CRT Glass	0.28	0.02
Copper Wire	0.46	0.03
Aluminum Sheet	7.15	0.52

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

Exhibit 15: Process Non-Energy Emissions Calculations for Virgin Production of PC Secondary Products

Product/Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Asphalt (Cold Patch)	0.00	–	–	–	–	0.00
Steel Sheet	1.43	0.00	–	–	–	1.47
Lead Bullion	0.02	0.00	–	–	–	0.03
CRT Glass	0.16	–	–	–	–	0.16

Copper Wire	0.00	–	–	–	–	0.00
Aluminum Sheet	1.41	–	0.00	0.00	–	2.69

– = Zero emissions.

Step 2. *Calculate GHG emissions for recycled production of one short ton of the secondary product.* EPA then applies the same carbon coefficients to the energy data for the production of the secondary products from recycled PCs, and calculates non-energy process GHGs by converting data found in FAL (2002) to metric tons of gas per short ton of secondary product. Exhibit 16, Exhibit 17 and Exhibit 18 present the results for secondary product process energy emissions, transportation energy emissions and process non-energy emissions, respectively.

Exhibit 16: Process Energy GHG Emissions Calculations for Recycled Production of PC Secondary Products

Product/Material	Process Energy per Short Ton Made from Recycled Inputs (Million Btu)	Energy Emissions ($MTCO_2E$/Short Ton)
Asphalt	5.49	0.32
Steel Sheet	12.53	0.72
Lead Bullion	19.50	1.14
CRT Glass	7.29	0.42
Copper Wire	101.05	5.91
Aluminum Sheet	16.59	0.94
Copper No. 1 Scrap	7.89	0.45
Copper No.2 Scrap	22.40	1.46

Exhibit 17: Transportation Energy GHG Emissions Calculations for Recycled Production of PC Secondary Products

Product/Material	Transportation Energy per Ton Made from Recycled Inputs (Million Btu)	Transportation Emissions ($MTCO_2E$/Short Ton)
Asphalt	0.98	0.07
Steel Sheet	0.67	0.05
Lead Bullion	4.01	0.29
CRT Glass	5.28	0.39
Copper Wire	2.17	0.16
Aluminum Sheet	1.01	0.07
Copper No. 1 Scrap	1.85	0.14
Copper No.2 Scrap	2.42	0.18

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

Exhibit 18: Process Non-Energy Emissions Calculations for Recycled Production of PC Secondary Products

Product/Material	CO_2 Emissions (MT/Short Ton)	CH_4 Emissions (MT/Short Ton)	CF_4 Emissions (MT/Short Ton)	C_2F_6 Emissions (MT/Short Ton)	N_2O Emissions (MT/Short Ton)	Non-Energy Carbon Emissions ($MTCO_2E$/Short Ton)
Asphalt	0.00	–	–	–	–	0.00
Steel Sheet	0.02	–	–	–	–	0.02
Lead Bullion	0.02	–	–	–	–	0.02
CRT Glass	–	–	–	–	–	–
Copper Wire	0.00	–	–	–	–	0.00
Aluminum Sheet	–	–	–	–	–	–

– = Zero emissions.

Step 3. *Calculate the difference in emissions between virgin and recycled production.* We then subtract the recycled product emissions (Step 2) from the virgin product emissions (Step 1) to get the GHG savings. These results are shown in Exhibit 19.

Exhibit 19: Differences in Emissions between Recycled and Virgin PC Secondary Products Manufacture ($MTCO_2E$/Short Ton)

Product/ Material	Product Manufacture Using 100% Virgin Inputs ($MTCO_2E$/Short Ton)			Product Manufacture Using 100% Recycled Inputs ($MTCO_2E$/Short Ton)			Difference Between Recycled and Virgin Manufacture ($MTCO_2E$/Short Ton)		
	Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy	Process Energy	Transpor-tation Energy	Process Non-Energy
Asphalt	0.03	0.01	0.00	0.32	0.07	0.00	0.29	0.06	0.00
Steel Sheet	0.85	0.10	1.47	0.72	0.05	0.02	-0.13	-0.05	-1.45
Lead Bullion	1.13	0.05	0.03	1.14	0.29	0.02	0.01	0.25	-0.01
CRT Glass	0.53	0.02	0.16	0.42	0.39	–	-0.11	0.37	-0.16
Copper Wire	7.39	0.03	0.00	5.91	0.16	0.00	-1.48	0.12	–
Aluminum Sheet	12.46	0.52	2.69	0.94	0.07	–	-11.52	-0.45	-2.69

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

Step 4. *Adjust the emissions differences to account for recycling losses.* In the case of PCs, data indicated an 18 percent recovery-stage loss rate for PCs (i.e., 82 percent of recovered PCs for recycling were actually sent to a recycler; the remainder were landfilled). For the manufacturing stage, data indicated a 35-percent loss rate for asphalt; a 0.5-percent loss rate for lead bullion; and a 1-percent loss rate for copper wire. Zero manufacturing-stage losses were reported for the other secondary products. Because losses occur in both the recovery and manufacturing stages, the net retention rate was calculated as the product of the recovery and manufacturing retention rates, as shown below, using asphalt as an example:

Net Retention Rate for Asphalt = Recovery Stage Retention Rate × Manufacturing Stage Retention Rate

= 82.2% × 65.2% = 53.6%

Exhibit 20 shows how the retention rates are calculated. The differences in emissions from process energy, transportation energy and non-energy processing are then adjusted to account for the loss rates by multiplying the final three columns of Exhibit 19 by the retention rates in column (d) of Exhibit 20.

Exhibit 20: Calculation of Adjusted GHG Savings for PCs Recycled into Secondary Products

(a) Product/ Material	(b) Recovered Materials Retained per Short Ton PCs Collected (%)	(c) Short Tons Product Produced per Short Ton Recycled Inputs (%)	(d) Short Tons Product Made per Short Ton PCs Collected (%) (= b × c)
Asphalt	82.2%	65.2%	53.6%
Steel Sheet	82.2%	100.0%	82.2%
Lead Bullion	82.2%	99.5%	81.8%
CRT Glass	82.2%	100.0%	82.2%
Copper Wire	82.2%	99.0%	81.4%
Aluminum Sheet	82.2%	100.0%	82.2%

Step 5. *Weight the results by the percentage of recycled PCs that the secondary product makes up.* Using the percentages provided in Exhibit 12, EPA weights the individual GHG differences from Step 4 for each of the secondary products. In the case of asphalt, the $MTCO_2E$/Short Ton estimates from Step 3, as modified by the loss rates in Step 4, were weighted by the percentage of recycled PCs converted to asphalt (38 percent), as shown below:

Process Energy: -0.16 $MTCO_2E/\text{short ton}_{\text{unweighted}}$ x 38 % = -0.06 $MTCO_2E$/short ton
Transportation Energy: -0.03 $MTCO_2E/\text{short ton}_{\text{unweighted}}$ x 38 % = -0.01 $MTCO_2E$/short ton
Process Non-energy: -0.00 $MTCO_2E/\text{short ton}_{\text{unweighted}}$ x 38 % = -0.00 $MTCO_2E$/short ton

Each product's process energy, transportation energy and process non-energy emissions are weighted by the percentages in Exhibit 12 and then they are summed as shown in the final column of Exhibit 21.

Exhibit 21: Personal Computer Recycling Emission Factors ($MTCO_2E$/Short Ton)

	Recycled Input Credit for Recycling One Short Ton of PCs			
Product/Material	**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 PCs Recycled)**
Asphalt	0.06	0.01	0.00	0.07
Steel Sheet	-0.03	-0.01	-0.32	-0.36
Lead Bullion	0.00	0.02	0.00	0.02
CRT Glass	0.00	0.01	0.00	0.00
Copper Wire	-0.06	0.01	0.00	-0.06
Aluminum Sheet	-1.74	-0.07	-0.41	-2.21
PC total	**NA**	**NA**	**NA**	**-2.53**

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

Step 6. *Factor in process emissions from demanufacturing PCs.* EPA assumes that PCs are shredded to extract the materials that are recycled into secondary products. The act of shredding computers consumes electricity, and the GHG emissions associated with this electricity use are allocated to the total emission factor for recycling one short ton of PCs. The final PC recycling emission factor is the sum of the weighted secondary products' emission factors from Exhibit 21 and the process emissions from demanufacturing PCs as shown in Exhibit 23.

Exhibit 22: Calculation of Recycling Emission Factor for PCs

Product/Material/Stage	**Total (GHG Emissions in $MTCO_2E$/Short Ton)**
Asphalt	0.07
Steel Sheet	-0.36
Lead Bullion	0.02
CRT Glass	0.00
Copper Wire	-0.06
Aluminum Sheet	-2.21
Demanufacturing Emissions	0.26
PCs (Sum)	**-2.26**

Totals may not sum due to independent rounding.

4.2.2 Limitations

Given the complex open-loop recycling process, the international flows of end-of-life electronics, and a lack of consistent and up-to-date information on PC recycling, the recycling factor for PCs is subject to important limitations. A primary data gap is the availability of representative life-cycle inventory (LCI) data for PCs and the materials recovered from them in the open-loop recycling process. For this analysis, we utilize an LCI from 2001 for PCs (FAL, 2002) and assume that these data are representative of the current processes used to collect and recover materials from PCs in the United States. This source was selected because it offered consistent and sufficient LCI data to produce an emission factor; however, but improved LCI data in at least three areas could have important effects on our results:

First, the recycling pathway for plastics recovered from PCs is largely unknown and poorly quantified. In this analysis, we assume that plastics are recycled as filler material in asphalt. This is very likely not representative of the dominant recycling pathway for plastics (Masanet, 2009). In reality, plastics are more likely sent overseas to Asia and recycled into low-grade plastic products (Masanet, 2009; McCarron, 2009; Moore, 2009). This might result in greater energy and GHG emissions savings from plastics recycling, but LCI data were not available for calculating a recycling credit for this pathway.

Second, the recycling pathways for CRT glass recovered from CRT monitors dismantled in the United States are not well quantified. It is uncertain what fraction of CRT glass is currently sent to smelters in North America versus recycled into new CRT glass in Asia, although it is likely that glass-to-glass recycling will diminish as the market for CRT monitors declines due to customers switching to flat-panel models (Gregory et al., 2009). Our analysis also assumes that CRT monitors are dismantled and sorted in the United States. A fraction of recovered CRT monitors, however, are likely exported to developing countries. This practice may increase transportation energy and GHG emissions, and result in different dismantling and recovery processes that could influence the energy and GHG emission implications of recycling PCs. The data were insufficient to quantify the flow of CRT monitors from the United States to other countries for recycling.

Finally, only a few integrated shredders are currently operated in the United States (Masanet, 2009). As a result, the emission factor for demanufacturing PCs may be inaccurate and dismantling PCs by hand may be a more common practice. Dismantling PCs by hand is likely to be less energy- and GHG-intensive than shredding them (Liu et al., 2009).

In addition, the life-cycle data for PCs assumes that the monitor is a CRT monitor. However, in the last several years, the sales and use of CRT monitors have been almost entirely supplanted by flat-panel monitors in the United States. This is a significant limitation of the analysis, as CRT and flat-panel monitors differ considerably in composition and weight.

4.3 COMPOSTING

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

4.4 COMBUSTION

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

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

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

Exhibit 23: Components of the Combustion Net Emission Factor for PCs ($MTCO_2E$/Short Ton)

Material/ Product	Raw Material Acquisition and Manufacturing (Current Mix of Inputs)	Transportation to Combustion	CO_2 from Combustion	N_2O from Combustion	Avoided Utility Emissions	Steel Recovery	Net Emissions (Post-Consumer)
PCs	–	0.03	0.38	–	-0.12	-0.45	-0.17

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

4.4.1 Developing the Emission Factor for Combustion of PCs

EPA estimates that PCs have a carbon content of 12 percent and that 98 percent of that carbon is converted to CO_2 during combustion. This carbon is contained within the plastics in PCs. The resulting direct CO_2 emissions from combustion of carbon in PCs are presented in Exhibit 25.

Exhibit 24: PC Combustion CO_2 Emission Factor Calculation ($MTCO_2E$/Short Ton)

Components	% of Total Weight	Carbon Content	Total $MTCO_2E$/Short Ton of PCs	Carbon Converted to CO_2 during Combustion	Combustion CO_2 Emissions ($MTCO_2E$/Short Ton of PCs)
ABS	8%	84%	7%	98%	0.23
PPO/HIPS	6%	85%	5%	98%	0.15
PCs (Sum)	**NA**	**NA**	**12%**	**98%**	**0.38**

NA = Not applicable.
Totals may not sum due to independent rounding.

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

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

Exhibit 25: Utility GHG Emissions Offset from Combustion of PCs

(a) Material/Product	(b) Energy Content (Million Btu per Short Ton)	(c) Combustion System Efficiency (%)	(d) Emission Factor for Utility-Generated Electricity ($MTCO_2E$/ Million Btu of Electricity Delivered)	(e) Avoided Utility GHG per Short Ton Combusted ($MTCO_2E$/Short Ton) (e = b × c × d)
PCs	3.1	17.8%	0.23	0.12

The combustion of PCs at WTE facilities also includes steel recovery and recycling processes. Approximately 90 percent of combustion facilities have ferrous recovery systems. FAL reports that one short ton of PCs contains 286 pounds of steel. Since some of this steel is lost during combustion, we included a ferrous recovery factor of 98 percent. The emission impacts of recycling of this recovered steel are shown in Exhibit 27.

Exhibit 26: Steel Production GHG Emissions Offset from Steel Recovered from Combustion of PCs

Material	Short Tons of Steel Recovered per Short Ton of Waste Combusted	Avoided CO_2 Emissions per Ton of Steel Recovered ($MTCO_2E$/Short Ton)	Avoided CO_2 Emissions per Ton of Waste Combusted ($MTCO_2E$/Short Ton)
PCs	0.25	1.80	0.45

4.5 LANDFILLING

4.5.1 Overview and Developing the Emission Factor for Landfilling of PCs

Roughly 60 percent of PCs entering the municipal solid waste stream are disposed of, and the vast majority of these end up in landfills. In WARM, landfill emissions comprise landfill CH_4 and CO_2 from transportation and landfill equipment. WARM also accounts for landfill carbon storage, and avoided utility emissions from landfill gas-to-energy recovery. However, since PCs are inorganic and do not contain biogenic carbon, there are zero emissions from landfill CH_4, zero landfill carbon storage, and zero avoided utility emissions associated with landfilling PCs, as shown in Exhibit 28. Greenhouse gas emissions associated with RMAM are not included in WARM's landfilling emission factors. As a result, the emission factor for landfilling PCs represents only the emissions associated with collecting the waste and operating the landfill equipment. EPA estimates these emissions to be 0.04 $MTCO_2E$/short ton of PCs landfilled. For more information, refer to the Landfilling chapter.

Exhibit 27: Landfilling Emission Factor for PCs ($MTCO_2E$/Short Ton)

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

NA = Not applicable.
– = Zero emissions.

5 LIMITATIONS

As outlined in the recycling section (4.2), the open-loop recycling process has several limitations, including limited availability of representative LCI data for PCs and the materials recovered from them.

- The recycling pathway for plastics recovered from PCs is largely unknown and poorly quantified. While we assume that plastics are recycled as filler material in asphalt, in reality they are more likely sent overseas to Asia and recycled into low-grade plastic products.

- The recycling pathways for CRT glass recovered from CRT monitors dismantled in the United States are not well quantified, and it is likely that glass-to-glass recycling will diminish as the market for CRT monitors declines due to customers switching to flat-panel models (Gregory et al., 2009).
- Emission factors are based on PCs comprising a CPU and a CRT monitor, but CRT monitors are no longer common in PCs sold in the United States, having been replaced by flat-panel monitors.
- While we assume that CRT monitors are dismantled and sorted in the United States, a fraction of recovered CRT monitors are likely exported to developing countries.
- Only a few integrated shredders are currently operated in the United States, and as a result, the emission factor for demanufacturing PCs may be inaccurate and dismantling PCs by hand may be a more common practice, reducing the associated energy and GHG intensities.

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